Prediction and analysis of quench propagation test results in the ITER TF Insert Coil using the 4C code

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Outline

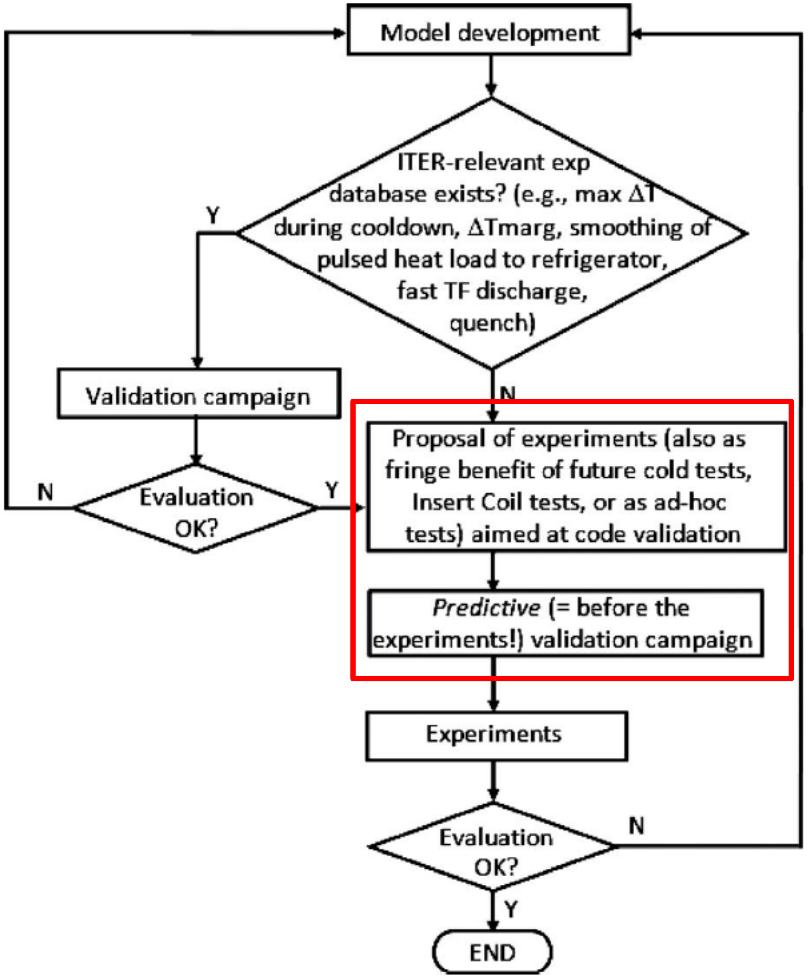
- Background and aim of the work
- The ITER TF Insert Coil
- The 4C code
- Experimental and predictive analysis setup
- Predictions vs. measurements
- Interpretive (post test) model upgrade and comparison with measurements
- Conclusions

Background and aim of the work

- Design, operation and protection of superconducting magnets may significantly benefit from reliable codes/models
- Reliability of codes must be demonstrated by continuous V&V, including predictive (i.e. blind) tests
- 2016-2017 experiments performed on the ITER Toroidal Field Insert (TFI) Coil at QST Naka, Japan → fringe benefit to verify the predictive capability of the 4C code concerning quench propagation in Nb_3Sn ITER magnets, which is the **aim of the present work**

.NSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013

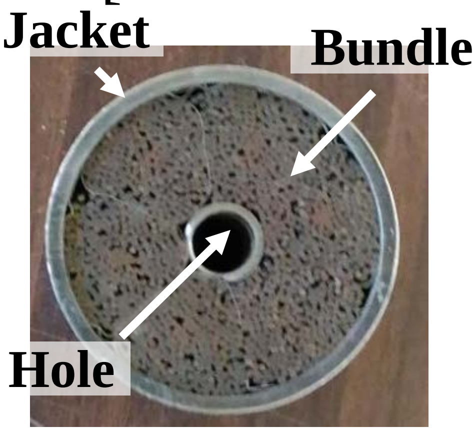
Roadmap of Code Verification&Validation



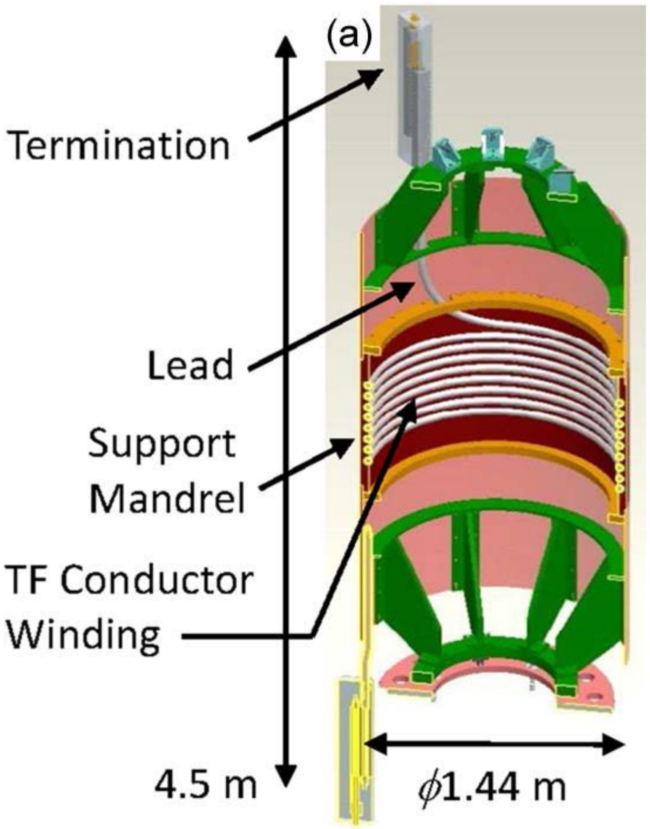
[R.Z.&L.S., IEEE TAS, 2013]

The ITER TFI coil

TFI test in the CSMC bore aimed at verifying superconducting performance of TF conductor for ITER [Database of TF Insert Coil Experiment in 2016]



Jacket ID (OD)	39.8 (43.83) mm
Void fraction	31.3 %
Central channel ID/OD	8/10 mm
# strands (SC + Cu)	900+522
Strand diam. (SC / Cu)	0.822 / 0.821 mm



[H. O., IEEE TAS, 2016]

The 4C code


Cryogenics 50 (2010) 167–176

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

ELSEVIER

The 4C code for the cryogenic circuit conductor and coil modeling in ITER

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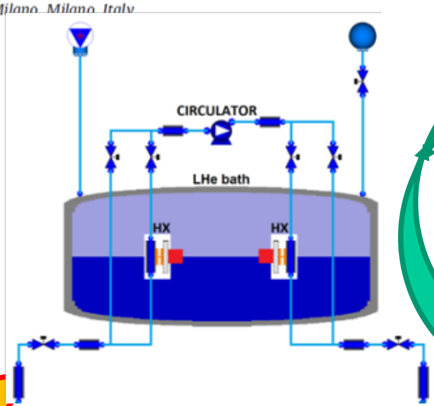
Multi-conductor thermal-hydraulic model of the **winding**

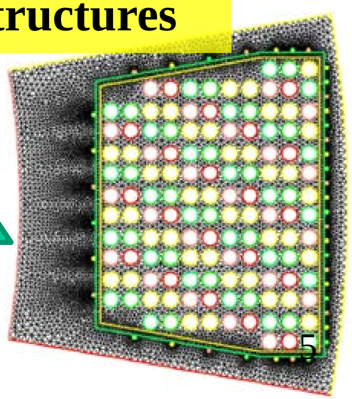


Simulation of TH transients in SC magnet systems

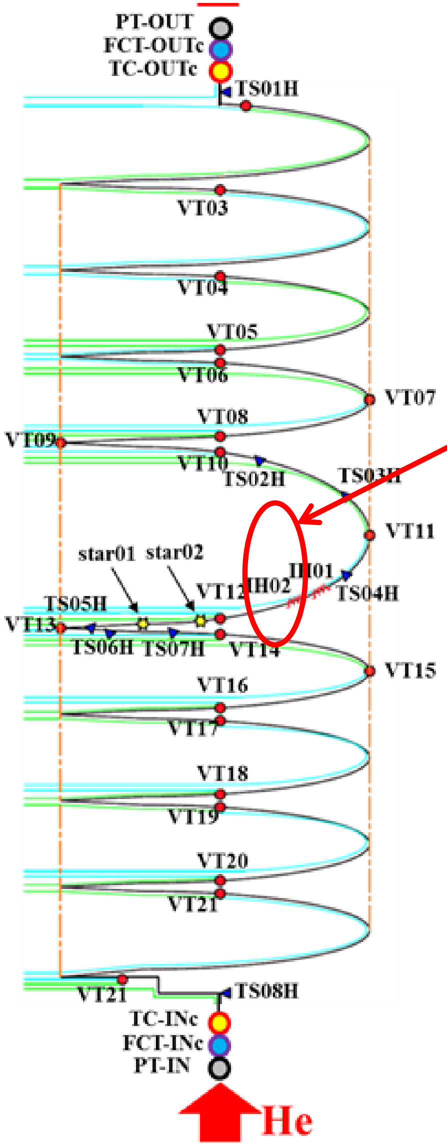
Quasi-3D FE model of the **structures**

Extensively **validated** (QUELL, all ITER Model and Insert Coils, EAST, KSTAR, W7X, …, HELIOS)

Cryogenic circuit(s) (winding + casing cooling channels)

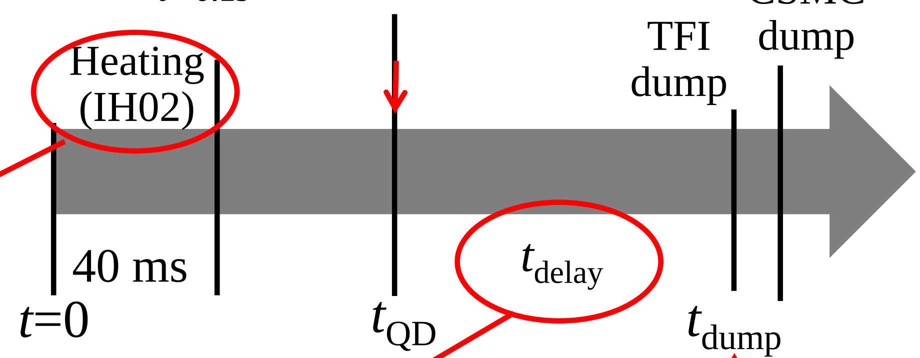


Experimental setup



Quench detection

$$\int_{t-0.1s}^{t} VD_{all}\, dt \geq 0.01\, V \times s$$



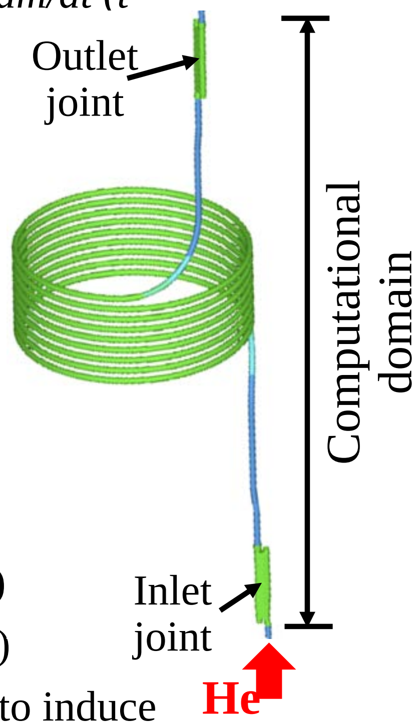
Stop simulations here

t_{delay}	Shot	IH
3 s	109 – 11	IH02
5 s	110 – 6	IH02
7.5 s	**113 – 10**	**IH02**
3 s	118 – 8	IH02+IH01
3 s	120 – 5	IH02

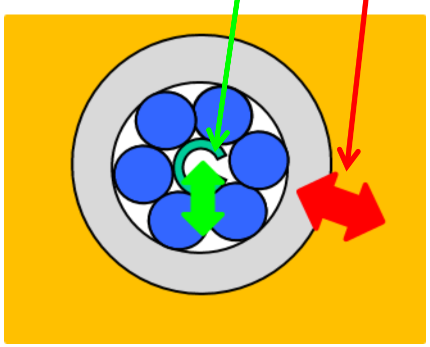
HERE we focus on shot 113-10 (comparison with shorter delays shows very good reproducibility, except T_{jk} and early *dm/dt*)

Predictive analysis setup

- Initial conditions
  - $T(x, t=0) = T_0 = 5.7$ K
  - Linear p profile between $p_{in}(t=0) = 5.6$ bar (assumed) and $p_{out}(t=0)$ set to give $dm/dt\ (t=0) = 8$ g/s (from test program)
- Boundary conditions
  - $T_{in}(t) = T_0$ (from test program)
  - $p_{in}(t) = 5.6$ bar
  - $p_{out}(t) = p_{out}(t=0)$
- Driver
  - ~11 cm heated zone (from data book)
  - 20% fraction in the strands (assumed)
  - Energy deposited > MQE (sufficient to induce a quench)

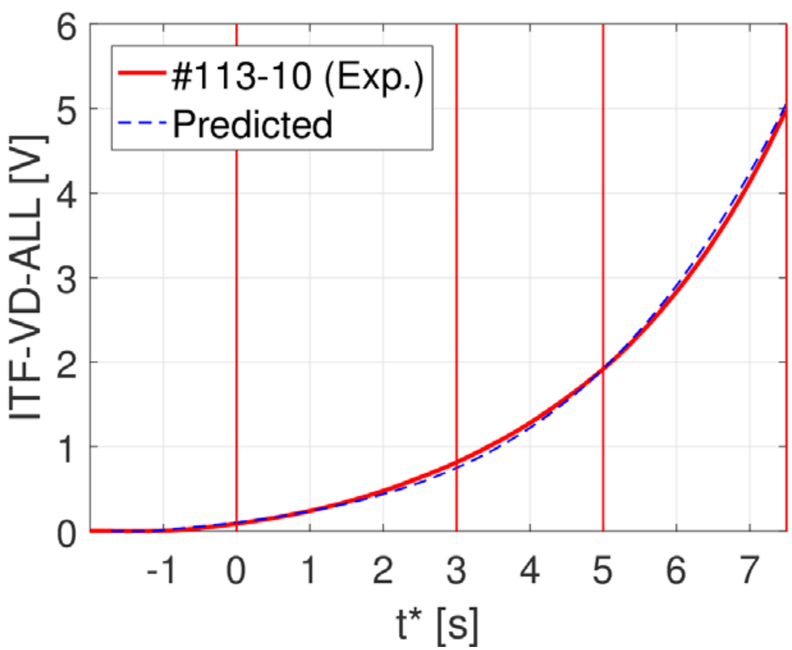


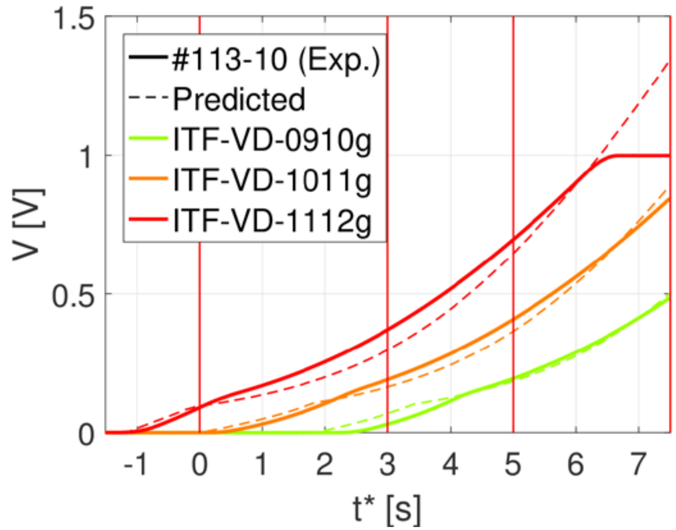
- TH parameters from [A. B. et al., EUCAS 2017]
  - Friction factors
  - Jacket – mandrel HTC_{mnd}
  - Hole-bundle HTC_{HB}
- Mandrel assumed to stay at constant T_0



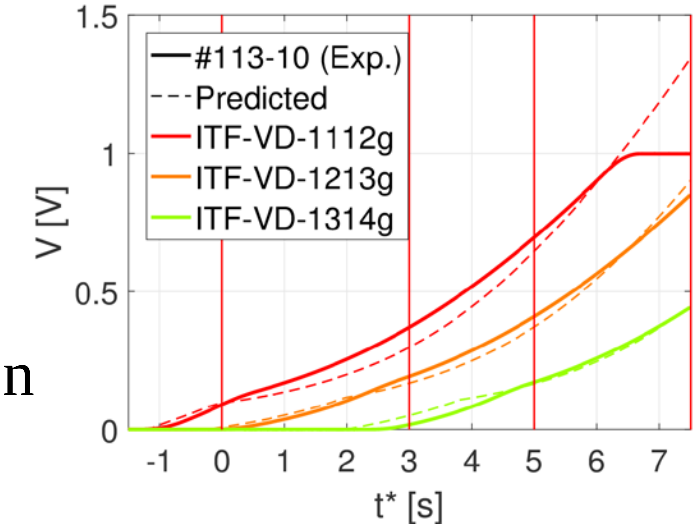
Predictions vs. experiment: voltages

$t^* \equiv t - t_{QD}$





Downstream

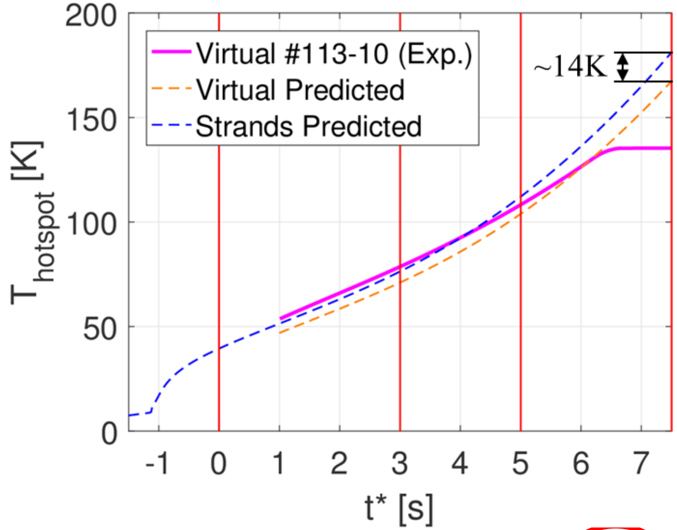


Upstream

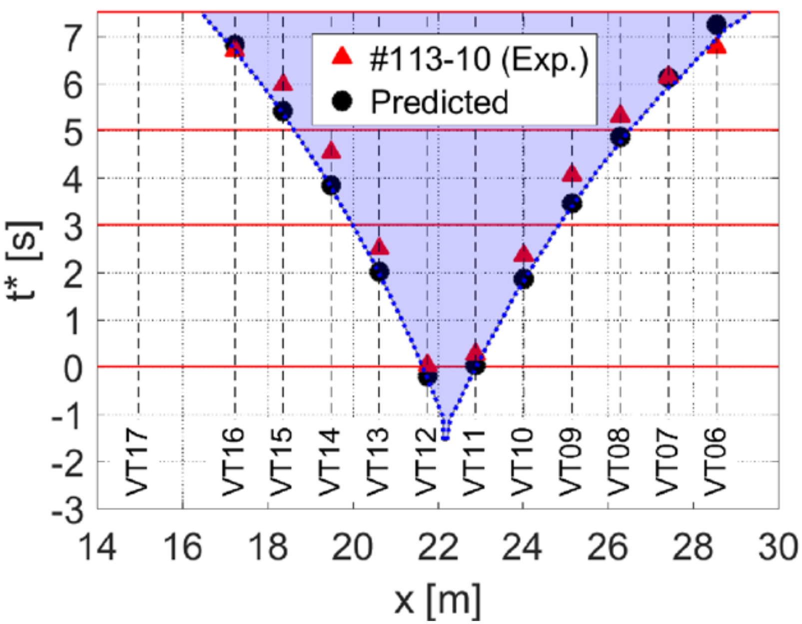
- VD-ALL reproduced within ~2-3%
- Mismatch on *local* VDs < ~15-20% "compensated" by faster propagation (anticipated take-off)

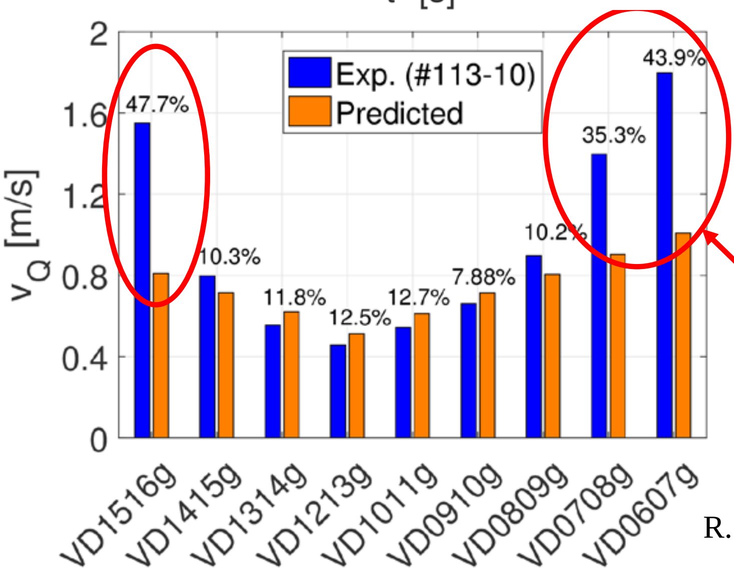
Predictions vs. experiment: hot spot T and NZ propagation

$T_{hotspot}$ well below 250 K design limit



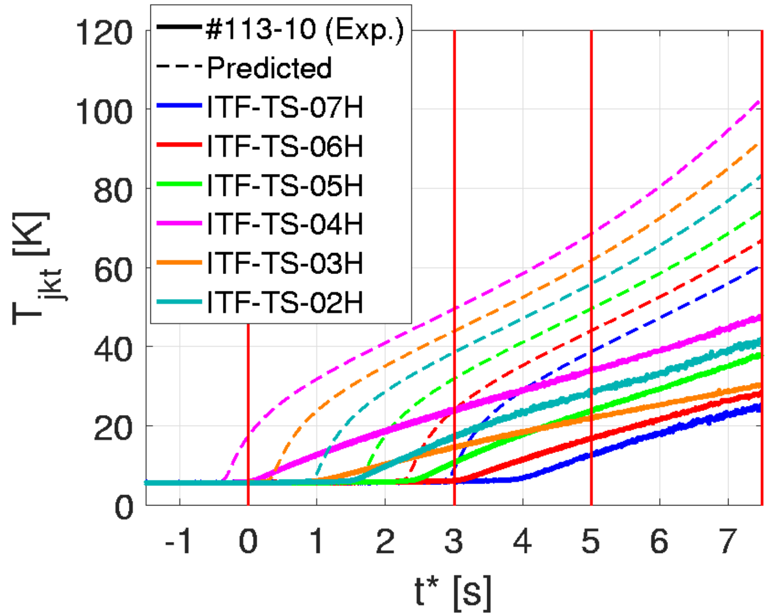
Very good reproduction of normal zone …





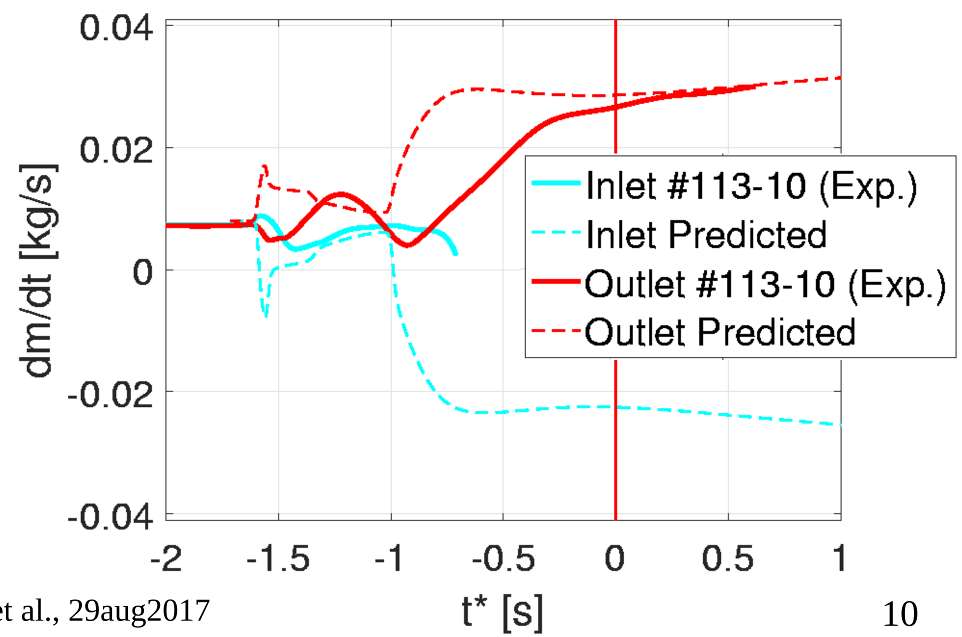
… BUT quench acceleration in later stages not captured by simulation **?**

Predictions vs. experiment: jacket T and dm/dt



Exp T_{jk} increase much slower than predicted ?

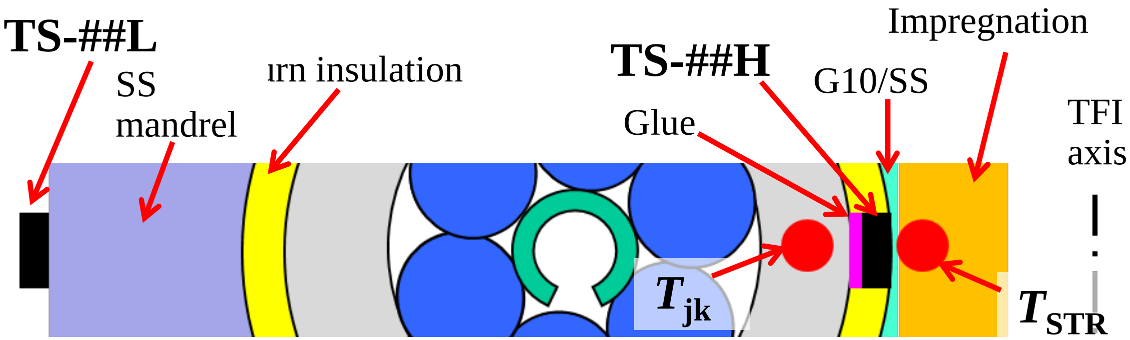
- Odd exp. *dm/dt* at boundaries in very initial phase
- Predicted *dm/dt* rate of change faster than exp in intermediate phase
- Prediction close to exp. *dm/dt* only in later phase



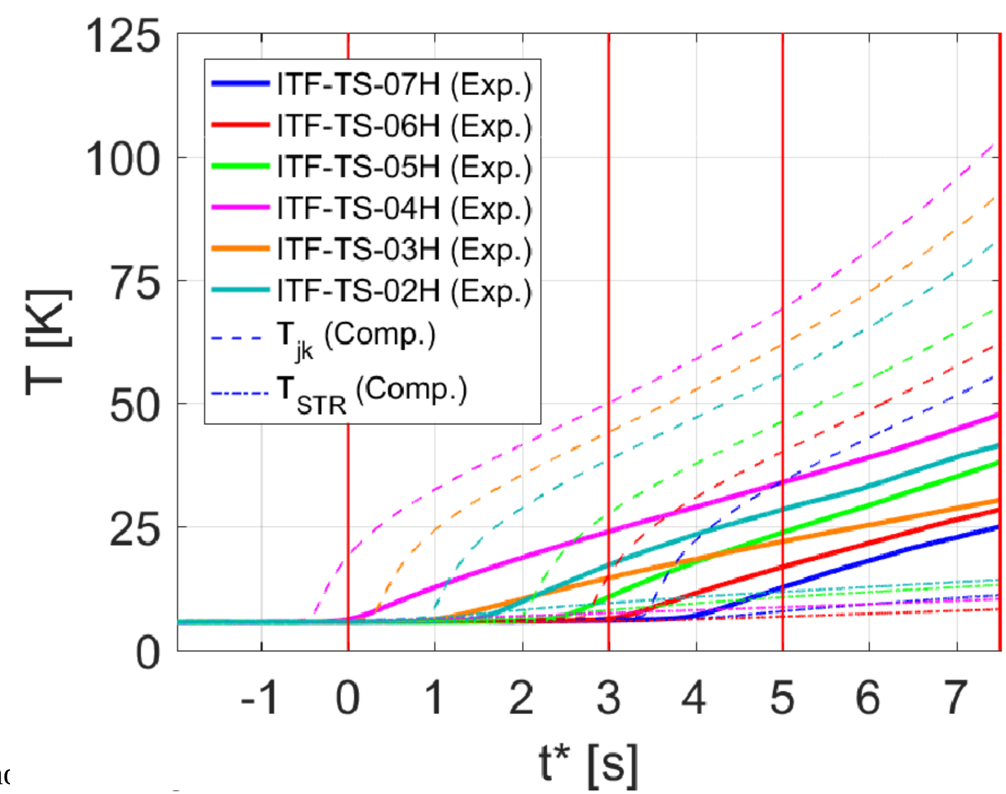
Interpretive analysis

- *After the experiment*, upgrade the model, based on comparison above between predictions and experiment
- Investigate effect of
  - Structures model → chasing T_{jk}
  - External circuit model → chasing p_{in}, p_{out}, *dm/dt*
  - Inter-turn thermal coupling → chasing V_Q
- Repeat comparison with experiment to assess accuracy of new model

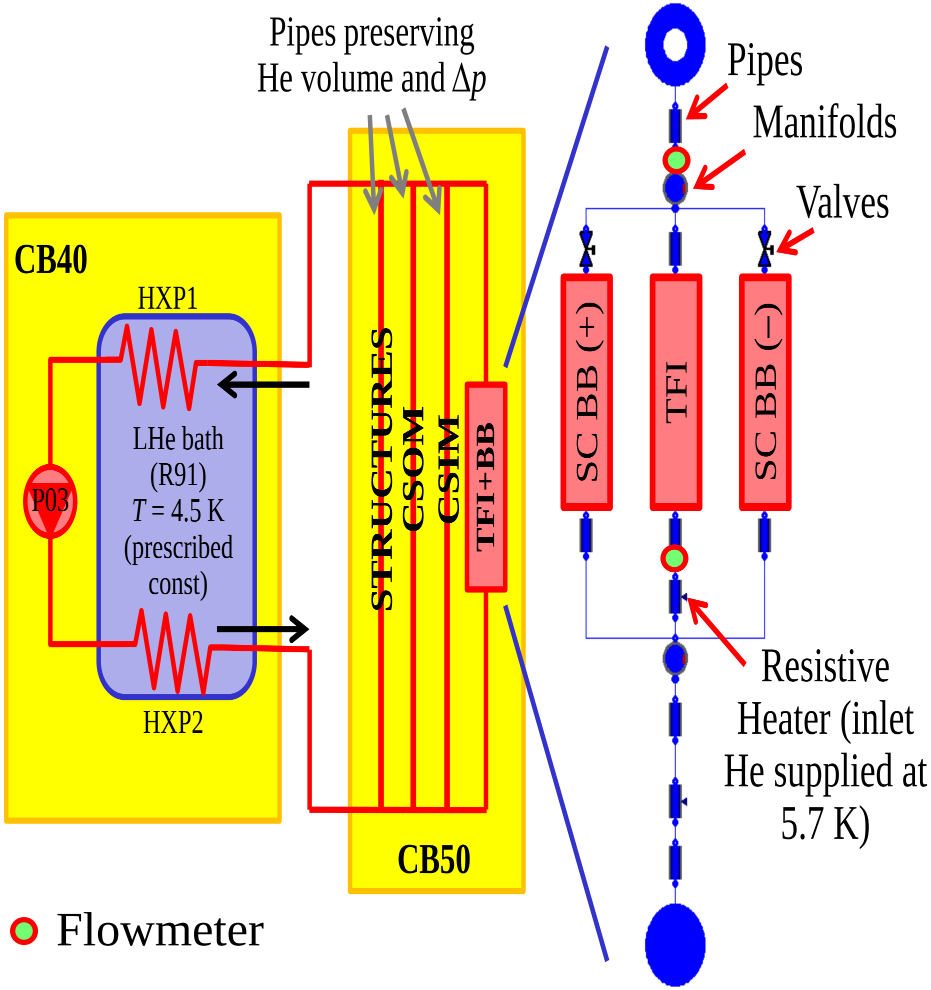
Effect of structures model



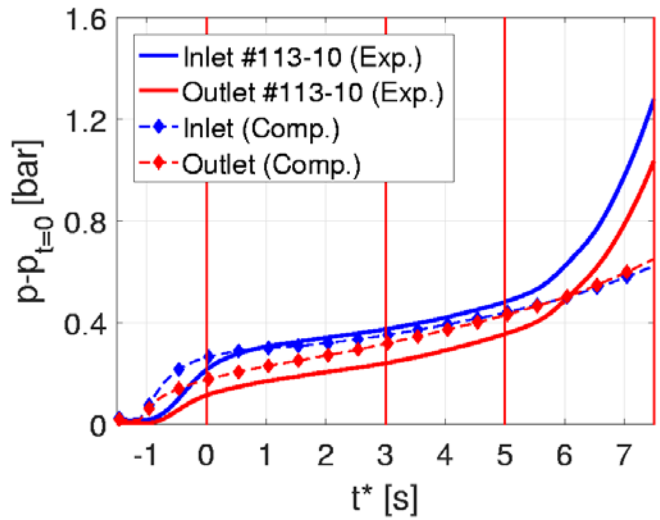
Computed T_{STR} and T_{jk} bracket the T_{jk} measurements … Which temperature are the TS-##H thermometers actually measuring?



Effect of cryogenic circuit model



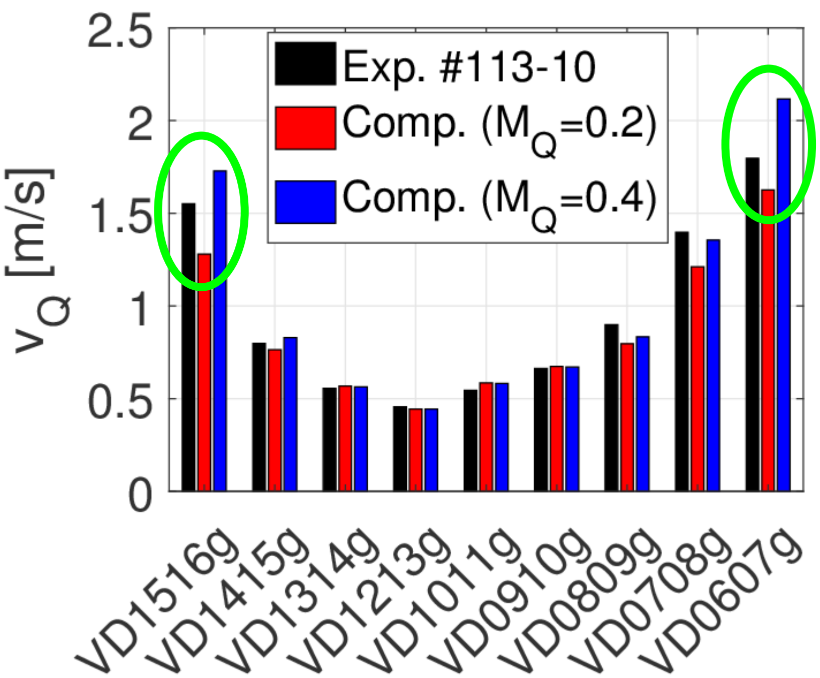
- Qualitative agreement in pressurization @ coil boundaries BUT later increase in pressurization slope is still not reproduced

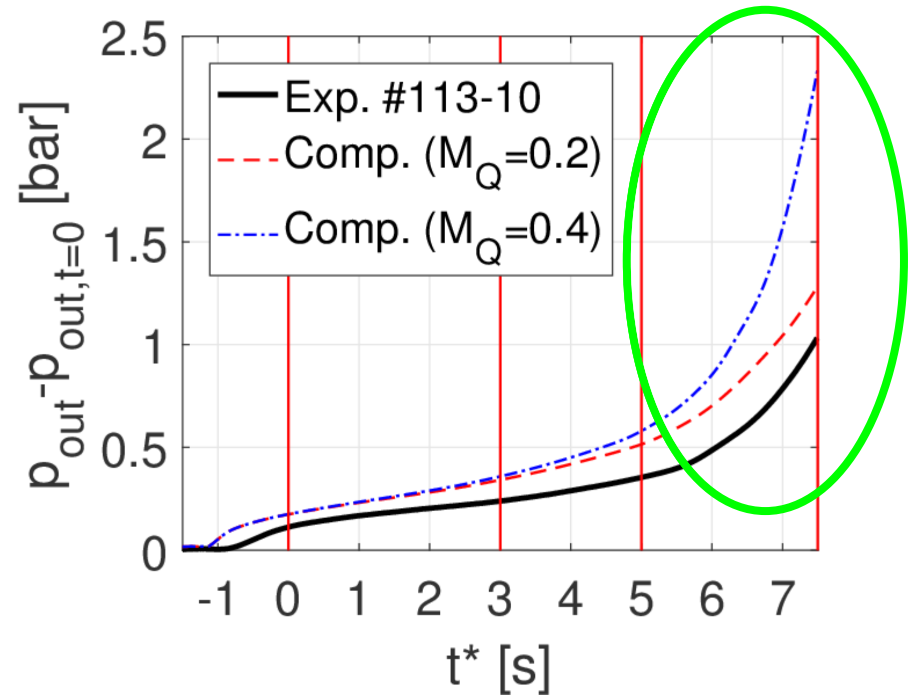


- p_{max} ~ 7.2 bar
- No significant improvement in *dm/dt* agreement

Effect of inter-turn thermal coupling

- Preheating ahead of quench front causes quench acceleration [R. Z., *IEEE TAS*, 1999] → Inter-turn thermal coupling more effective than assumed above?
- Model inter-turn heat flux as $\boldsymbol{\Phi}_{\#} = \boldsymbol{\Phi}^{\mathbf{nom}}_{\#} \cdot \boldsymbol{M}_{\mathbf{Q}}$





Improved agreement in acceleration of propagation and pressurization for $t^* > 5$ s

Conclusions

Ref.	Prediction	V_{tot} (t*)	V_{loc} (t*)	T_{HS} (t*)	V_q (t*<5s)	V_q (t*>5s)	T_{jk} (t*)	dm/dt (t*)	p (t*)
PRESENT WORK	☺	☺	☺😐	☺😐	☺😐	☺😐	☹?	😐?	☺😐
R. B. et al., *IEEE TAS*, 2017	NA	☺😐	☺😐	☺😐	😐	😐	☺	☺?	😐☹
Y. Takahashi, *IEEE TAS*, 2006	NA	😐	NA	NA	NA	NA	NA	NA	NA
T. Inaguchi, *Cryogenics*, 2004	NA	☺😐	NA	☺😐	☹	☺☹	NA	NA	NA
L. S. et al., *IEEE TAS*, 2003	NA	☺😐	NA	☺	☹	☺☹	NA	NA	NA
L. S. et al., *Adv. Cryo. Eng., 2002*	NA	☺😐	NA	☺	☹	😐☹	☺	☺	☹
R. Z. et al., *IEEE TAS*, 1997	NA	☺😐	NA	NA	☺😐	☺😐	NA	NA	☺😐

- Scope/accuracy of quench modeling for ITER Nb_3Sn magnets significantly extended/improved over the last 20 years
- *Predictive* code capabilities confirmed here for the first time for quench transient in Nb_3Sn ITER-relevant conductors
- Some open issues remain, which might be partly model-, partly experiment-related

Back up slides

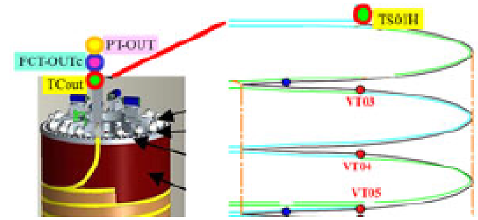
Major background

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 27, NO. 4, JUNE 2017 4700308

Analysis of Quench Propagation in the ITER Central Solenoid Insert (CSI) Coil

Roberto Bonifetto, Takaaki Isono, Nicolai Martovetsky, Laura Savoldi, *Member, IEEE*, and Roberto Zanino, *Senior Member, IEEE*

***Abstract*—The Central Solenoid Insert (CSI) coil, a single-layer Nb_3Sn solenoid, wound using the same conductor of the 3L module of the ITER Central Solenoid, was tested in 2015 at the National Institutes for Quantum and Radiological Science and Technology (former JAEA) Naka, Japan, inside the bore of the Central Solenoid Model Coil. At the end of the test campaign, quench tests were carried out to study the quench initiation and**



… but focus today is on PREDICTION

Literature

- Previous predictive simulations

[R. Zanino, R. Bonifetto, C. Hoa, and L. Savoldi Richard, "Verification of the Predictive Capabilities of the 4C Code Cryogenic Circuit Model," *AIP Conference Proceedings*, vol. 1573, 2014, pp. 1586-1593]

Uncertainty quantification (I)

The developed model needs some uncertain parameters in input

Parameter	Value and uncertainty	Assumption
Initial Temperature	5.7 ± 0.1 K	5.7 K (test program)
Mass flow rate	8 g/s ± 6 %	8 g/s (test program)
Pressure	Depends on actual cryoplant operation	5.6 bar (from previous days operation)
Energy deposition	Unknown	Sufficient to induce a quench propagation in the simulation
Mandrel temperature in contact with CICC	Unknown	Assumed constant $T = T_0$ in view of the estimated heat transfer time scales across the mandrel

Uncertainty quantification (II)

Parameter	Value and uncertainty	Assumption
Hole friction factor	[Tronza, 2015] * 1.1 (unc. unknown)	Same as before WUCD
Bundle friction factor	[Tronza, 2015] * 1.1 (unc. unknown)	Same as before WUCD
H_{HB} multiplier	10 (unc. unknown)	Same as before WUCD
HTC_{MND}	1.2 W/m^2K (unc. unknown)	Same as calibrated before WUCD
Fraction of energy deposited directly in the strands	Unknown	Assumed 20 % (from previous experiences)
B(x) ans strain(x)	[NM, personal communication, 18 Nov. 2016] (unc. unknown)	

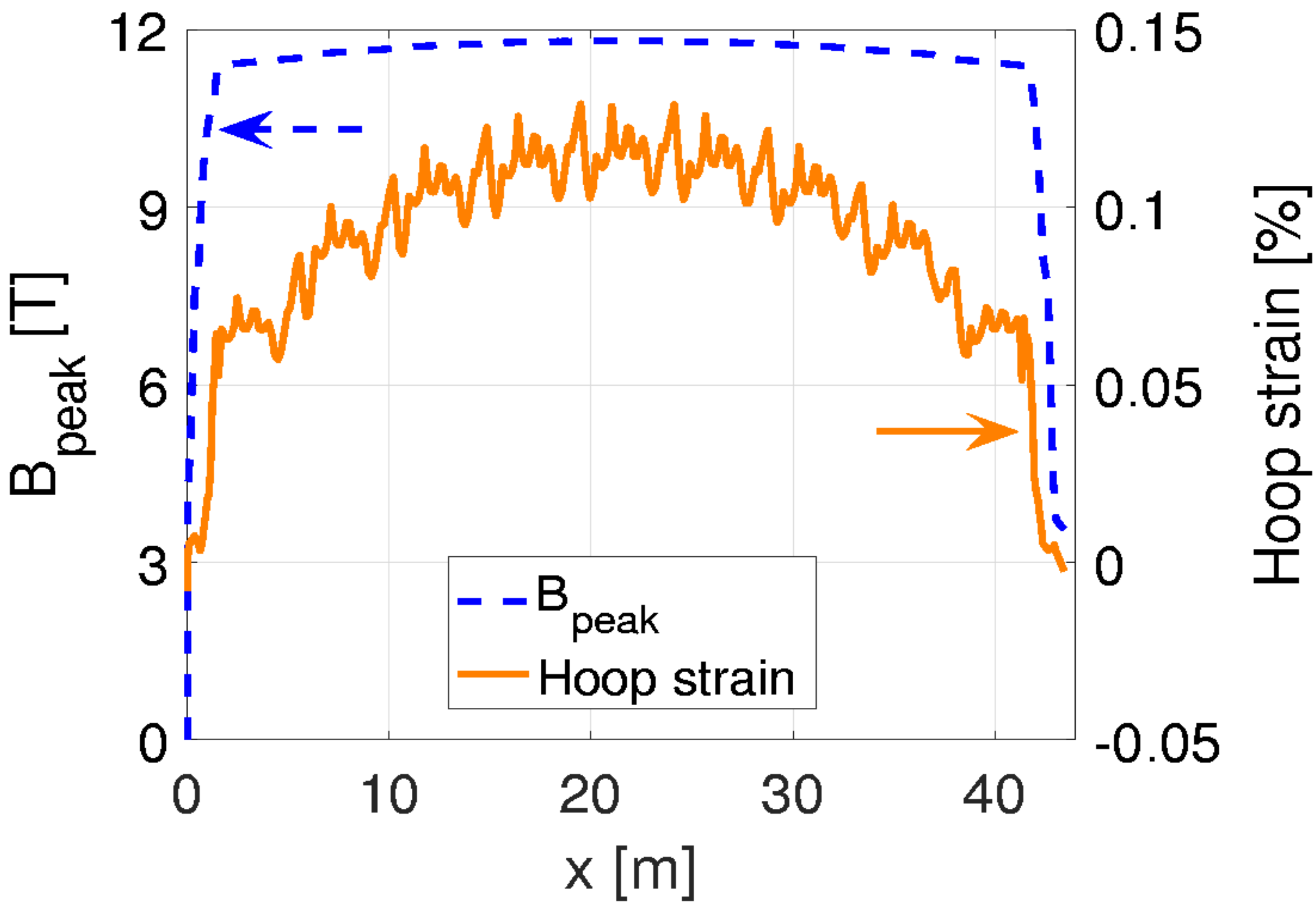
Interpretive simulation setup

- Initial conditions from the measurements
- Updated calibration of friction facttors and HTCs

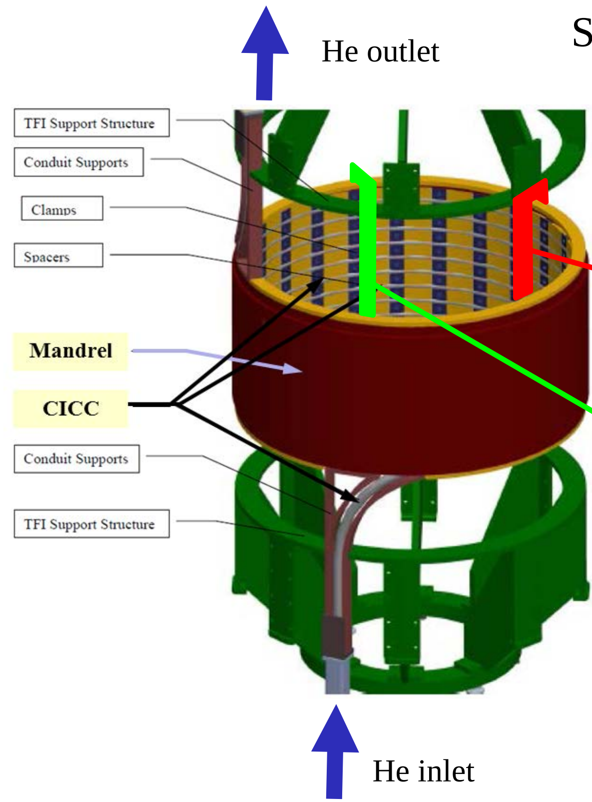
Parameter	Value
Hole friction factor	[Tronza, 2015] * 1.75 (unc. unknown)
Bundle friction factor	[Tronza, 2015] * 1.2 (unc. unknown)
H_{HB} multiplier	4 (unc. unknown)
HTC_{MND}	10 W/m^{2}K (unc. unknown)

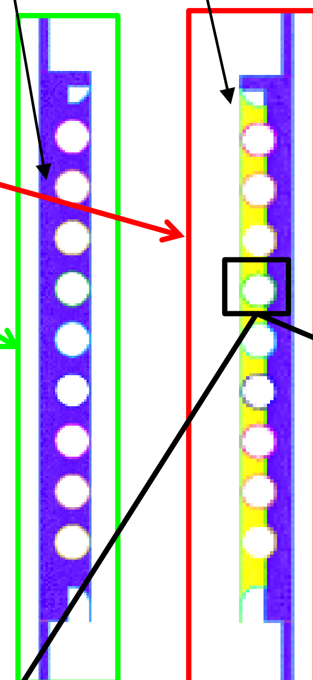
- Investigate dm/dt disagreement → introduce simple model of cooling circuit to provide self consistent boundary conditions
- Investigate T_{jk} overstimation→ add structures model (including their thermal capacity)

B(x), eps_{hoop} (x)


12
9
6
3
0
0.15
0.1
0.05
0
-0.05
0
10
20
30
40
x [m]
B_{peak} [T]
Hoop strain [%]
B_{peak}
Hoop strain

Interpretive analysis: TFI structure model





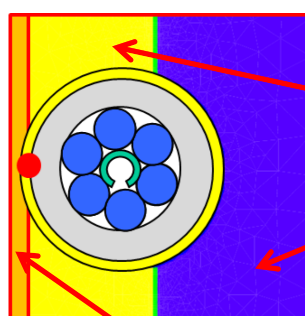
Mandrel model:
- 2D radial-vertical slices
- accounts for different material (from data book [drawing 310PB67-509]):
  1. SS on the outer side
  2. on the inner side
     a. SS (~27%)
     b. G10 (~73%)

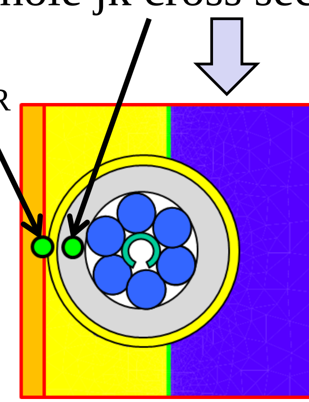
Model
Virtual temperature sensors

T_{jk} assumed uniform in the whole jk cross section

Sensors installation

Cernox T taps are glued (uncertainty on glue properties) on the TFI jacket (local kapton insulation is removed)

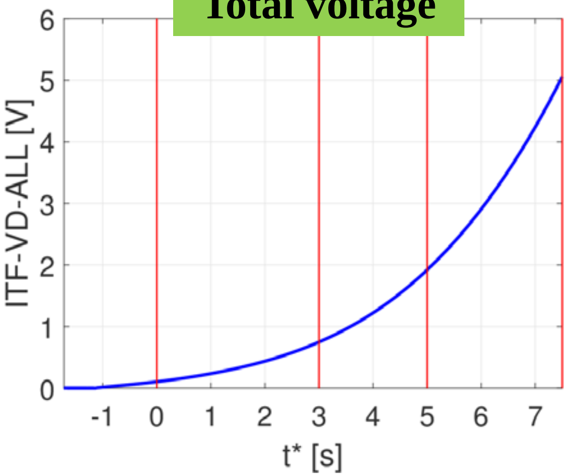




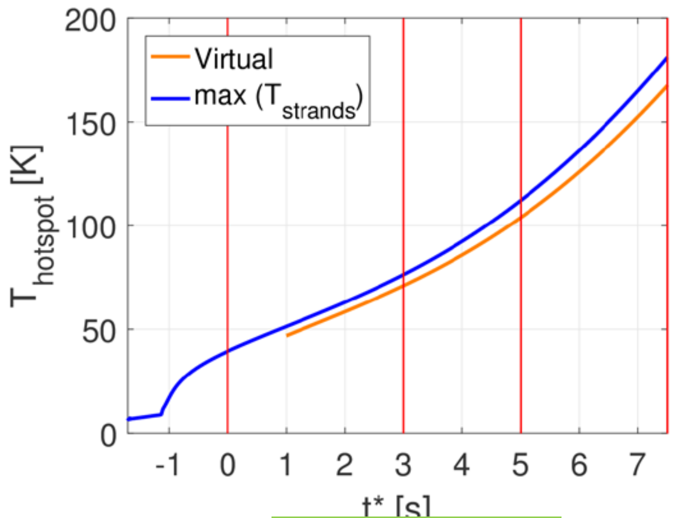
Predictive analysis: example of results

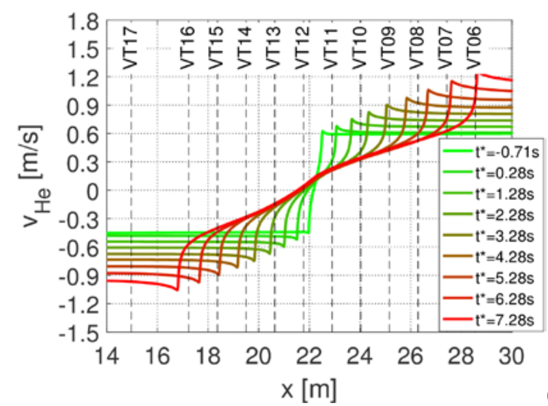
$t^* \equiv t - t_{QD}$

Total voltage



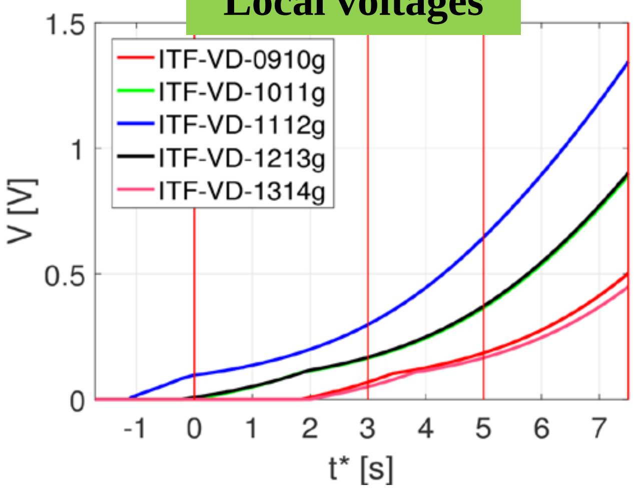
Maximum and virtual hot spot temperature



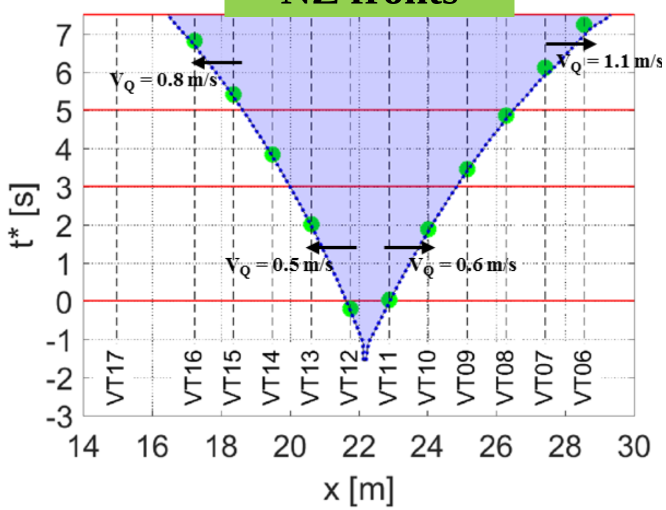


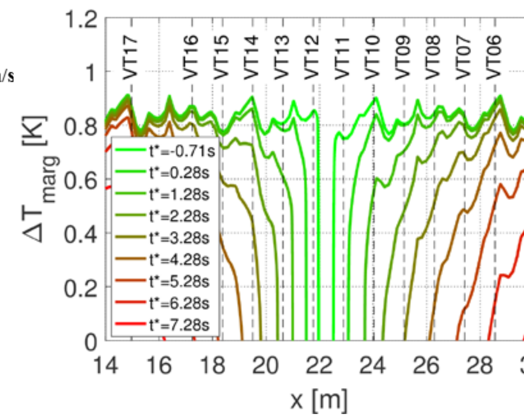
(a)

Local voltages



NZ fronts

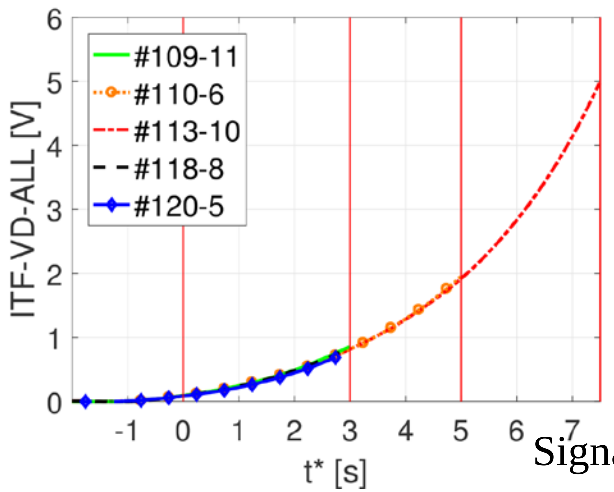


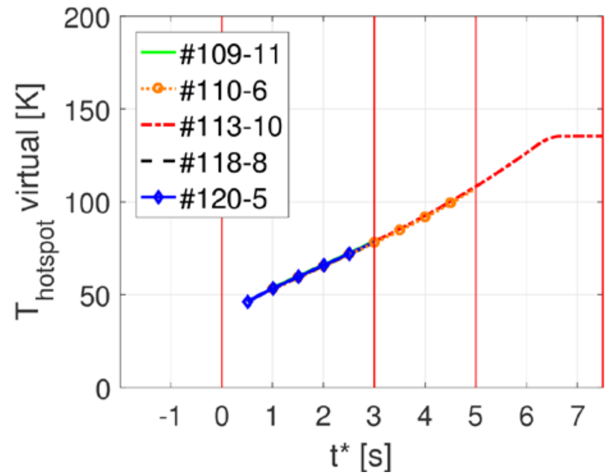


(b)

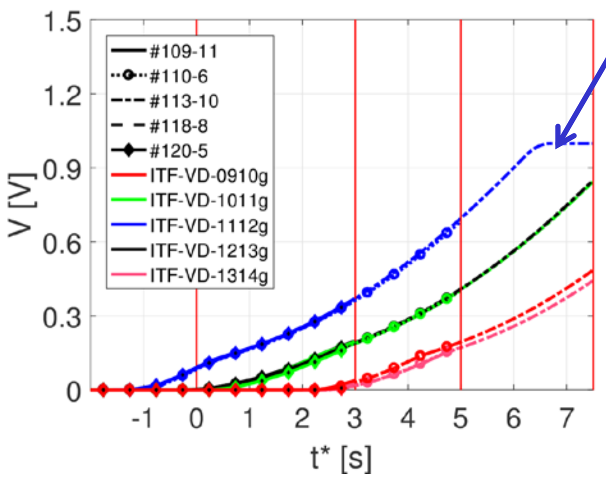
R. Zanino et al., 29aug2017

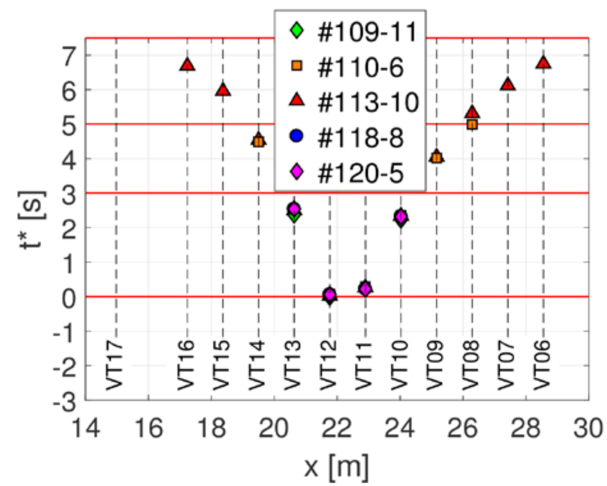
Example of experimental results





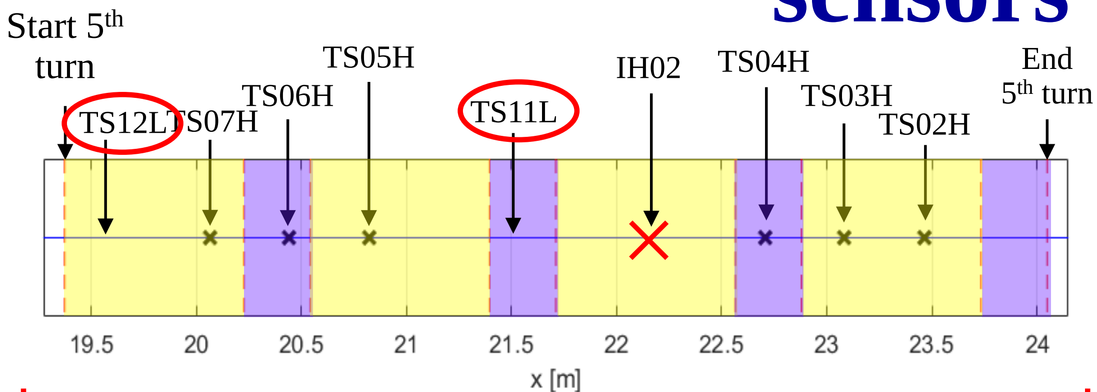
Signal saturation



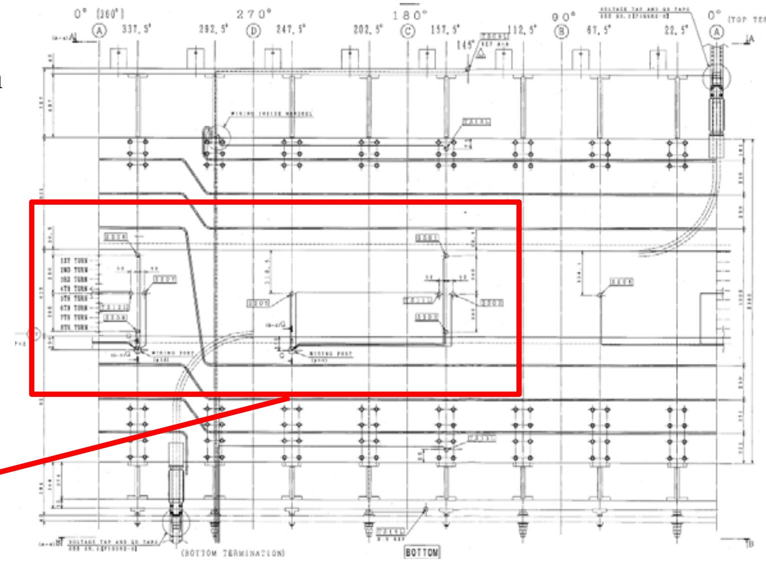


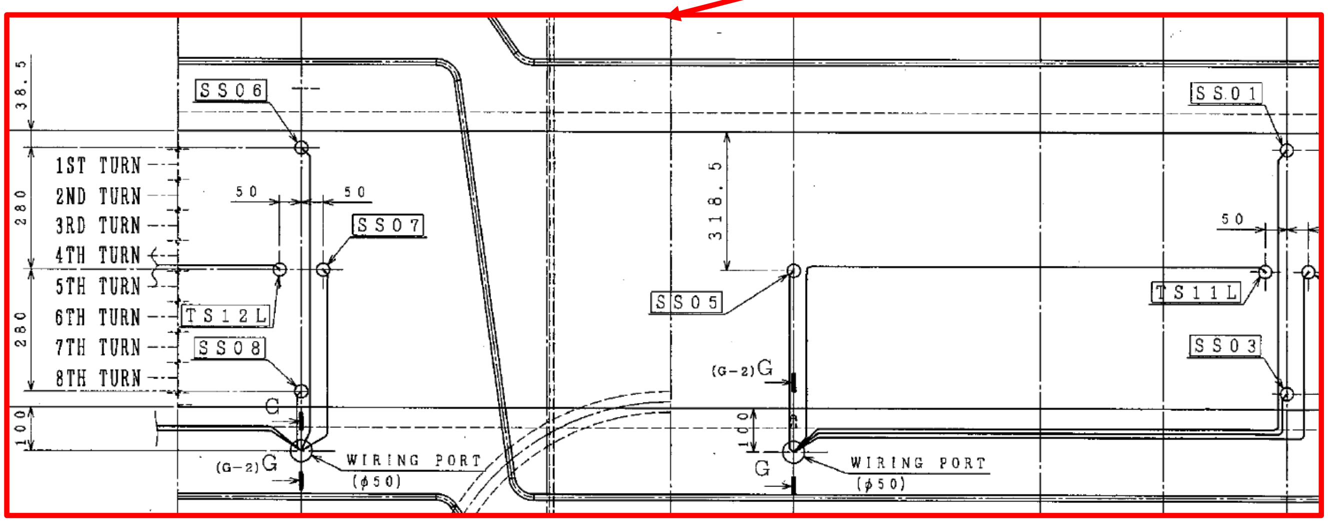
- Excellent reproducibility

Location of mandrel temperature sensors



Central turn





TS12L and TS11L sensors are located around the beginning and the mid-length of the 5th turn respectively