Application of the 4C code to the thermal-hydraulic analysis of the CS superconducting magnets in EAST

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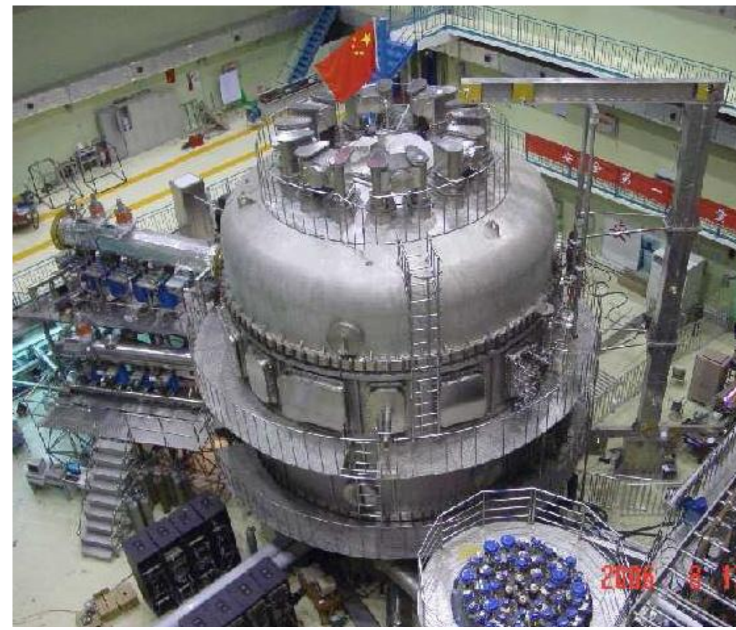
Outline

1) Problem
2) Tool
3) Model
4) Preliminary results
5) Conclusions and perspective

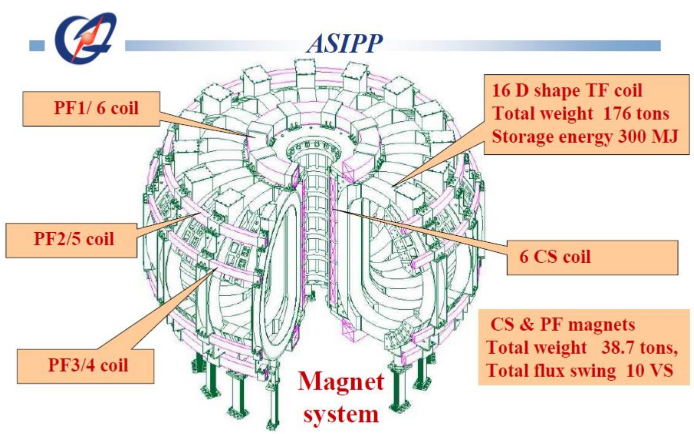
EAST tokamak

- Experimental Advanced Superconducting Tokamak operates since 2006 in Hefei, China

Toroidal field, B	3.5 T
Plasma current, I_P	1.0 MA
Major radius, R_0	1.7 m
Minor radius, a	0.4 m

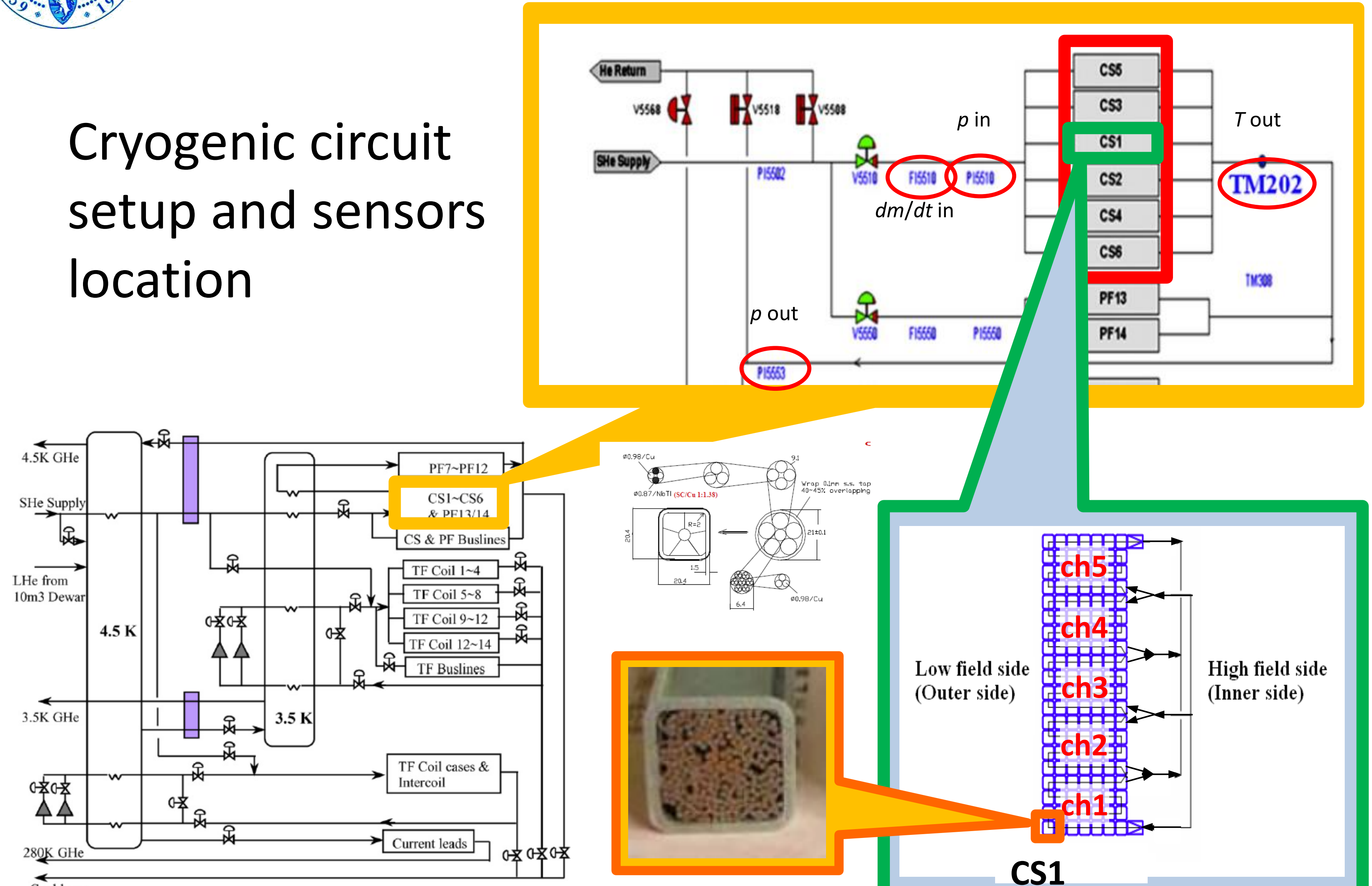


- SC coils based on NbTi strands



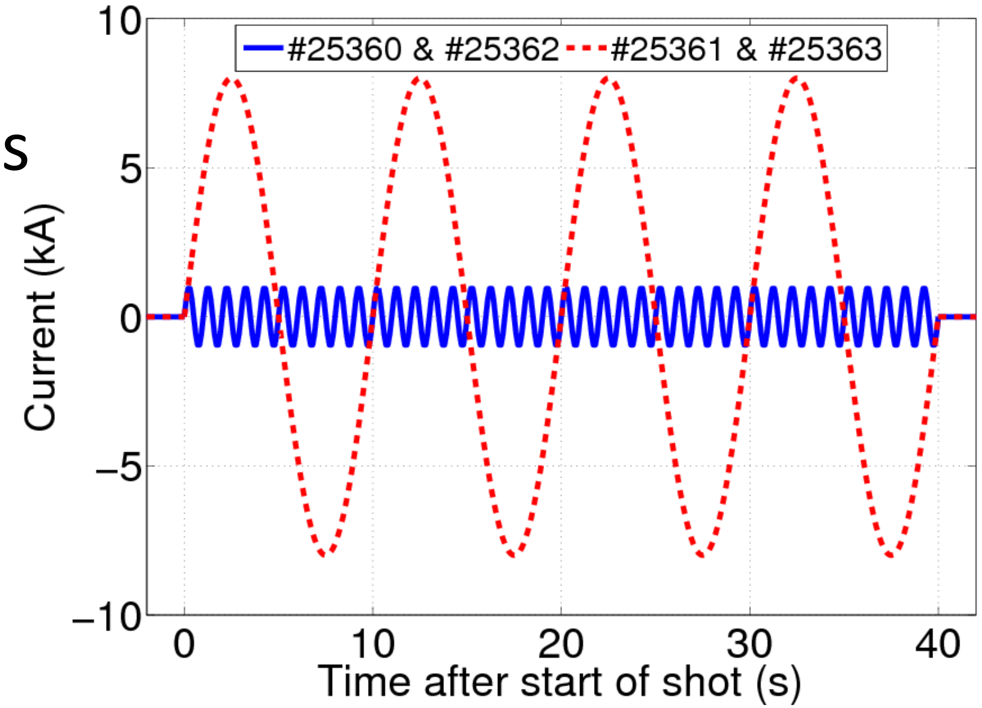
EAST Central Solenoid

Cryogenic circuit setup and sensors location

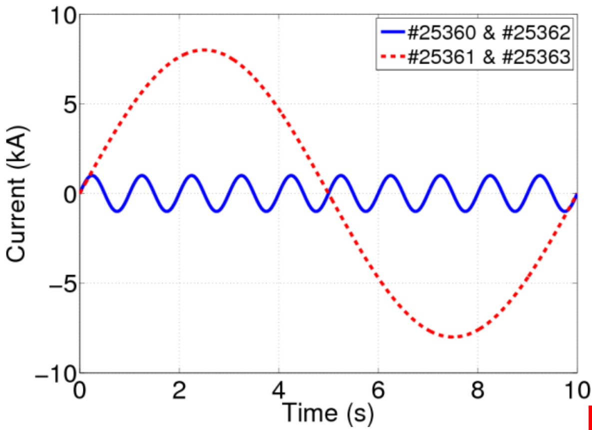


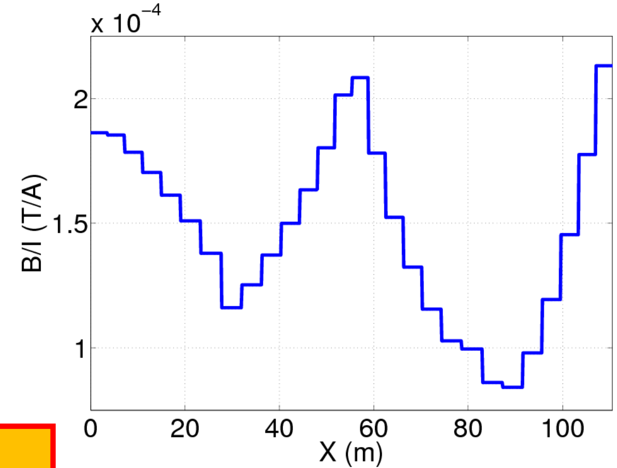
Selected shots

- Current in CS1 only
  - #25360: 1kA, 40 cycles
  - #25361: 8kA, 4 cycles
- Current in CS2 only
  - #25362: 1kA, 40 cycles
  - #25363: 8kA, 4 cycles

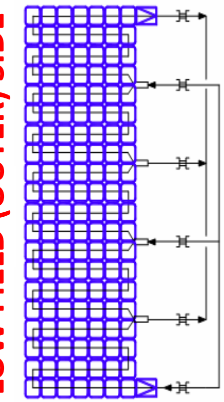


I(t) → B(x,t) → AC losses (x,t)

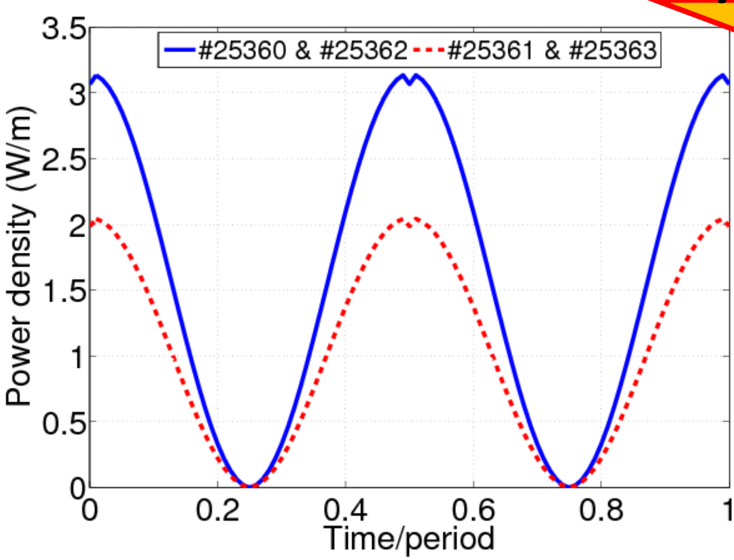


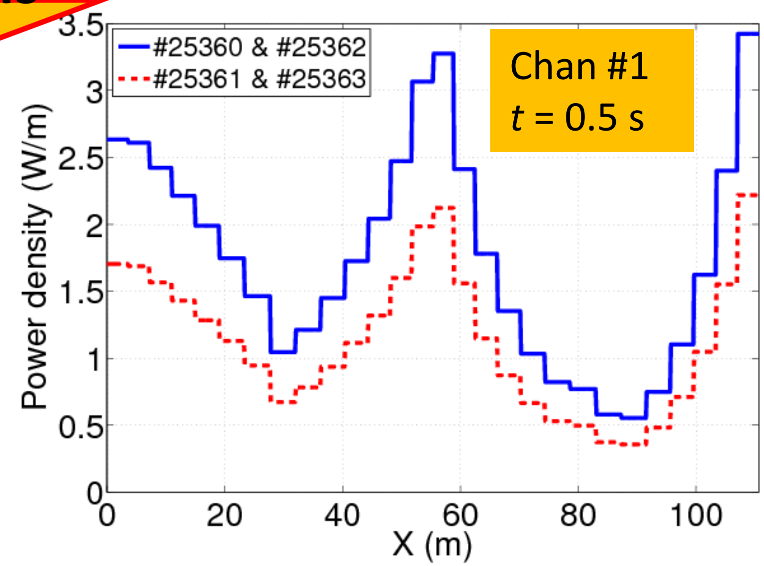


LOW FIELD (OUTER) SIDE

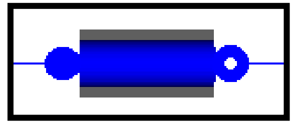


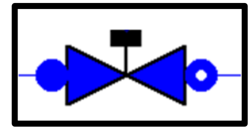
nτ = 34 ms



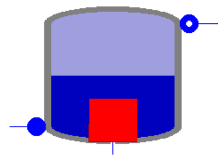


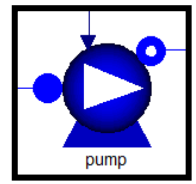
The 4C code





Cryogenic circuit(s) 0D/1D model

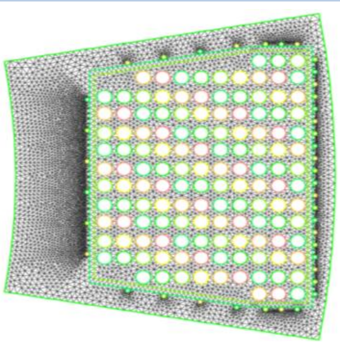


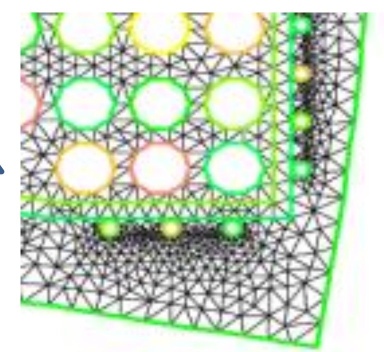


<u>Validated</u> quasi-3D thermal-hydraulic model of the **winding** + casing cooling channels ← Compressible 1D SHe flow in dual channel CICC + pipes, thermally coupled to neighbors

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

Quasi-3D FE thermal model of the **structures** (casing, radial plates, …)



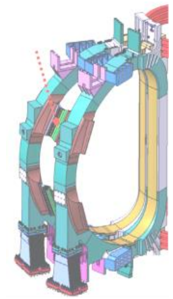


4C roadmap

Institute of Plasma Physics Chinese Academy of Sciences

TODAY



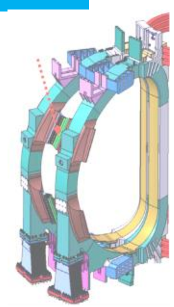

Interpretive validations

Development

Benchmarks

Predictive validations

Applications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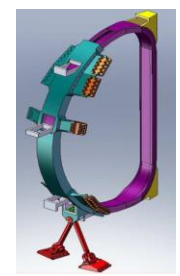
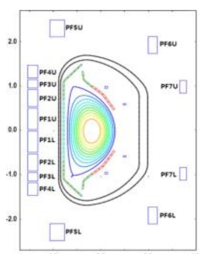
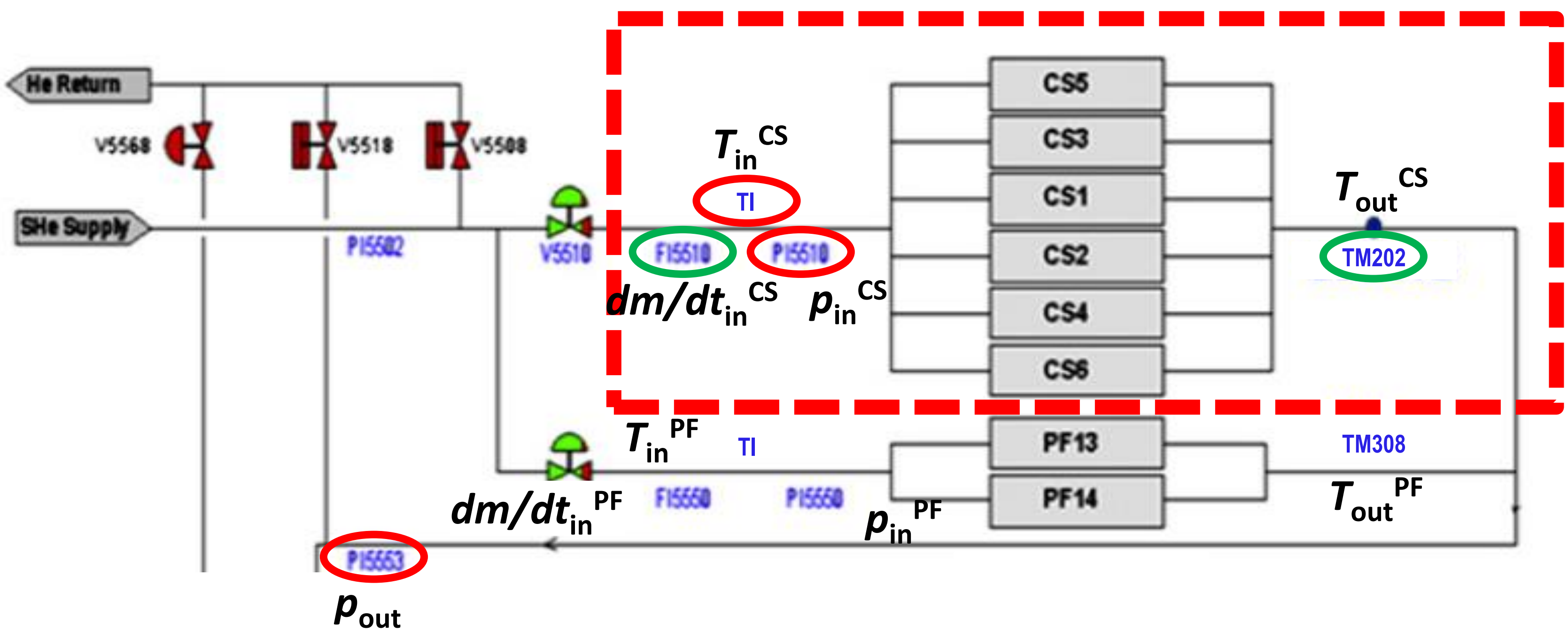



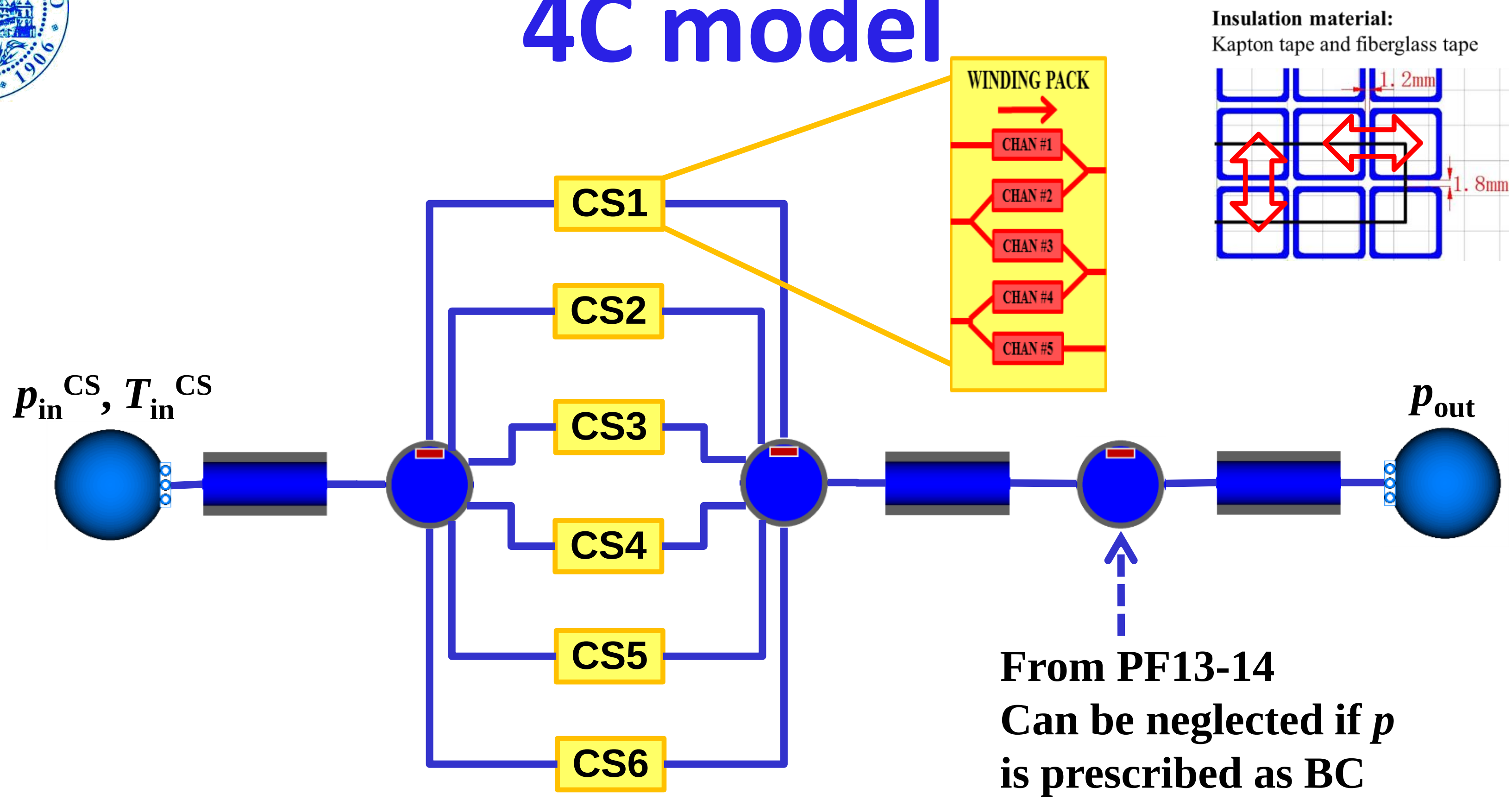
4C analysis domain

Available experimental data

- BCs (red ellipse)
- Exp-comp comparison (green ellipse)

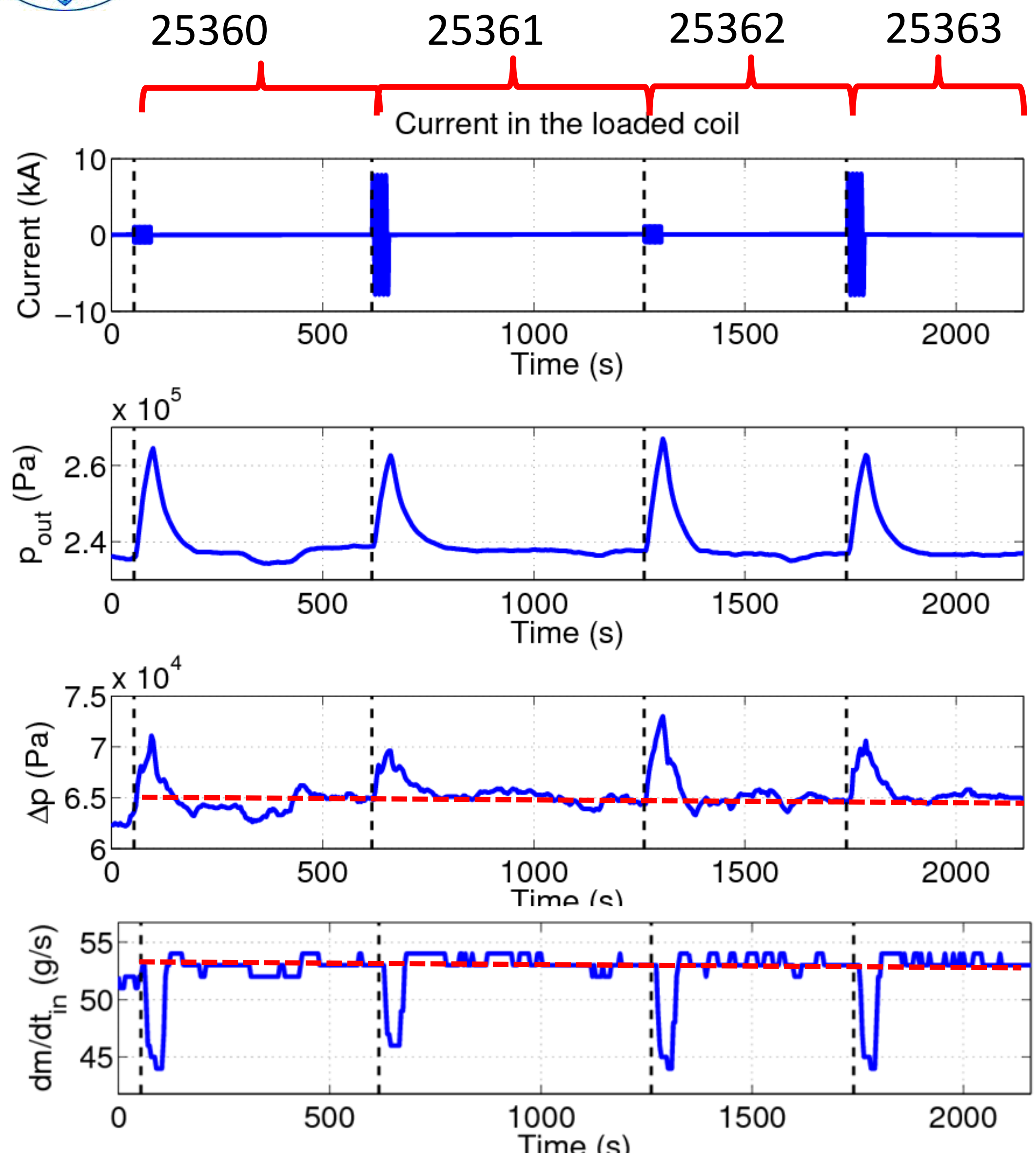


4C model



- No structures
- Common inlet and outlet manifolds (including the volume of the short pipes connecting the manifolds to the coils inlets and outlets)
- All coils are same ➔ well balanced d*m*/d*t* repartition @ steady state
- Inter-turn/inter-pancake (ITIP) coupling accounted for
- Heat transfer between neighboring coils neglected ($\delta^{ins}_{coils} = 10 \times \delta^{ins}_{pancakes}$)

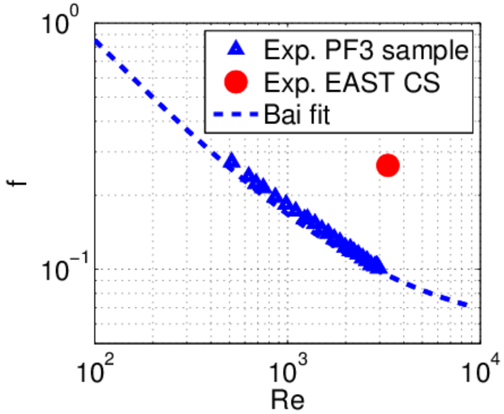
Hydraulics (exp)



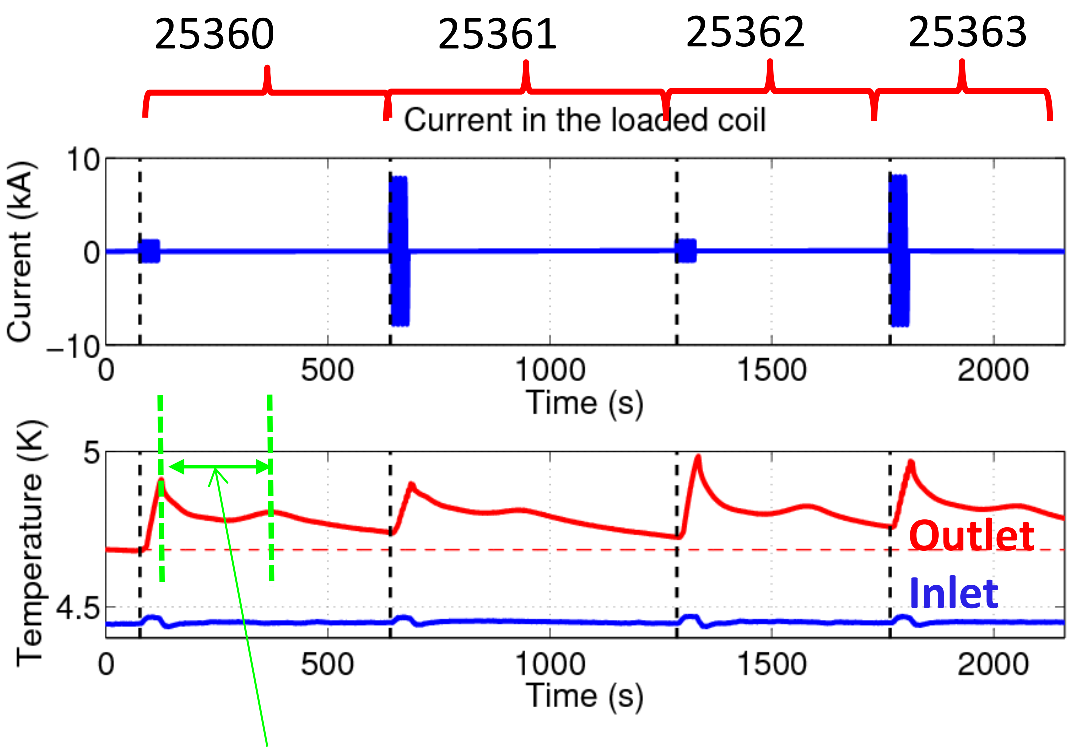
- CS1 and CS2 behave very similarly ➔ concentrate simulations on first two pulses
- Pressurization (reacting directly to the power deposition) starting from operation pressure very close to p_c (~2.27 bar)
- ~ steady state $\Delta p = (p_{in} - p_{out})$ and (dm/dt) can be used for conductor characterization

Hydraulics (comp)

- Friction factor *f*(*Re*) is needed for the simulation
- Katheder-type and porous medium type correlations (Long, RZ et al, Bottura, Bagnasco, Lewandowska, …)
- EAST PF3 sample (*should* be same as used in CS) tested in the past well reproduced by Katheder using ~38% void fraction (Bai)
- In order to reproduce the present CS steady state operation significantly smaller void fraction is needed (?) or ad-hoc multiplier of "standard" *f*



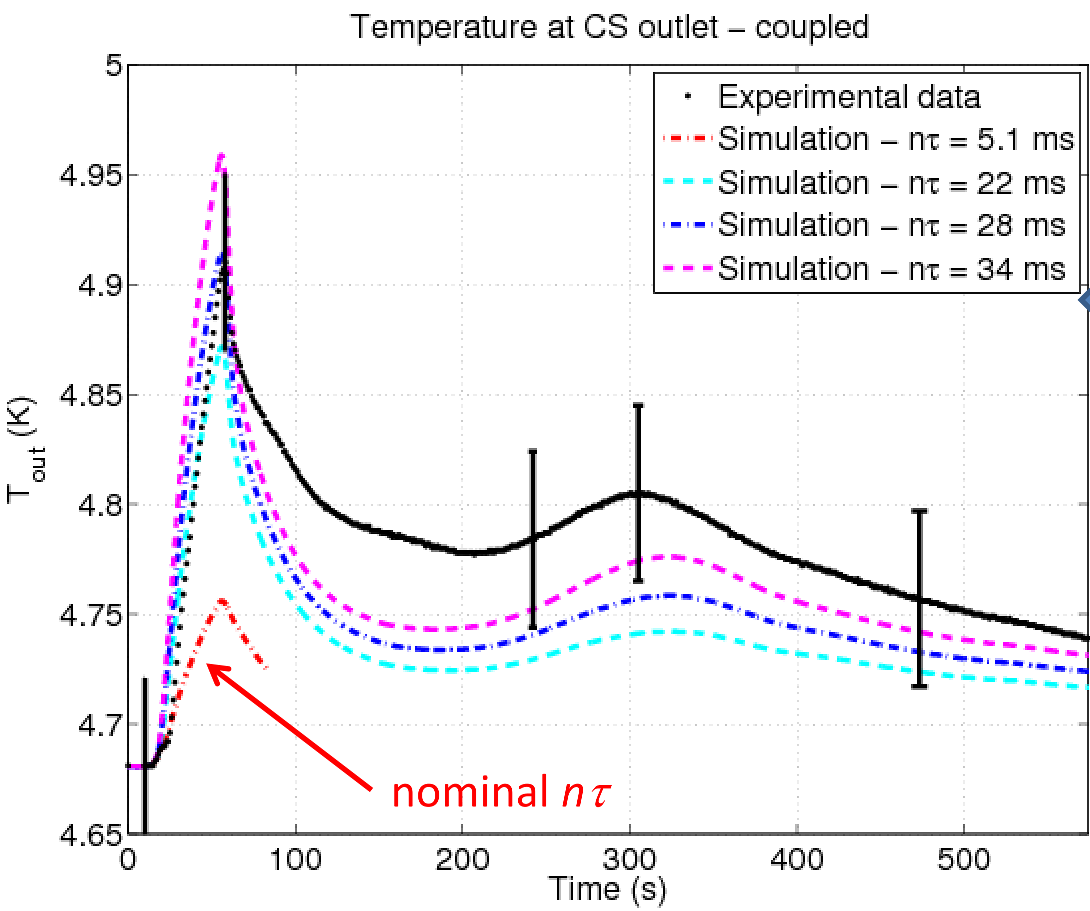
Thermal-hydraulics (exp)



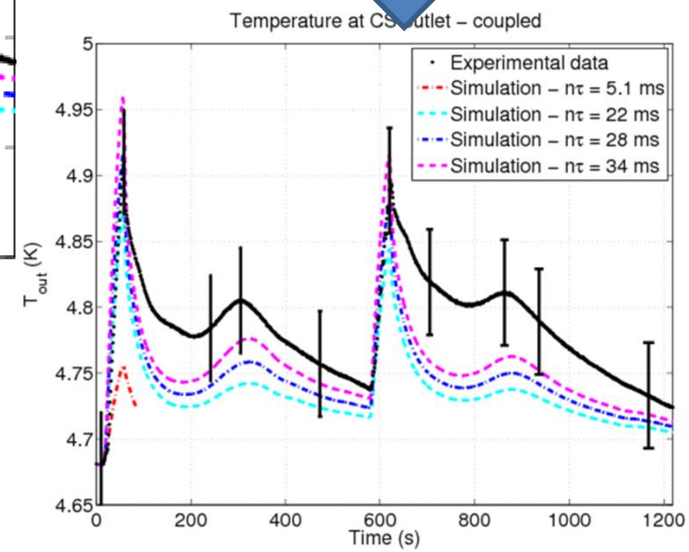
Estimate of He speed compatible with measured mass flow rate only for reduced flow area/void fraction wrt design value

- Steady state NOT reached before the subsequent shot is triggered
- Maximum temperature increase < 0.3 K, BUT it is average T after mixing ➔ Much larger effect expected in single loaded coil
- Static load ➔ $T_{out} > T_{in}$ @ steady state: assume constant load ➔ initial $T_{out} - T_{in}$ treated as constant offset

nτ parameterization

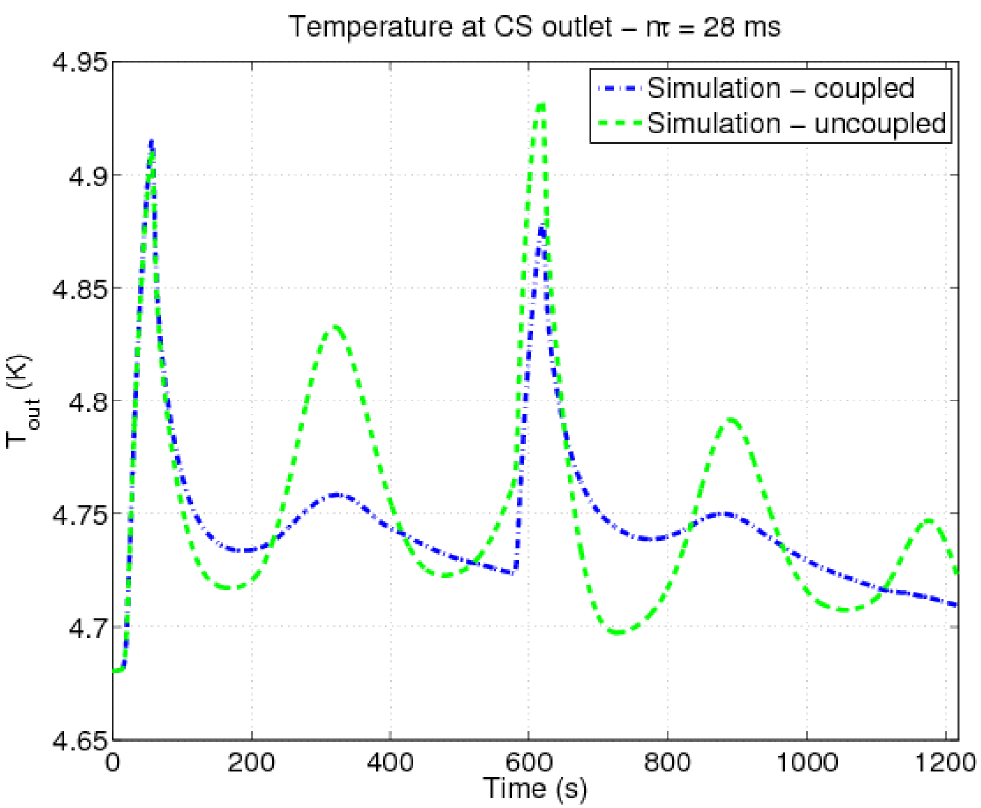


- Nominal nτ gives too small losses
- Increasing nτ leads to agreement within exp error bars at first pulse …
- … but agreement at second pulse is only qualitative



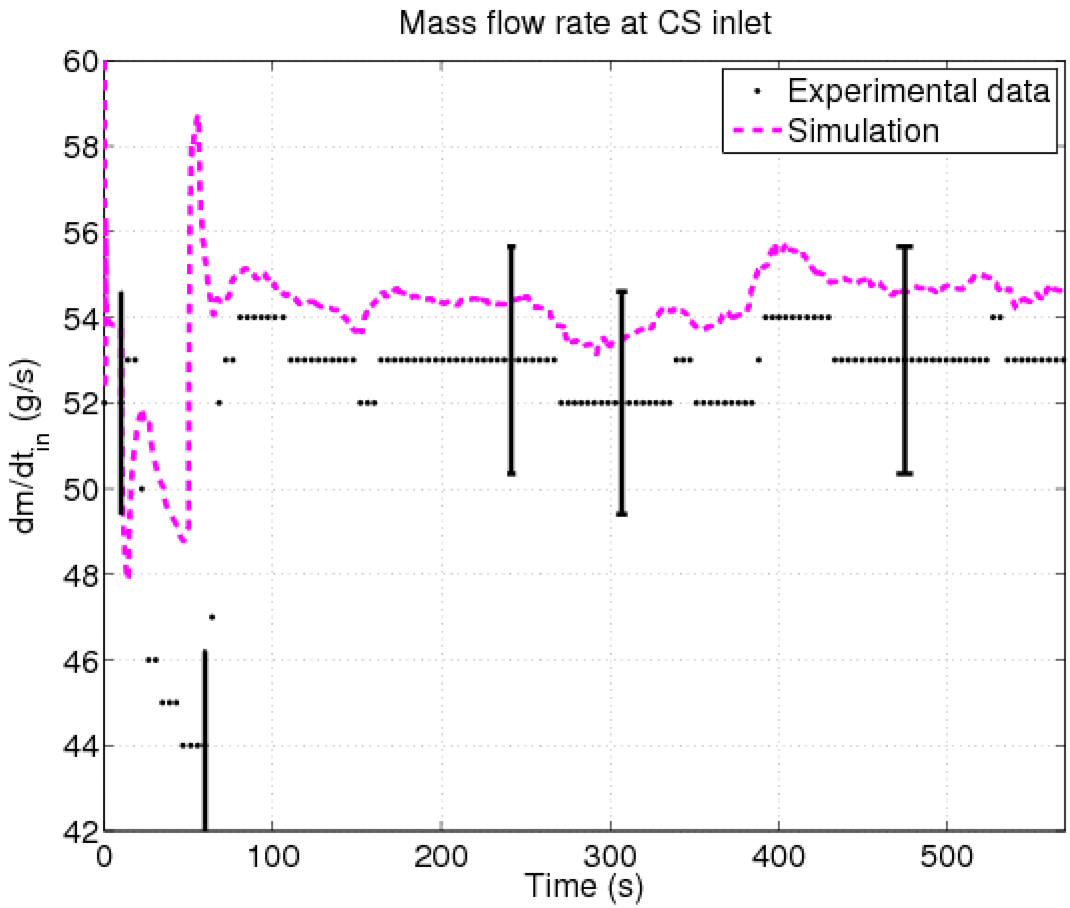
Effect of ITIP thermal coupling

- <u>Coupled</u> = nominal thermal coupling between turns and between pancakes
- <u>Uncoupled</u> = thermally insulated turns and pancakes



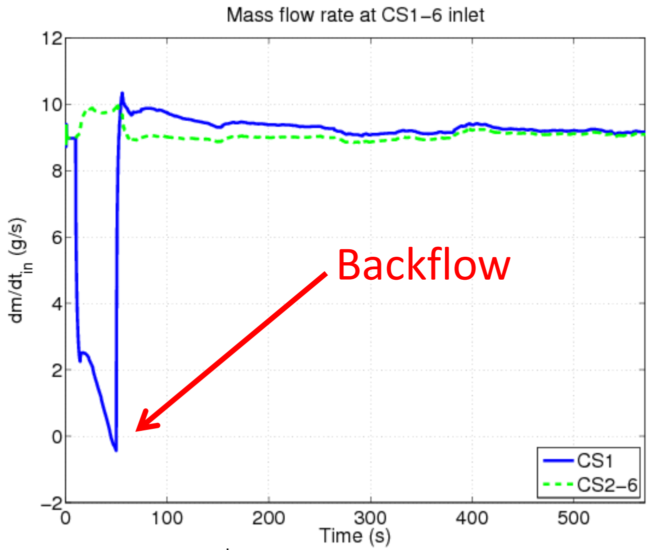
- First peak of the first pulse not influenced due to short He path
- Without coupling the temperature of the helium flowing between the high power deposition regions is lower than in the coupled case because no heat comes from the hotter neighbors.
- The reverse happens for the temperature peaks
- **Uncoupling (eg, contact resistance) should improve agreement at the second peak but worsen at the dip**
- Excessive uncoupling leads to third peak in simulation (not seen in exp)

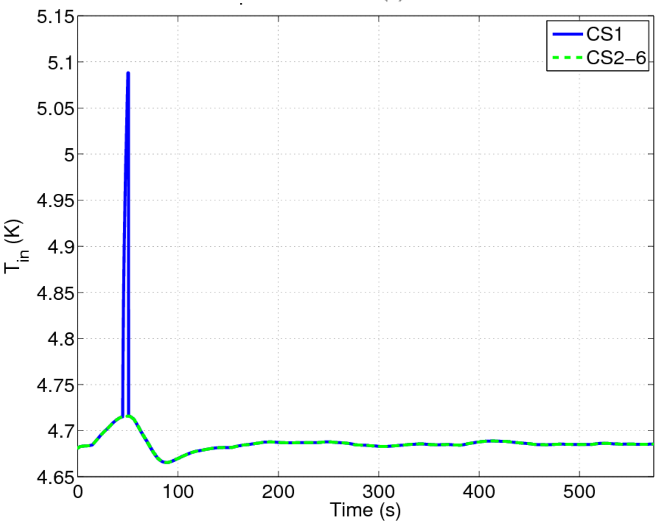
Inlet mass flow rate



Qualitative agreement, possibly still too low energy

Computed behavior at the inlet of the single coils





Conclusions and perspective

- The thermal-hydraulic effects of AC losses in the EAST central solenoid have been investigated with 4C
- The problem is affected by several experimental uncertainties concerning both the hydraulics of the CICC and the losses, and the number of available diagnostics is limited
- Preliminary results of the simulations are in qualitative agreement with the experiment, but larger $n\tau$ and smaller void fraction than expected are needed
- In perspective we should like to first clarify the experimental uncertainties, before performing further simulations with firmer input basis

Backup slides

Voidfraction and n*tau

- [Weng P.D., et al., "Test results and analyses of conductor short samples for HT-7U", Cryogenics 43, pp. 165-171 (2003)]

Table 2
The description of short samples

Conductor	TF	PF1	PF2	PF3
Cable pattern	$(2Sc + 2Cu) \times 3 \times 4 \times 5$	$(2Sc + 2Cu) \times 3 \times 4 \times 5$	$(2Sc + 2Cu) \times 3 \times 4 \times 5$	$(2Sc + 2Cu) \times 3 \times 4 \times 5$
NbTi strands	120	120	120	120
Cu strands	120 + 21	120 + 21	120 + 21	120 + 21
Twist pitches (mm)	50/86/117/200	40/86/117/260	40/86/117/260	40/86/117/260
Coating	Solder	Solder	Ni	Ni
Void fraction (%)	37.32	36.67	36.67	38.44

Table 3
The coupling time constants $n\tau$ of TF, PF1, PF2 and PF3

Name of conductors	TF (ms)	PF1 (ms)	PF2	PF3 (ms)
Time constant $n\tau$ (f = 0.05–0.1)	36.8	13.5	2.3	5.1
Time constant $n\tau$ (f = 2–6)	12.4	7.8	2.37	1.43

$B_{cp} = \mu \lambda_{SC} J_c R$

AC losses formulae

$$\frac{dB}{dt} = \frac{B}{I}\frac{dI}{dt}$$ (self field)

Provided — Computed (cosine)

Coupling losses

$$Q_{cp} = A_{strands} \begin{cases} \frac{n\tau}{\mu_0}(1-\beta_{cp})\left(\frac{dB}{dt}\right)^2 & (\beta_{cp} < 0.31) \\ \frac{4}{3\pi}\frac{B_{cp}}{\mu_0}\left(\frac{dB}{dt}\right) & (\beta_{cp} \geq 0.31) \end{cases} \quad \text{W/m}$$

B_{cp} is penetration field

$$B_{cp} = \mu_0 \lambda_{SC} J_c R$$

$$\beta_{cp} = \frac{\tau}{B_{cp}}\left|\frac{dB}{dt}\right| \qquad \lambda_{SC} = \frac{1}{1+CuRatio}$$

n=2, R=R_{strand}

+

Hysteresis losses (perpendicular field part)

$$Q_{hys} = \begin{cases} \frac{B^2}{6\mu_0 B_p}\left|\frac{dB}{dt}\right|\left(1-\frac{B}{4B_p}\right) A_{nonCu} \; (B<B_p) \\ \frac{2}{3\pi} J_c d_{eff}\left(1+\frac{I_{tr}^2}{I_c^2}\right)\left|\frac{dB}{dt}\right| A_{nonCu} \; (B \geq B_p) \end{cases} \quad \text{W/m}$$

$$B_p = \frac{\mu_0 J_c}{\pi} d_{eff}$$

d_{eff}=6µm

+

Eddy current losses in pure Cu strands

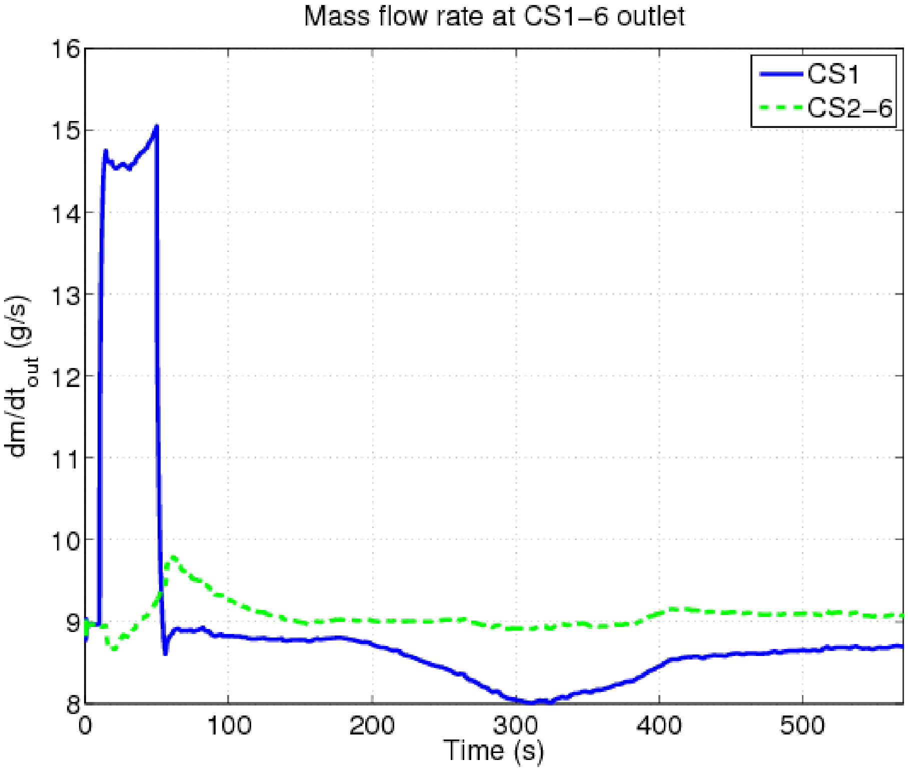
$$Q^{Cu}_{eddy\perp} = \left(\frac{R_{st}^2}{4\eta_{cu}}\right)\left(\frac{dB_\perp}{dt}\right)^2 A_{pure-Cu} \quad \text{W/m}$$

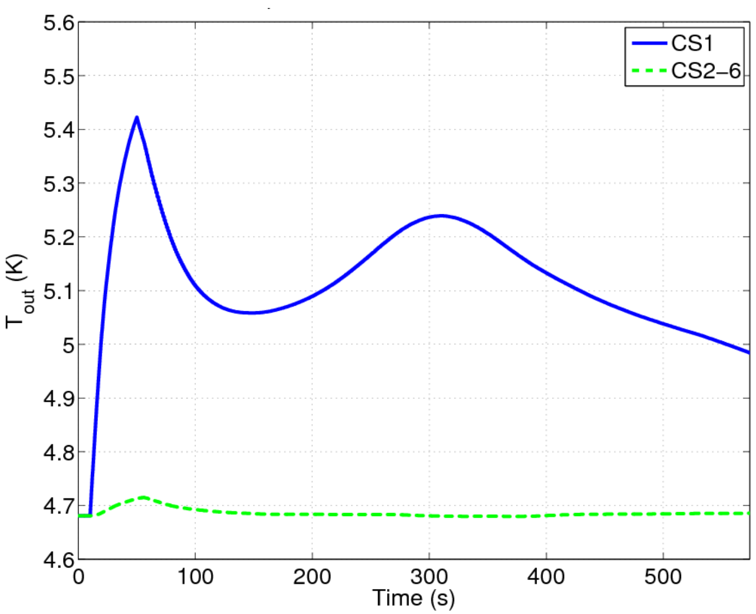
[Wang Q., et al., “Operating Temperature Margin and Heat Load in PF Superconducting Coils of KSTAR”, IEEE Trans. Appl. Supercond. 12, pp. 648-652 (2002)]

$n\tau_{CS}$=5.1 ms ≤ n$\boldsymbol{\tau}_{samples}$ ≤ nτ_{TF}=36.8 ms for ν~ 0.05–0.1 Hz, lower for ν~2-6 Hz

[Weng P.D., et al., “Test results and analyses of conductor short samples for HT-7U”, Cryogenics 43, pp. 165-171 (2003)]

Outlet mass flow rate





Calorimetry

Energy deposited (kJ)	Experiments	$n\tau$ = 22 ms		$n\tau$ = 28 ms		$n\tau$ = 34 ms	
		Simulation (1)	Simulation (2)	Simulation (1)	Simulation (2)	Simulation (1)	Simulation (2)
Shot 1 (564 s)	49.0 REF	39.8 -19%	39.6 -19%	41.8 - 15%	41.6 - 15%	44.0 -10%	43.5 -11%
Shot 2 (645 s)	60.5 REF	44.8 -26%	44.8 -26%	48.7 -19%	48.4 - 20%	50.0 -17%	49.7 -18%
Total	109.5 REF	84.6 -23%	84.4 -23%	90.5 - 17%	90.0 -18%	94.0 -14%	93.2 -15%

- Experiments → $\int \dot{m}_{in}^{\exp}(h_{out}^{\exp} - h_{in}^{\exp})dt$
- Simulation (1) → $\int \dot{m}_{in}^{sim}(h_{out}^{sim} - h_{in}^{sim})dt$
- Simulation (2) → $\int (\dot{m}_{out}^{sim}h_{out}^{sim} - \dot{m}_{in}^{sim}h_{in}^{sim})dt$