Analysis of current redistribution in a Cable-in-Conduit Conductor

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CHATS-2002, FzK, Karlsruhe, September 2002

Introduction

- Goal:
  - To understand an experiment investigating the current redistribution among the strands in a CICC, upon a local transient energy deposition (i.e. thermo-hydraulic and electric transients)
- Method:
  - Reconstruction of current displacement from experimental self-field measurements
  - Simulations with code THEA®

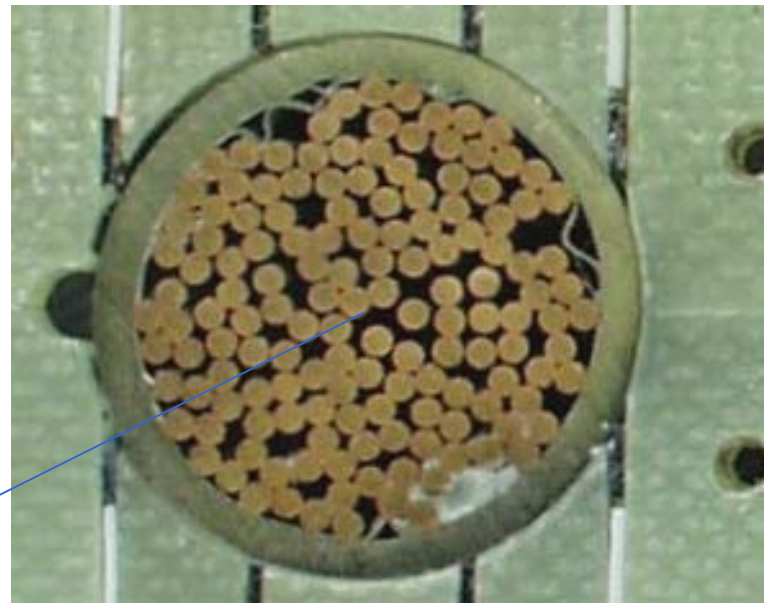
Experiment

- Transient stability experiment on short length CICC's
- Conductor 'SecB'
- 4 Arrays of Hall probes (8 per array)
- Completed in Sultan in 2001

IEEE Appl. Superc., 12, 512-515 (2002)

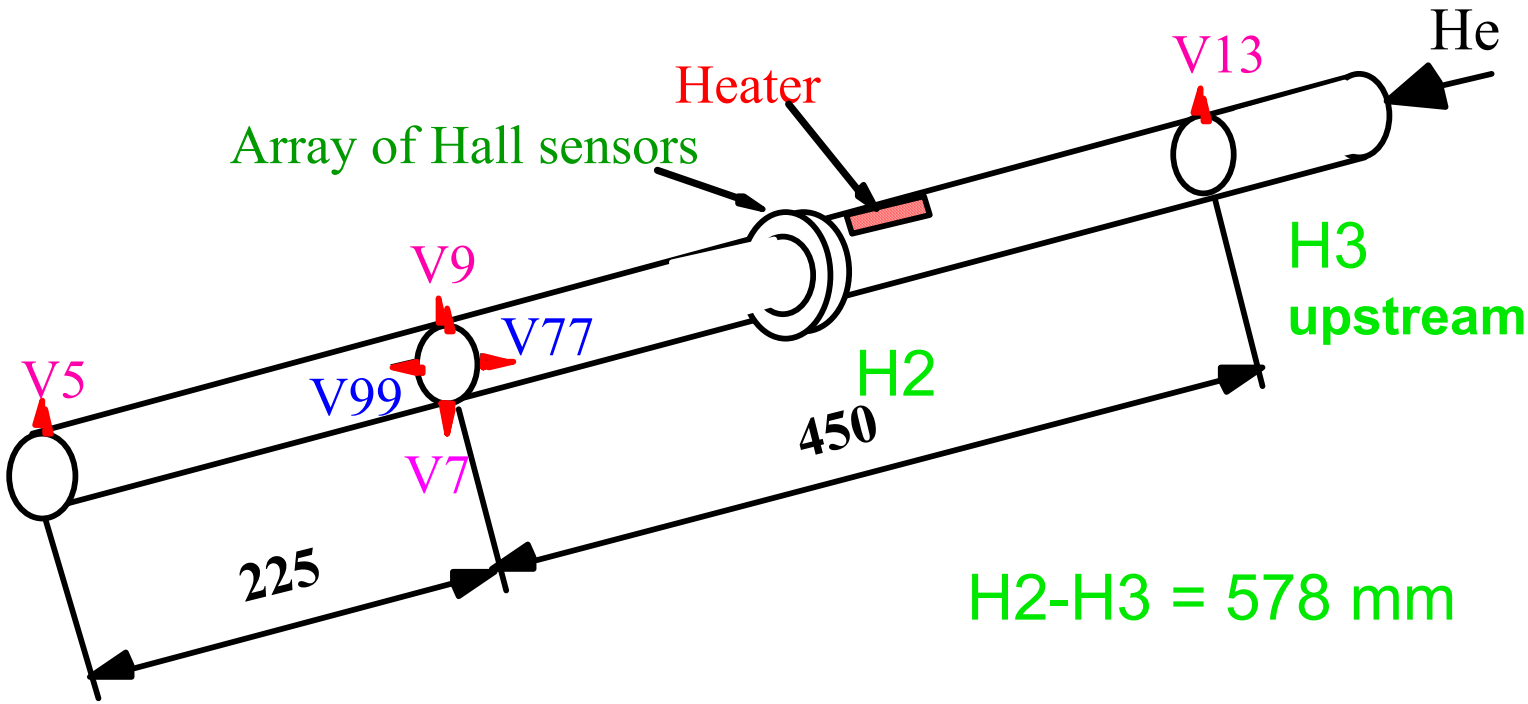
Conductor

- Nb3Sn
  - (1+7)x4x4
- CICC
  - Void fraction 37.2%

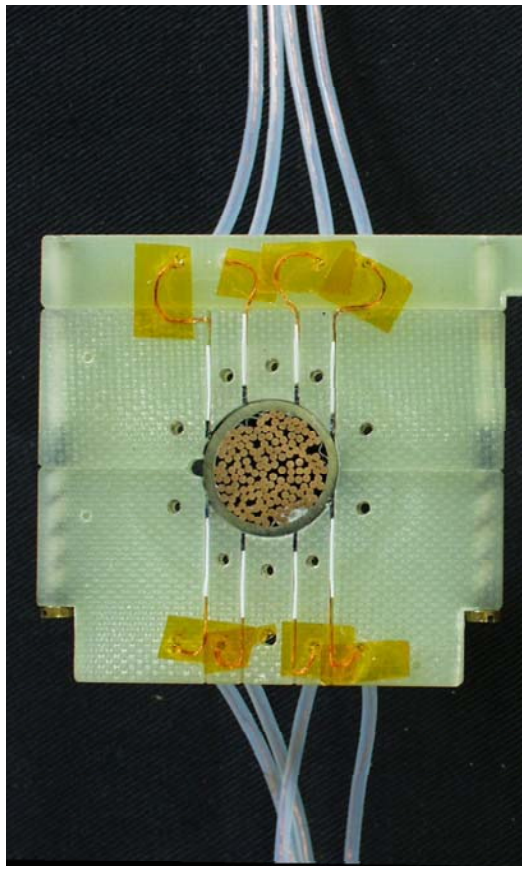


Sample

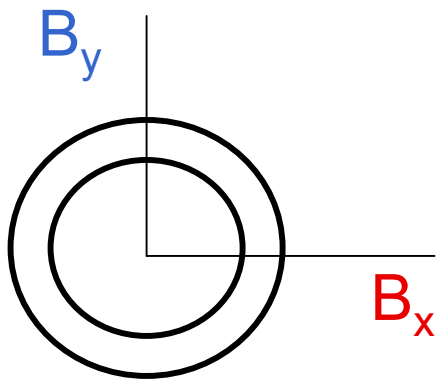
Details of sample



Hall probes



B_{Sultan} // Y



Hall signal =
B_x of self field

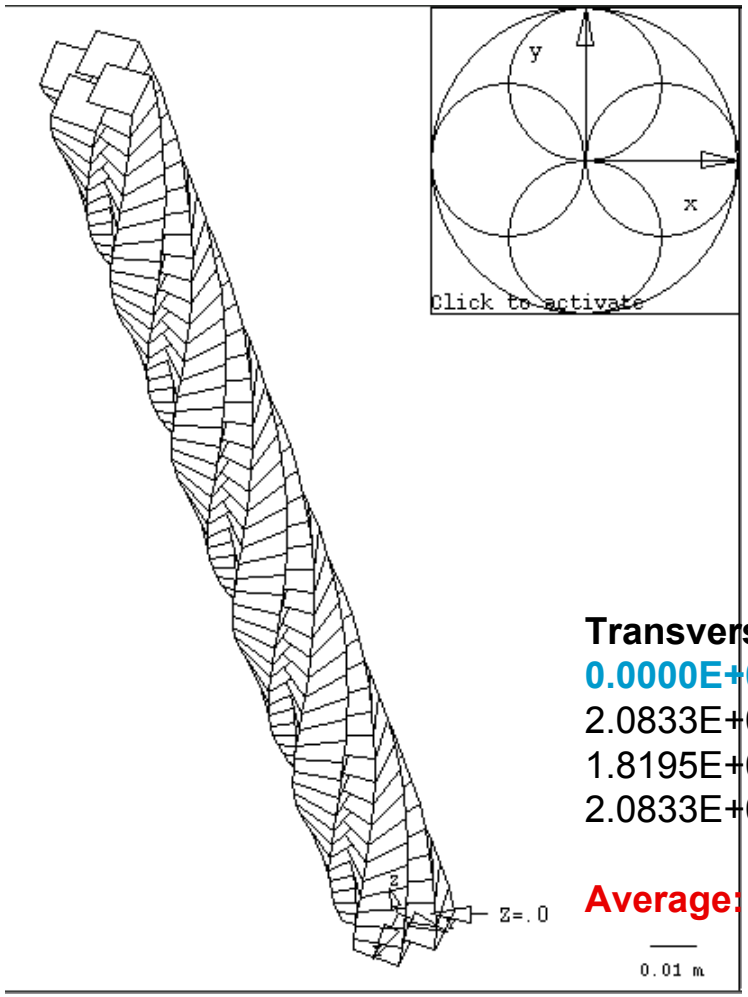
Resistive Heater

Tools used

- Cable Interactive Designer (code CID® v 1.0) [this workshop]
- Thermal Hydraulic Electric Analysis (code THEA® v 1.0) [CHATS-2000]

Both by CryoSoft

CID® Model



- 4 Superstrands
- 3 x Lp
- Matrices
  - Inductance
  - Influence @H2/H3
  - Conductance

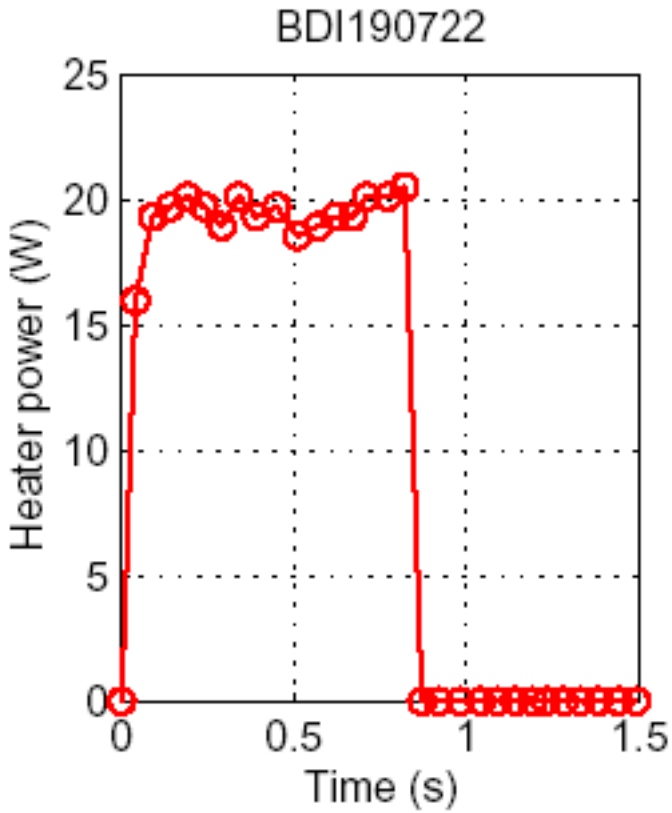
Transversal conductance per unit length

0.0000E+00	2.0833E+06	1.8195E+06	2.0833E+06
2.0833E+06	**0.0000E+00**	2.0833E+06	1.8472E+06
1.8195E+06	2.0833E+06	**0.0000E+00**	2.0833E+06
2.0833E+06	1.8472E+06	2.0833E+06	**0.0000E+00**

Average: 1.92 MSiemens/m

Experiment description

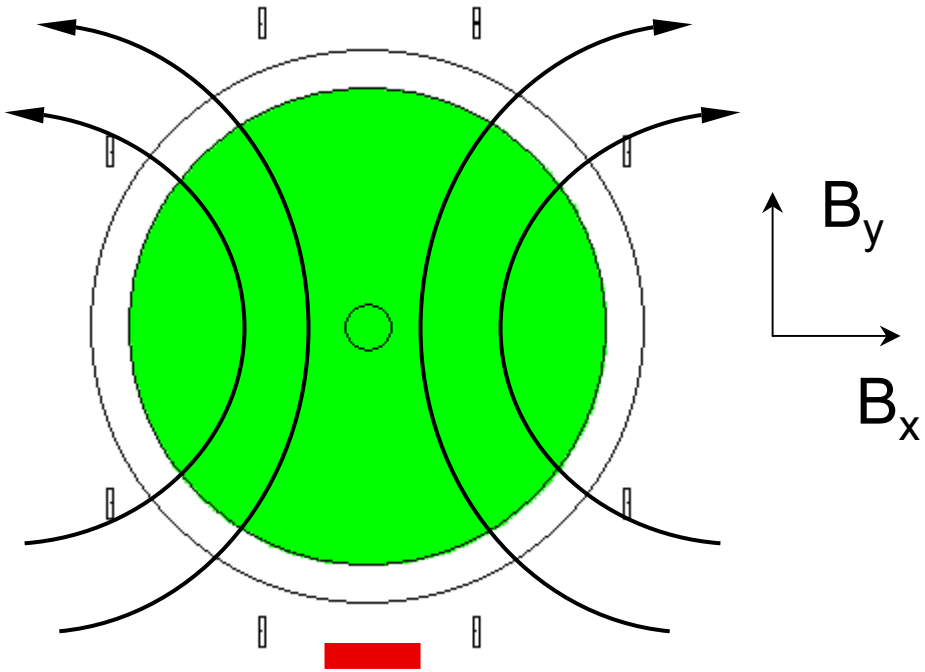
- He Flow: 3 g/s @ 4.6 K
- Sultan field: 10 T
- Current: 14.2 A
  - current sharing, I/Ic=1.1
  - n=8 (after cycling)
  - E > 0.2 μV/cm
- Heater



Reconstruction of currents

- Model
  - Computation of *influence matrices* relating $\mathbf{B_x}$ on the Hall plates to the current in the 4 superstrands
  - Pseudo-inversion of the influence matrix (singular value decomposition)

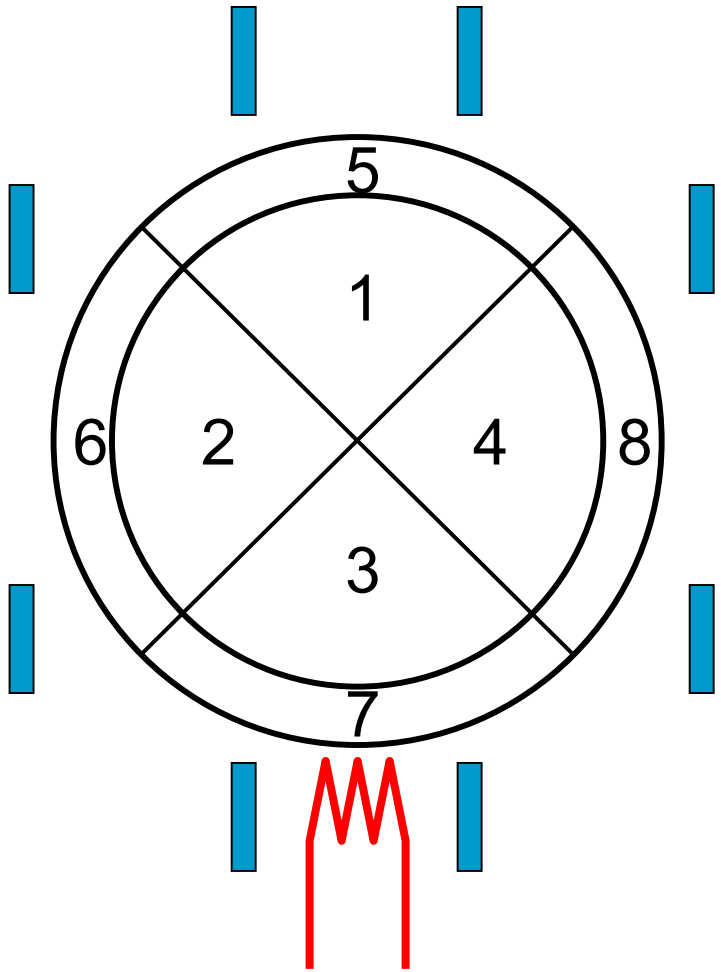
Results of reconstruction



Current redistribution from blue (≈-500 A) to red (≈+500 A)

THEA® Model

- Heated leg (~3m)
- 4 Electric
- 8 Thermal
  - 4 superstrands
  - 4 jacket
- 1 Hydraulic
- Heat pulse of 0.7s



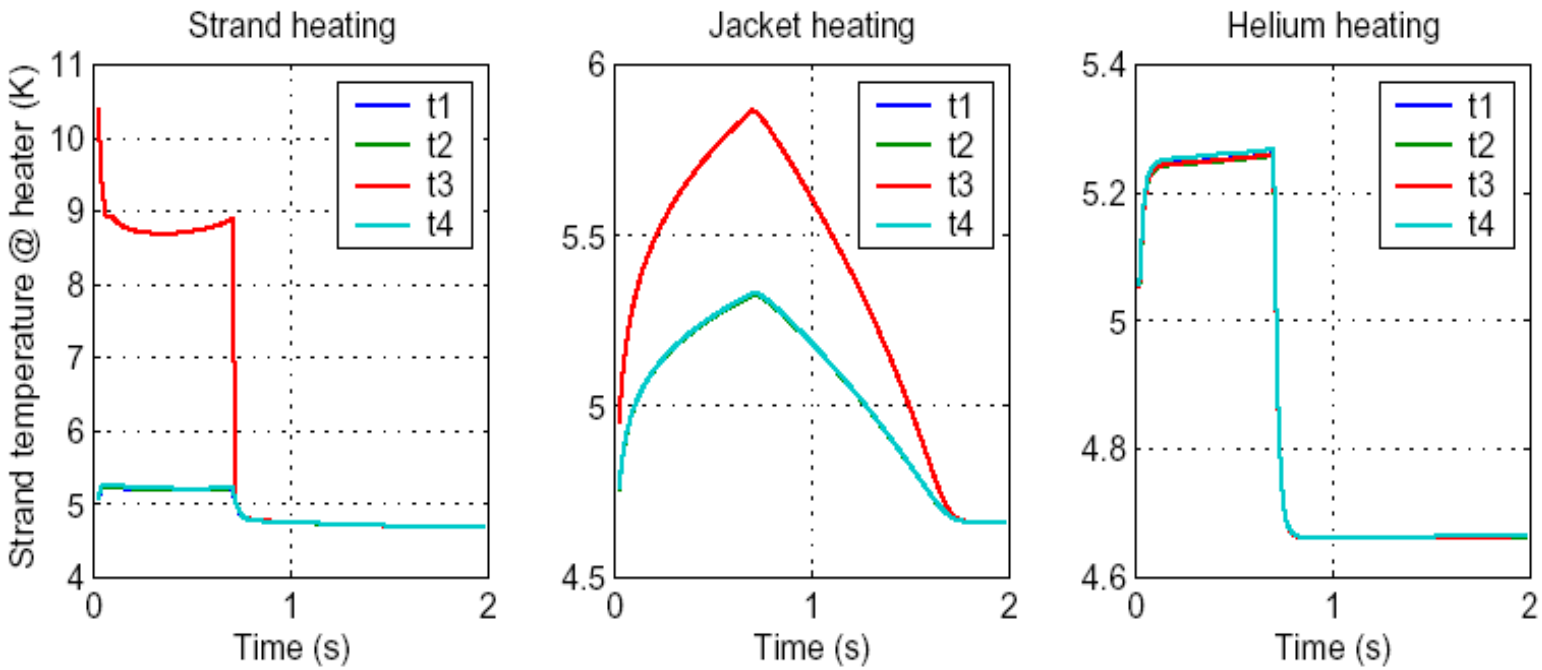
Simulations

- Parameters explored
  - Heating in jacket, helium and strand
  - Interstrand transversal conductance
  - Thermal contact among components
- Variables investigated
  - Strand temperature at heater
  - Currents at H2/H3
  - Stability margin
  - Resistive voltage
  - Signals at Hall probes

Strand temperature at heater

Strand (T3 only), jacket (T7 only) and helium heating

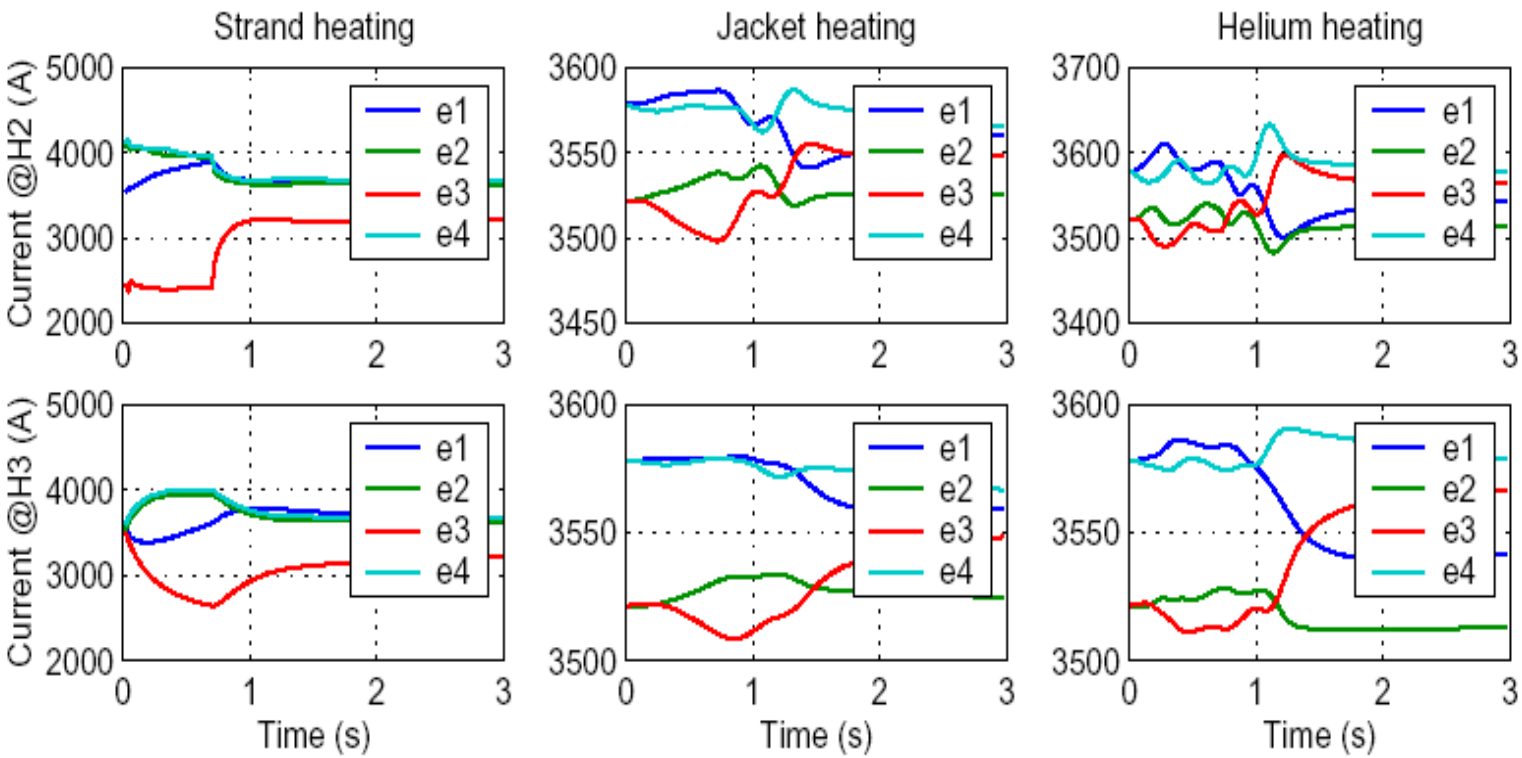
Different scale / Thermal gradient decreases ->



Strand currents @ H2/H3 (1)

Strand, jacket and helium heating

Different scale / Current displacement correlates with thermal gradient / Diffusion from H2 to H3

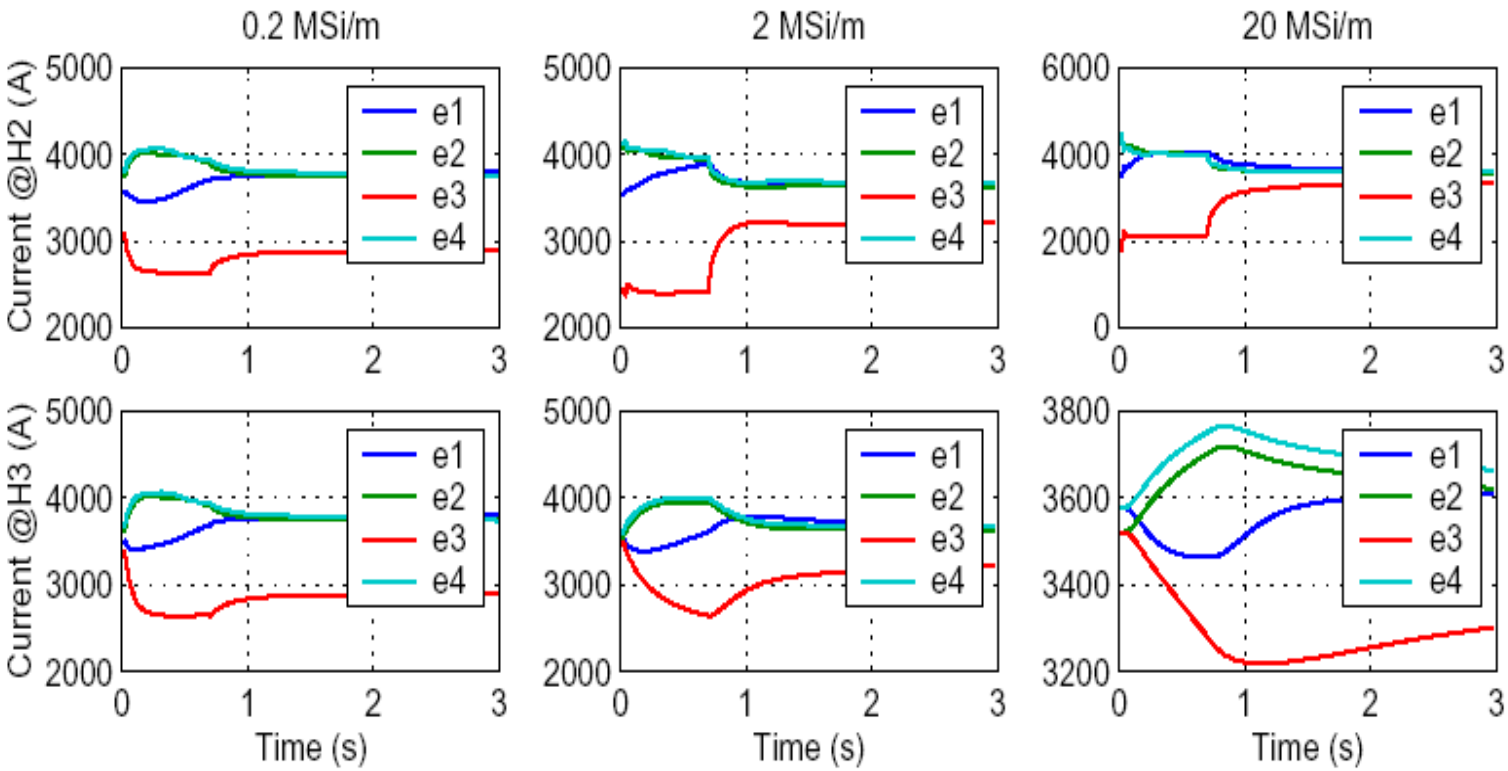


Strand currents @ H2/H3 (2)

Strand heating, increasing conductance

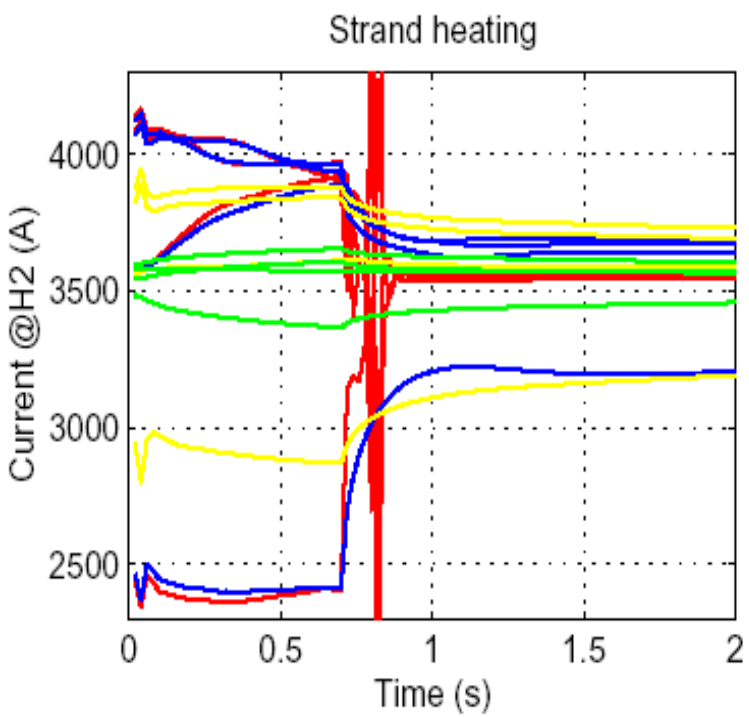
Not same power / different scale

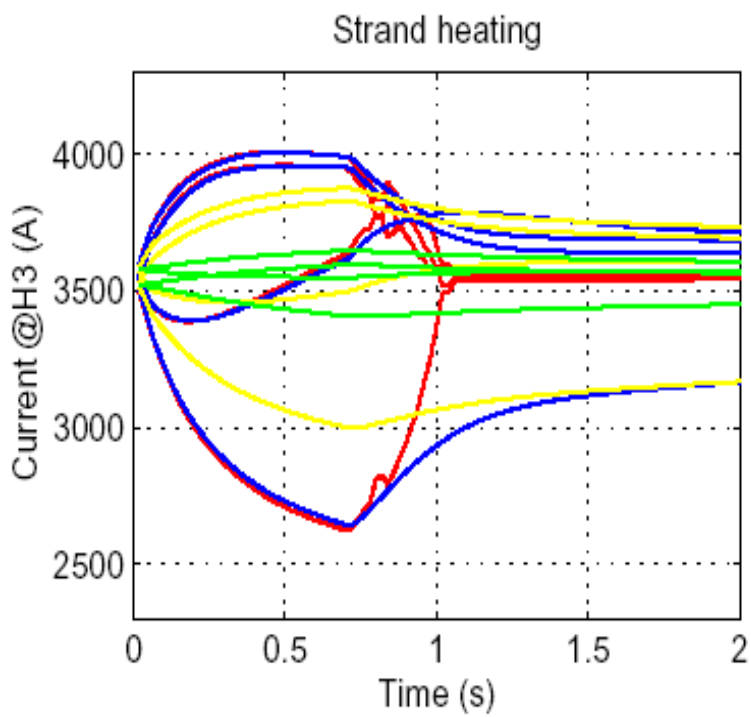
Longer time scale, smaller current difference at H3 because of shorter redistribution length



Strand currents @ H2/H3 (3)

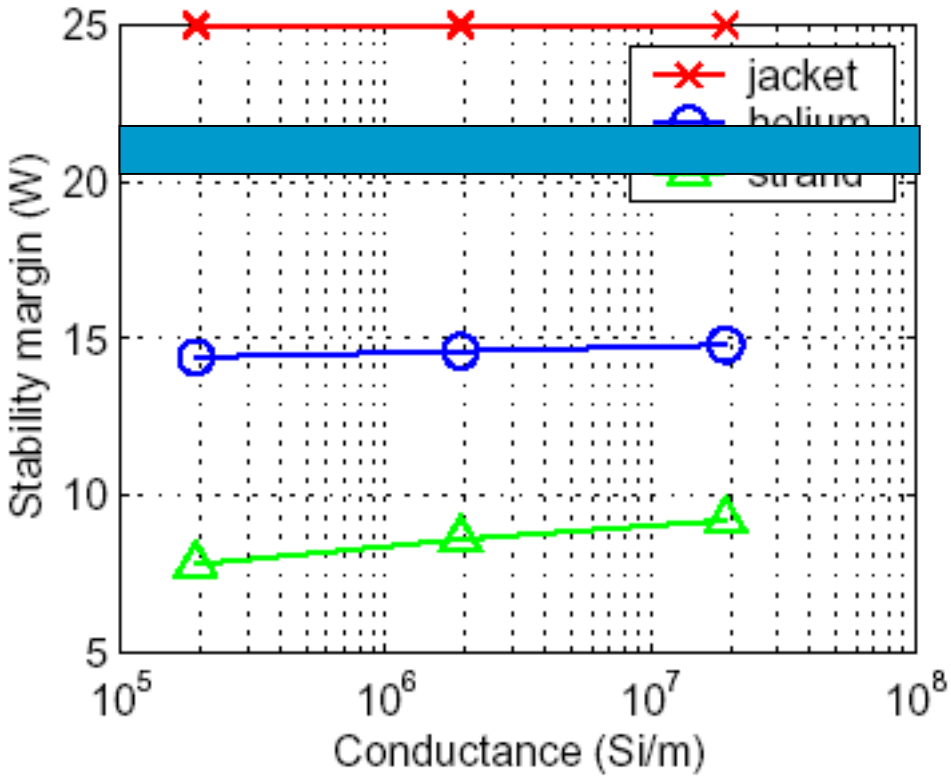
Strand heating, increasing heating power (4.6 - 8.8 W)





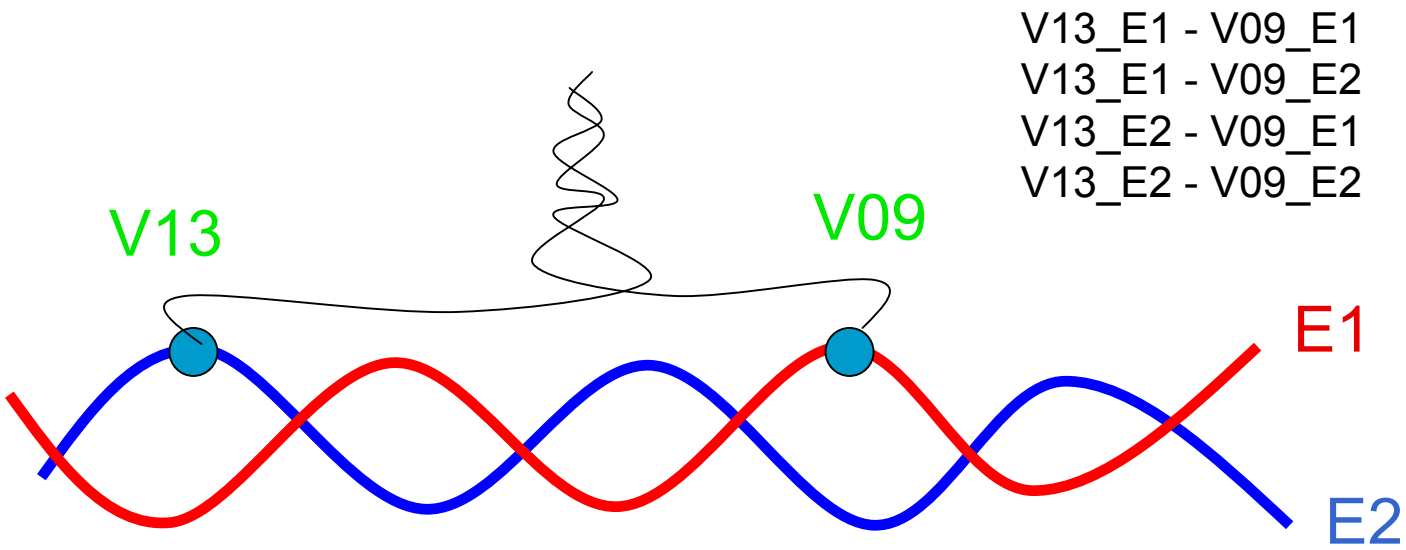
Stability margin

- Experiment vs Simulations
- Parametric effects
  - Heating mode
  - Interstrand conductance
  - Thermal resistance (strand-to-strand)



Resistive voltage

- Simulated signals: all differences at each pair of voltage taps

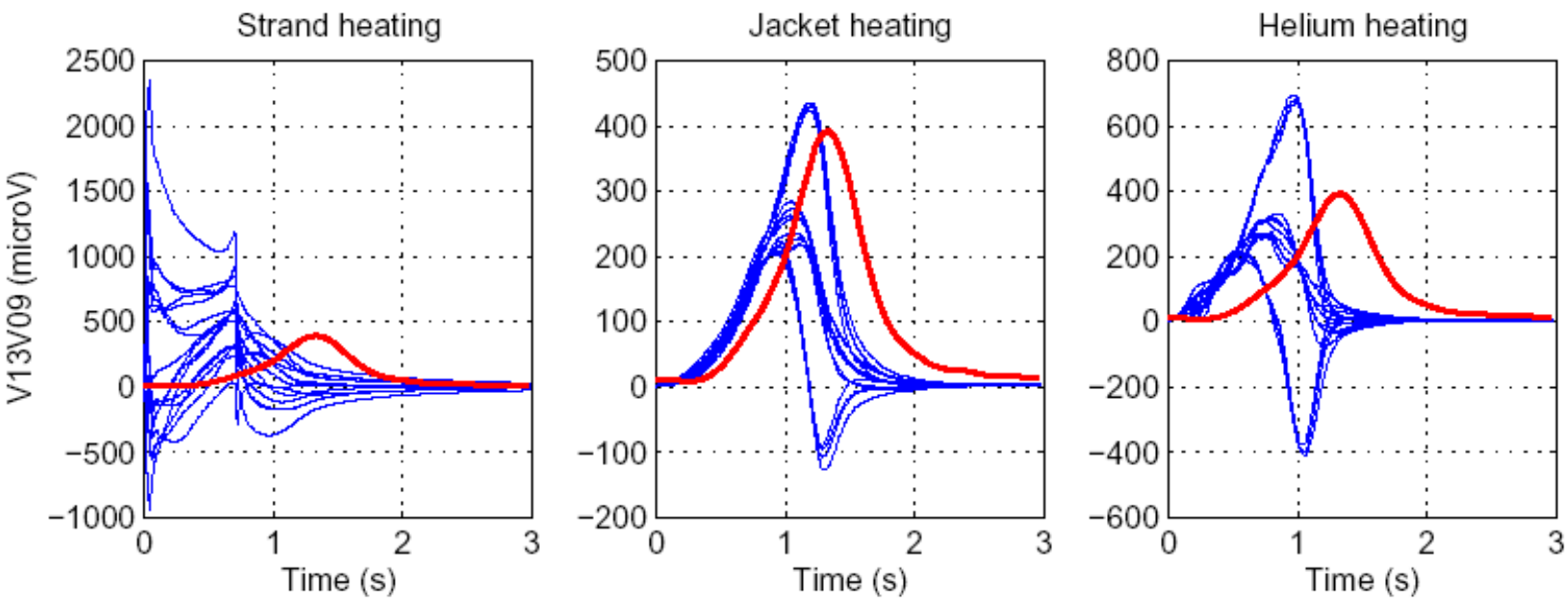


Resistive voltage (1)

Experimental V13V09

Jacket heating: amplitude and time scale is OK

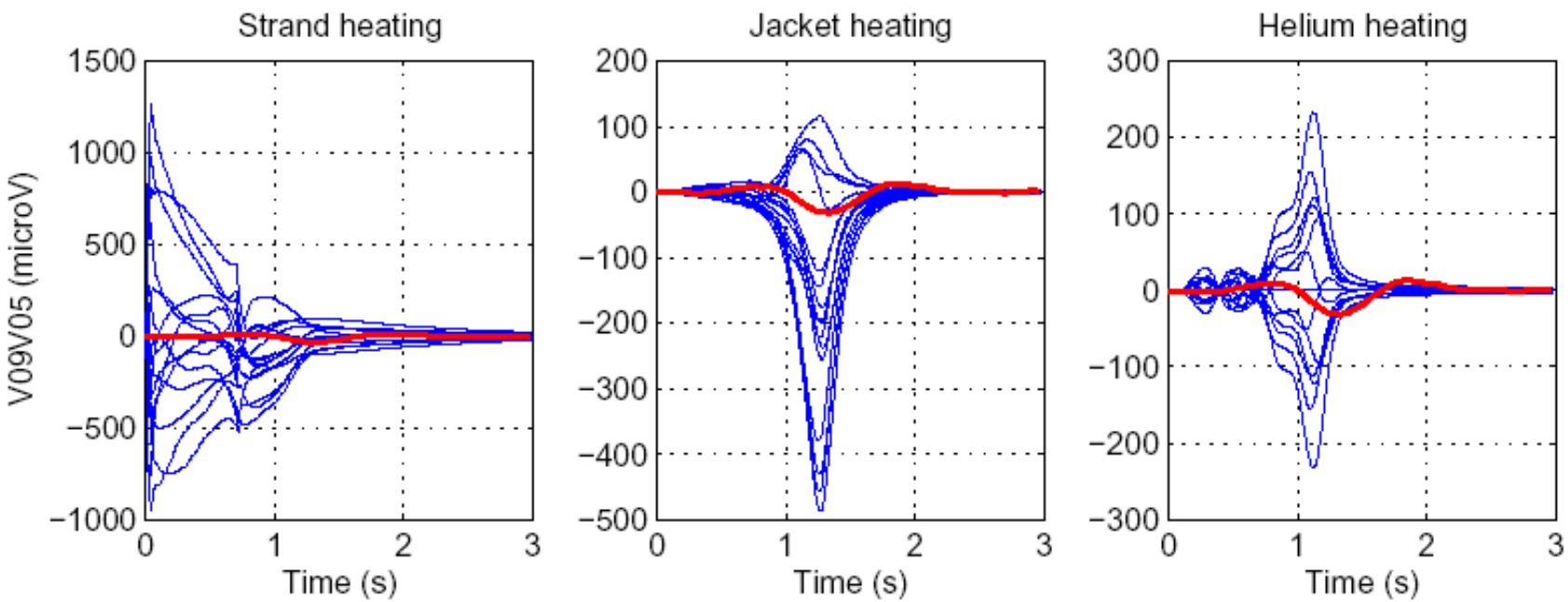
REMARK : electronics in experiment is slow



Resistive voltage (2)

Experimental V09V05

Time scale ~ OK / Amplitude: experimental signal in jacket, simulated in strands / Extremely dependent on EM model



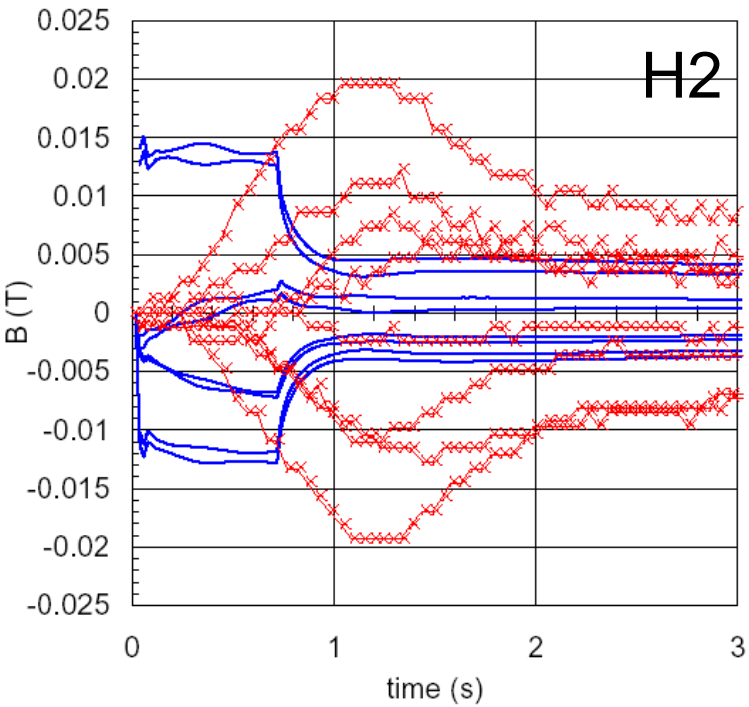
Signals at Hall probes (1)

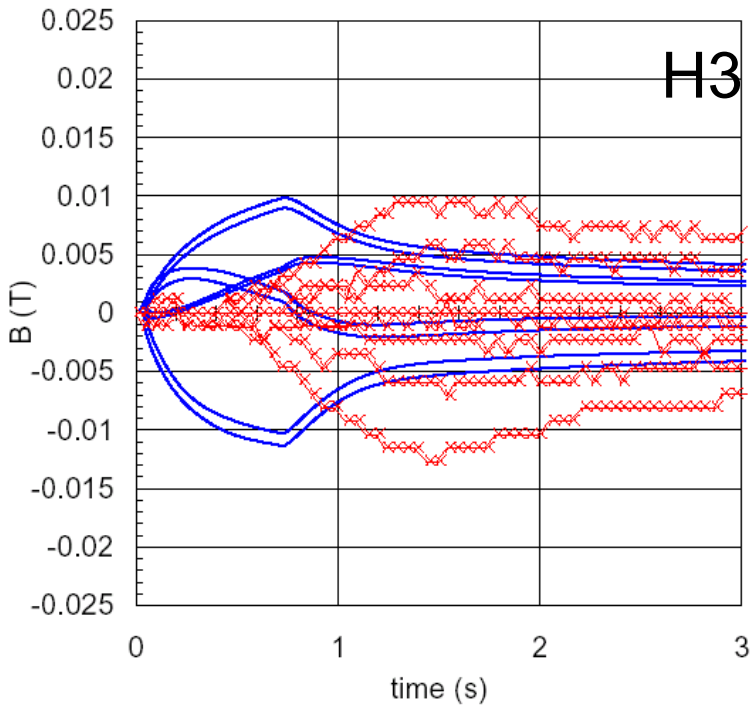
Strand heating, 2 MSi/m

Orders of magnitude ~ matched in H2 and H3

Strong transients not visible in experiment

REMARK: Hall signals were filtered in the experiment





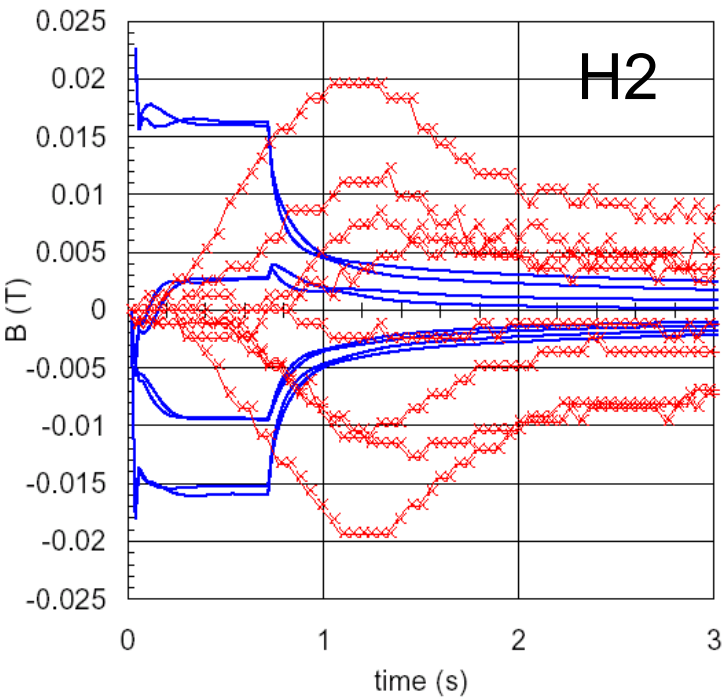
Signals at Hall probes (2)

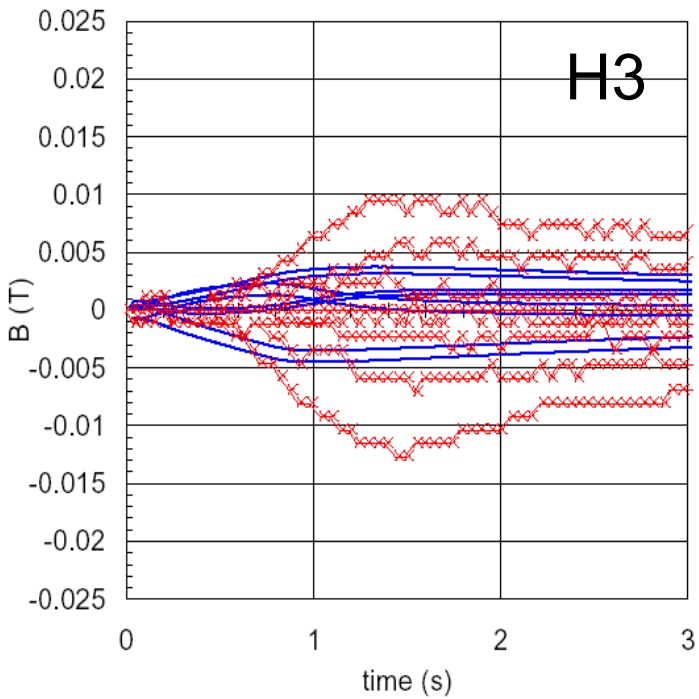
Strand heating, 20 MSi/m

Amplitude at H2 still ~ OK, at H3 on the low side

Diffusion time from H2 to H3 ~ OK

REMARK: effect of filter ?

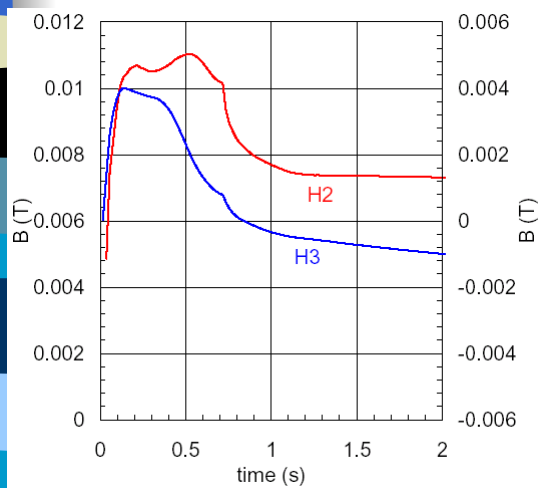




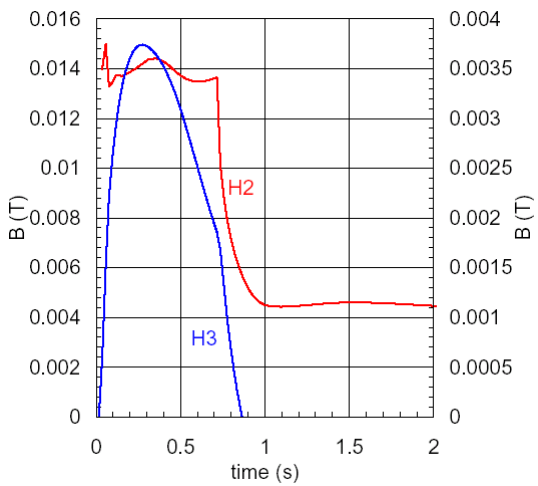
Signals at Hall probes (3)

Strand heating

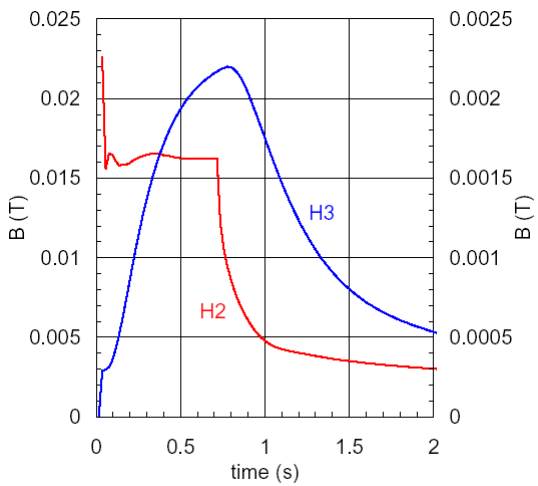
Current diffusion delay increases at increasing conductance



0.2 MSi/m



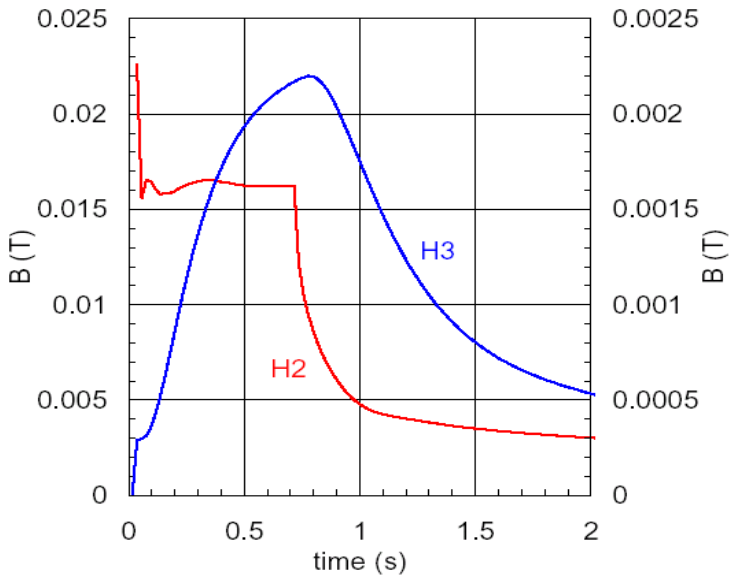
2 MSi/m



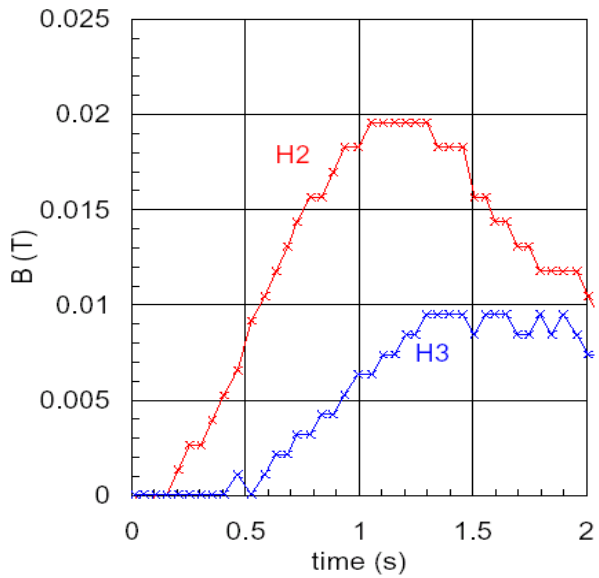
20 MSi/m

Signals at Hall probes (4)

20 MSi/m produces diffusion time in agreement with experimental diffusion



Strand heating, 20 MSi/m



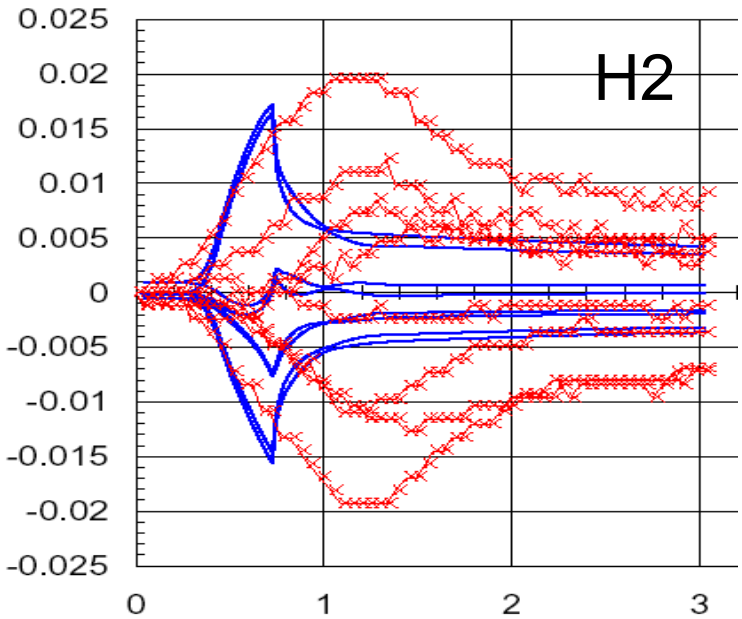
Experiment

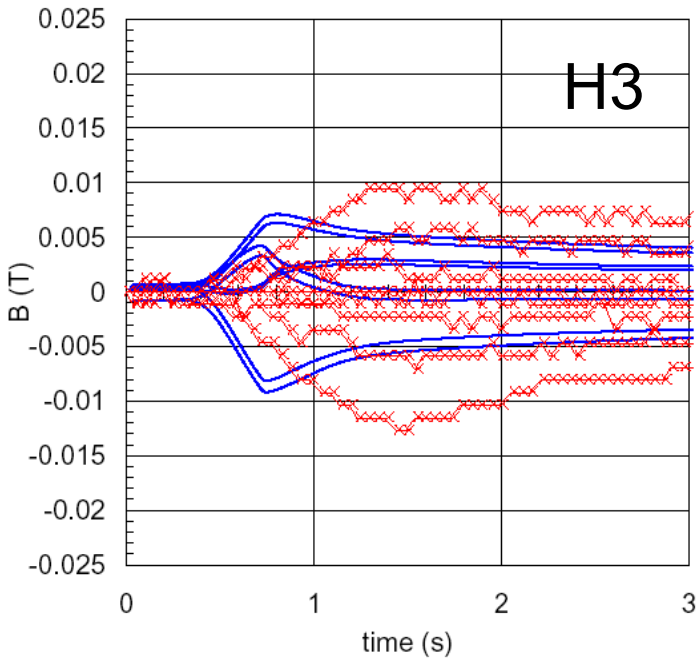
Signals at Hall probes (5)

Ramp, strand heating, 2MSi/m

Rough approximation of heat buffer effect of jacket, or equivalent to a filter

Improvement of results at H2/H3





Summary of Hall signals

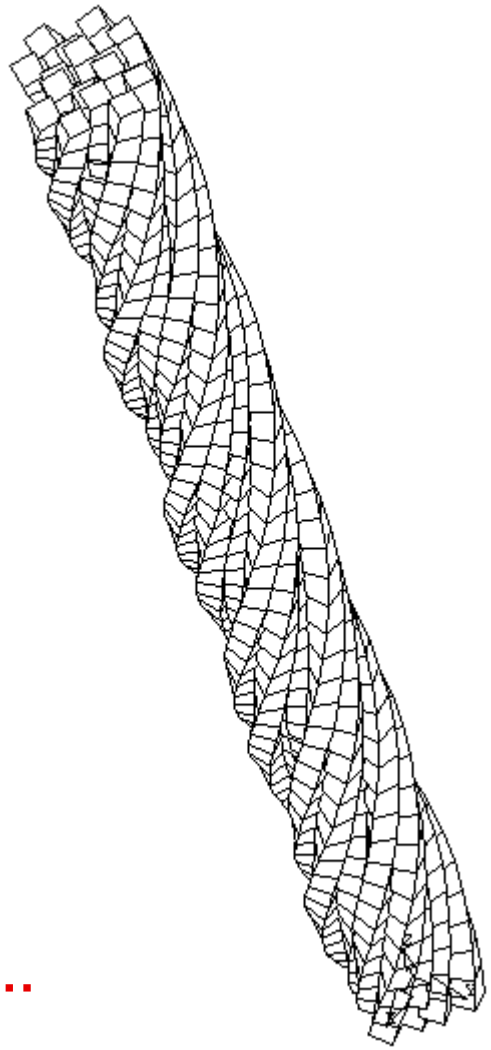
- Strand heating
  - 2 MSi/m: Order of magnitude OK, but delay (diffusion) not long enough
  - 20 MSi/m: Diffusion OK, but H3 signals too small
- Ramp (= buffer or filter): Diffusion and signals @ H2/H3 both OK
- Jacket heating signals too small, but overall dynamics OK

Summary

- Modeling of the experimental local disturbance is complex
- Orders of magnitude appear to be reasonably matched
- Calls for more involved modeling
  - more superstrands
  - thermal resistance network
  - multiple hydraulic channels (?)

Next steps

16 Superstrands
4 Hydraulic channels
Filter
Jacket heating
…



And a lot of interesting work …