Quench Characteristics of EUCARD-2 Roebel Cable Pancake Coil

Jorge Pelegrin, Qingbo Zhang, Wendell Bailey, Yifeng Yang

Institute of Cryogenics,
University of Southampton, UK

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Anna Kario KIT
EuCARD2

Contents

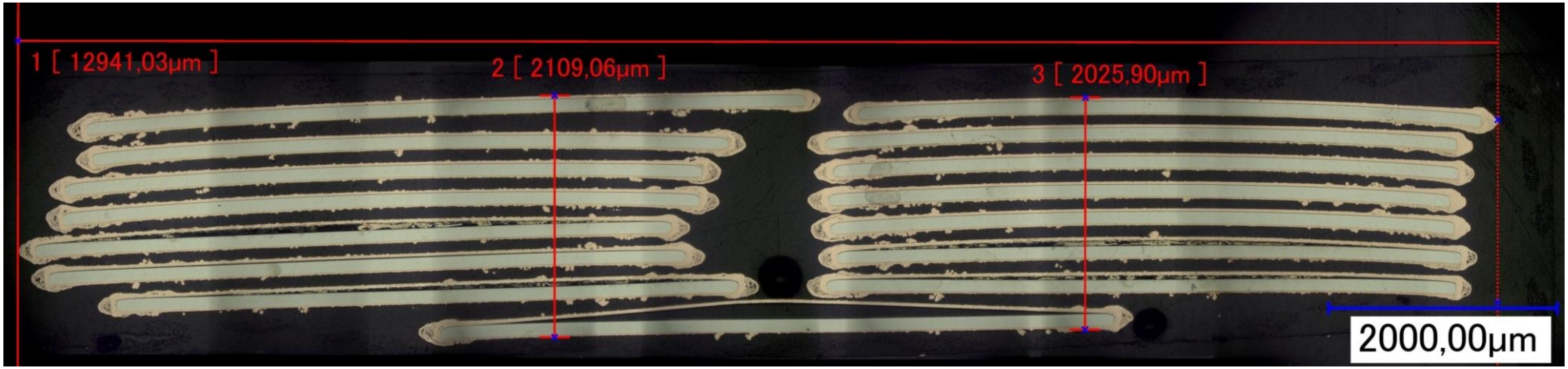
- Background
- Roebel cable and pancake coil construction
- Experimental setup
- Results
- Discussion
  - Adiabatic quench attainable?
  - MQE: cable vs single tape
  - Measurement at different temperatures and fields
  - A better understanding through modelling
- Conclusions

Background

- Challenges to quench measurement of Roebel cables
  - Current sharing at a length scale of the transposition pitch, much longer than the MPZ of a single strand
  - The "standard" 1D adiabatic quench measurement requires sample length of multiples pitch length about 1m long: difficult to realise experimentally
  - Use pancake as compromise and the quench behaviour becomes 2D: more complex but better relevance to coils
- A robust coil construction with *insultation* is needed
  - Strands able to withstand multiple thermal cycles
  - Uniform current injection with sufficient low contact resistances

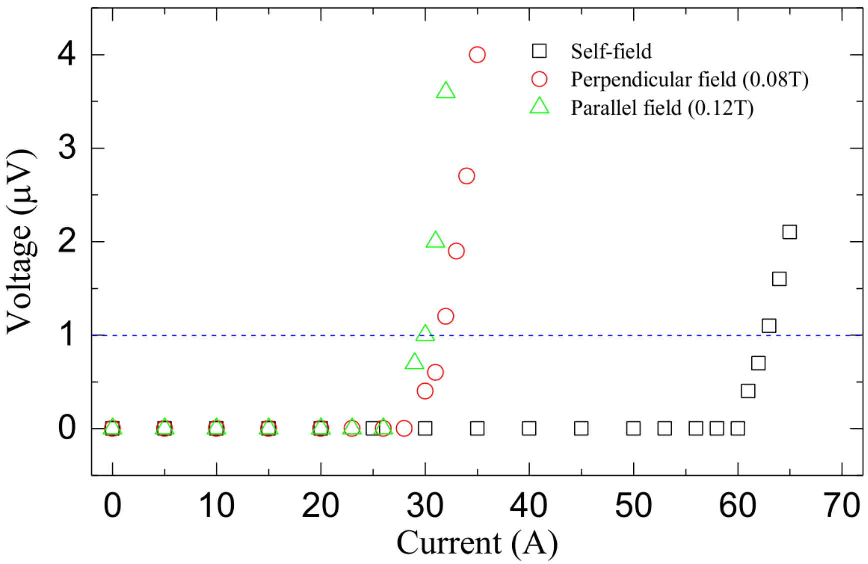
EuCARD2 Roebel Cable by KIT
Courtesy of A Kario

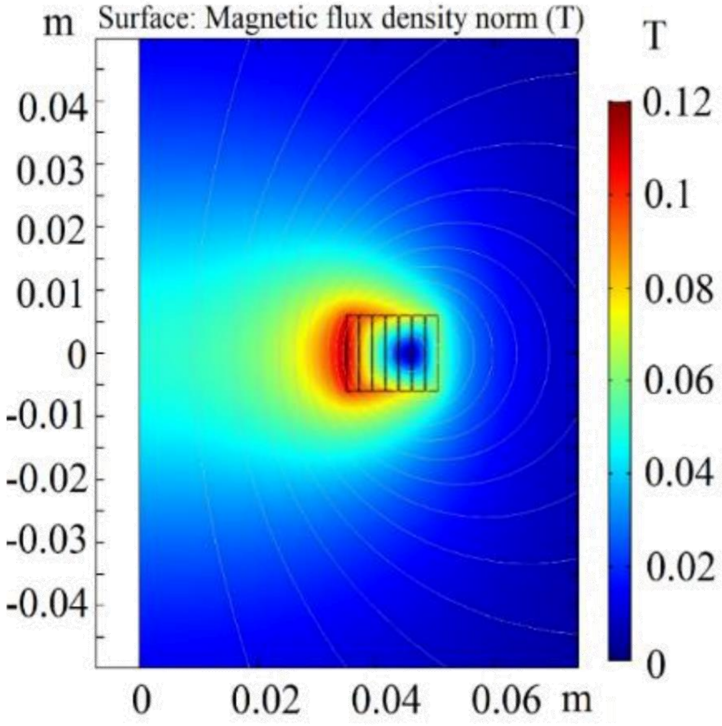
- Punch + Coat
- Assembled
- 2 m long
- 15 transposed strands at a pitch of 226mm
- Rough surface prevents dense packing
- Delamination is caused during grinding/polishing of cross-section preparation



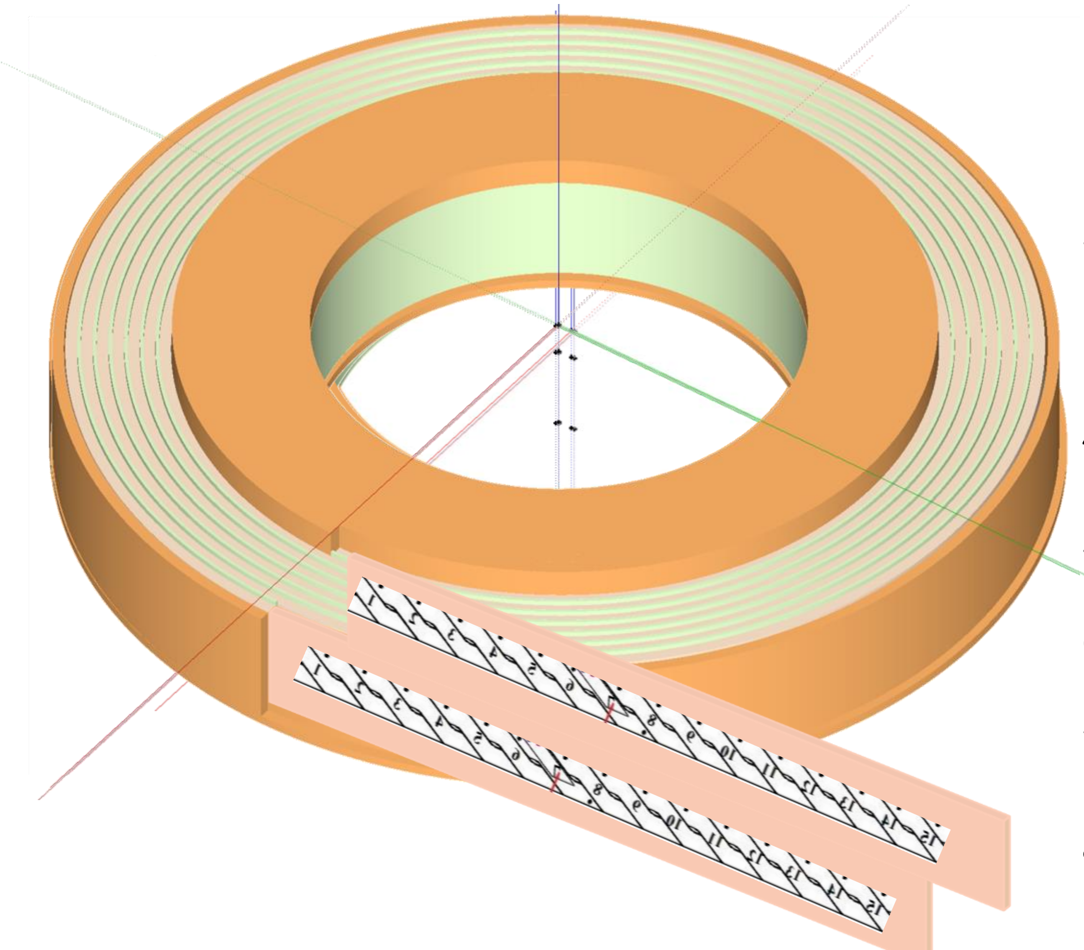
Strands, Conductor and Coil Performance

- Bruker 2G YBCO strands with doping for enhanced pinning (and a relative low I_c(4mm) = 60A at 77K)
- I_c~ 30A at 80mT perpendicular and 120mT parallel fields
- 15 strands assembled into a Roebel cable with a pitch of 226mm
- The coil critical current is around 465A

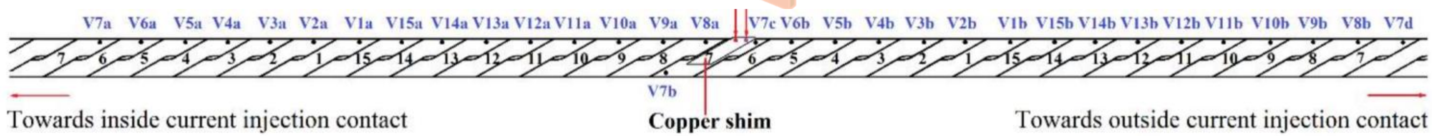




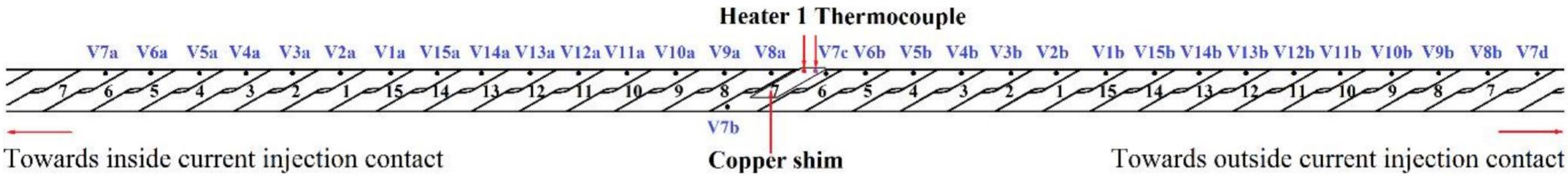
Pancake Coil Construction

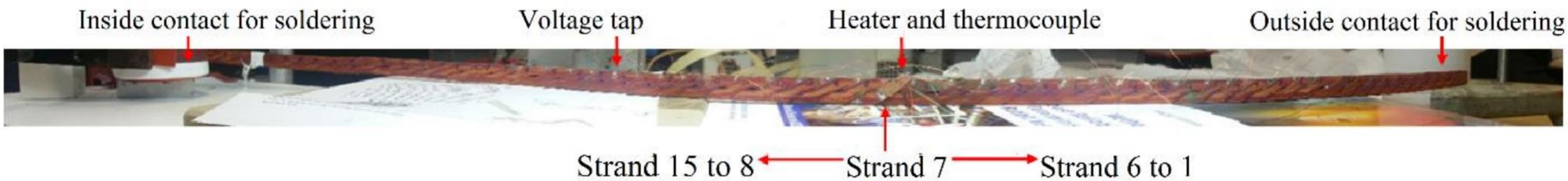


1. G10 former with a cylindrical inner current injection terminal
2. Insert inner copper contact machined precisely for the first turn of winding
3. Wind and solder the first turn on the copper contact, via exposed transposition area to every strand equally with the superconductor side facing the copper
4. Continue winding with a layer of fibre-glass insulation
5. Attach instrumentation/heater during winding
6. Insert the outer copper contact to a whole turn from below
7. Wind the last turn on the outer copper contact and solder the strands
8. Epoxy impregnation

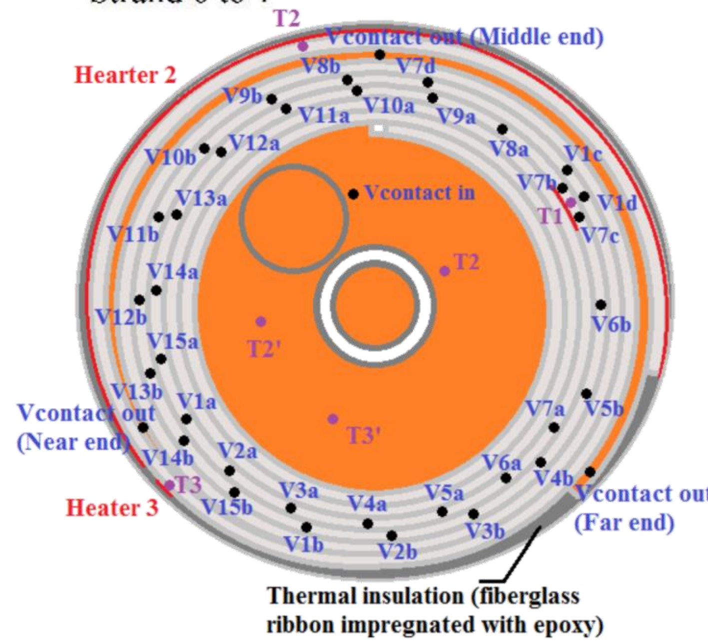


Instrumentations and Experimental Setup





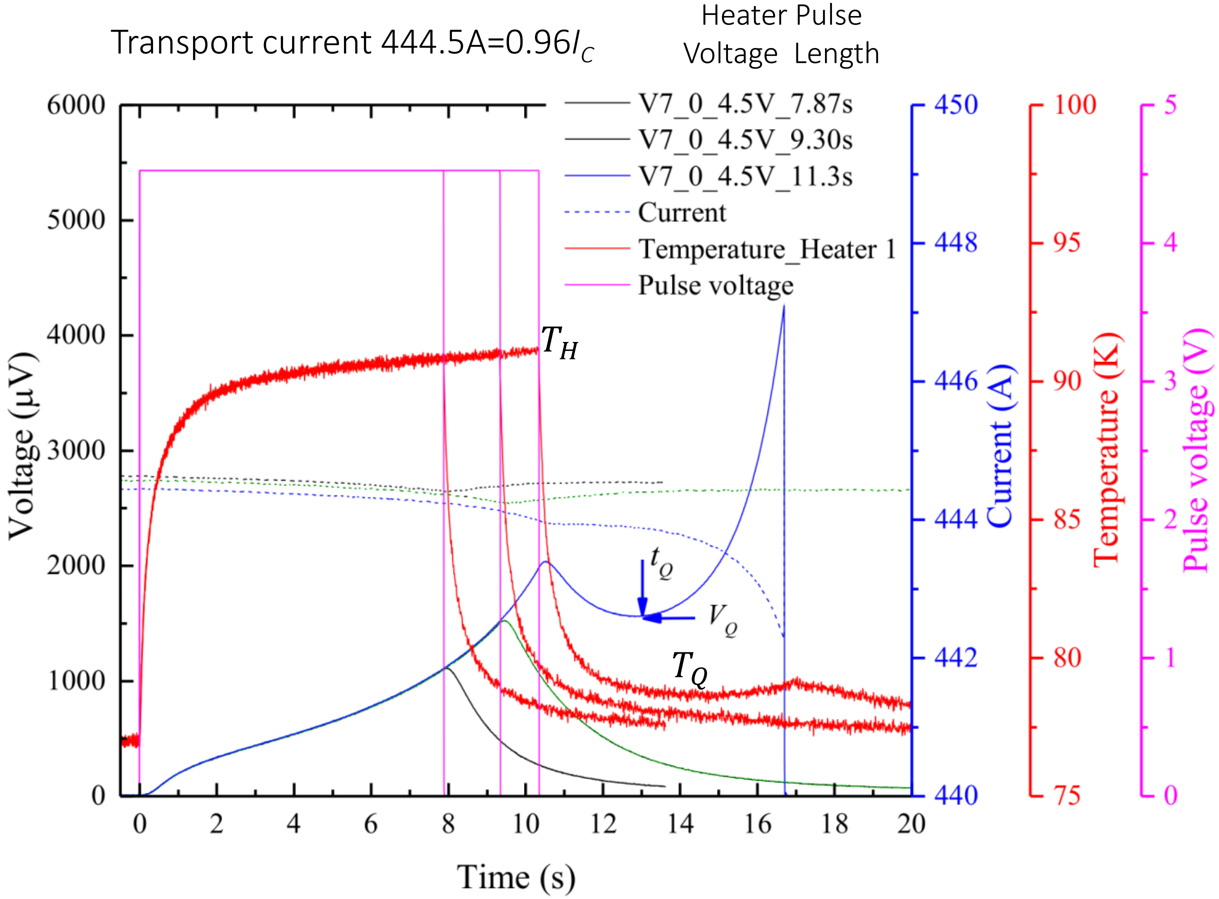
- A heater attached to a copper shim soldered to the exposed transition section of strand No. 7
- A thermocouple soldered on the heated spot
- A pair of voltage taps on every strand enclosing the heated spot
- The voltage pairs spread over 2 pitch length and 2+ turns, but not symmetrically distributed about the hot spot
- Coil submerged in liquid nitrogen pool for measurement



A Typical Quench Measurement in LN_2

- Heater power limited to ~<1.1W
- Heater pulse length increased gradually until irreversible quench was reached
- Reproducible T(t) and V(t) for given pulse power and length
- Refine heater pulse length to find Minimum Quench Energy (MQE)
- V_Q for the voltage minimum at the heated spot before quenching irreversibly
- T_H for maximum temperature at the heated spot at the end of the heater pulse
- T_Q for the minimum temperature at the heated spot before quenching irreversibly
- V(t) is more sensitive for quench detection

Hot spot voltage (V7) and temperature (T7) at different pulse length



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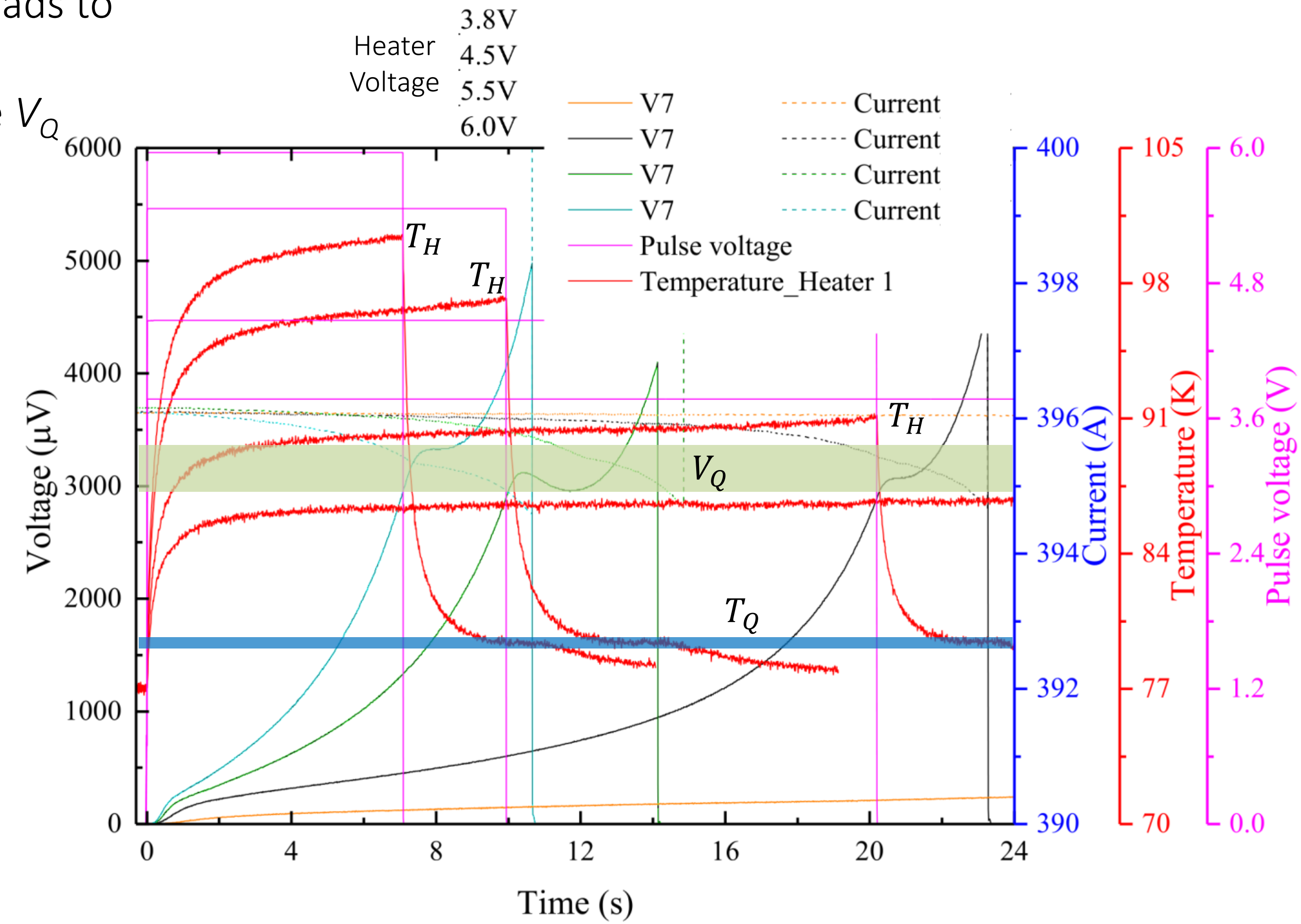
Measurement of MQE at Different Heater Power

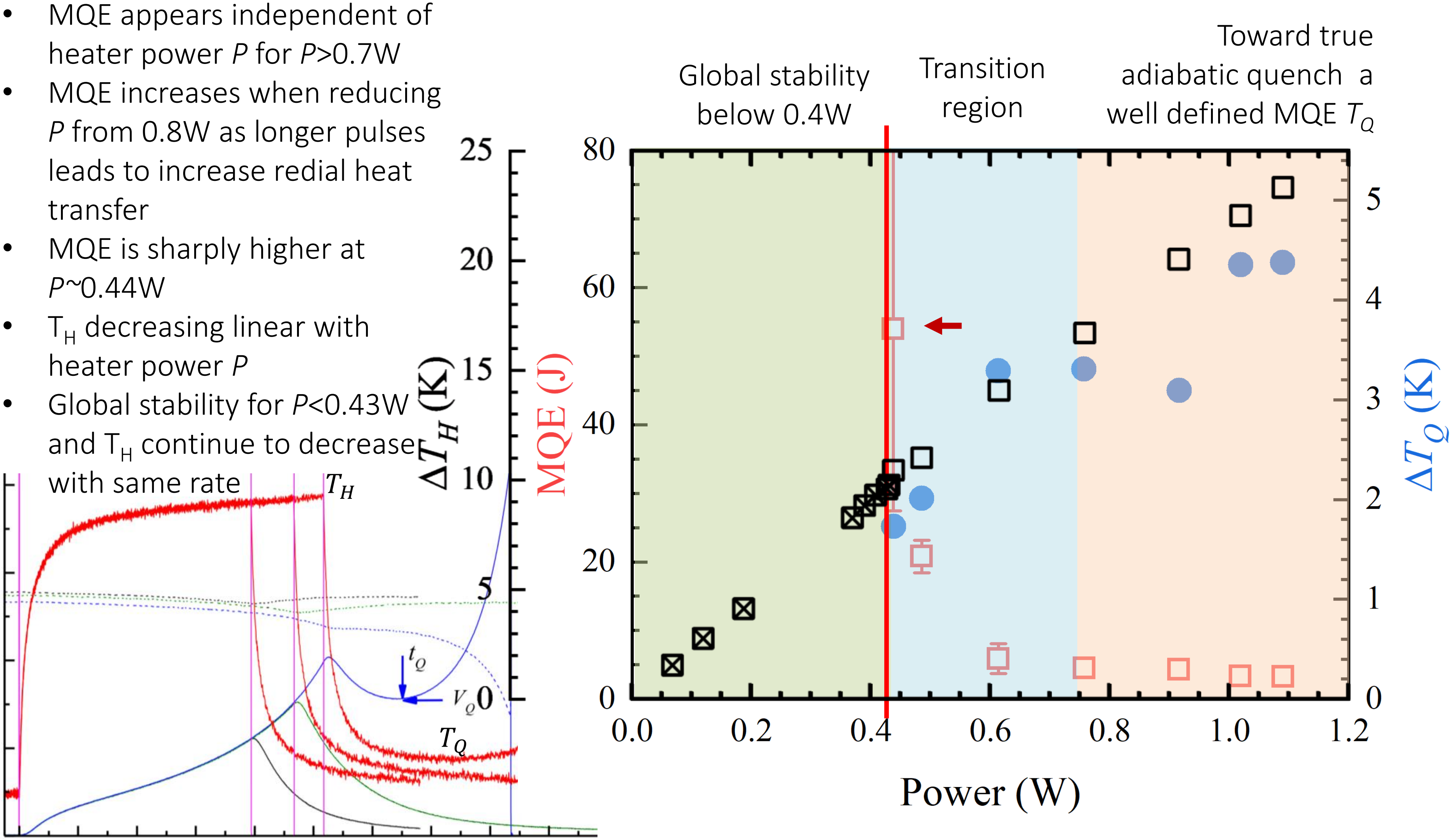
Reducing heater power leads to

- Lower T_H
- Similar quench voltage V_Q
- A "constant" quench temperature T_Q



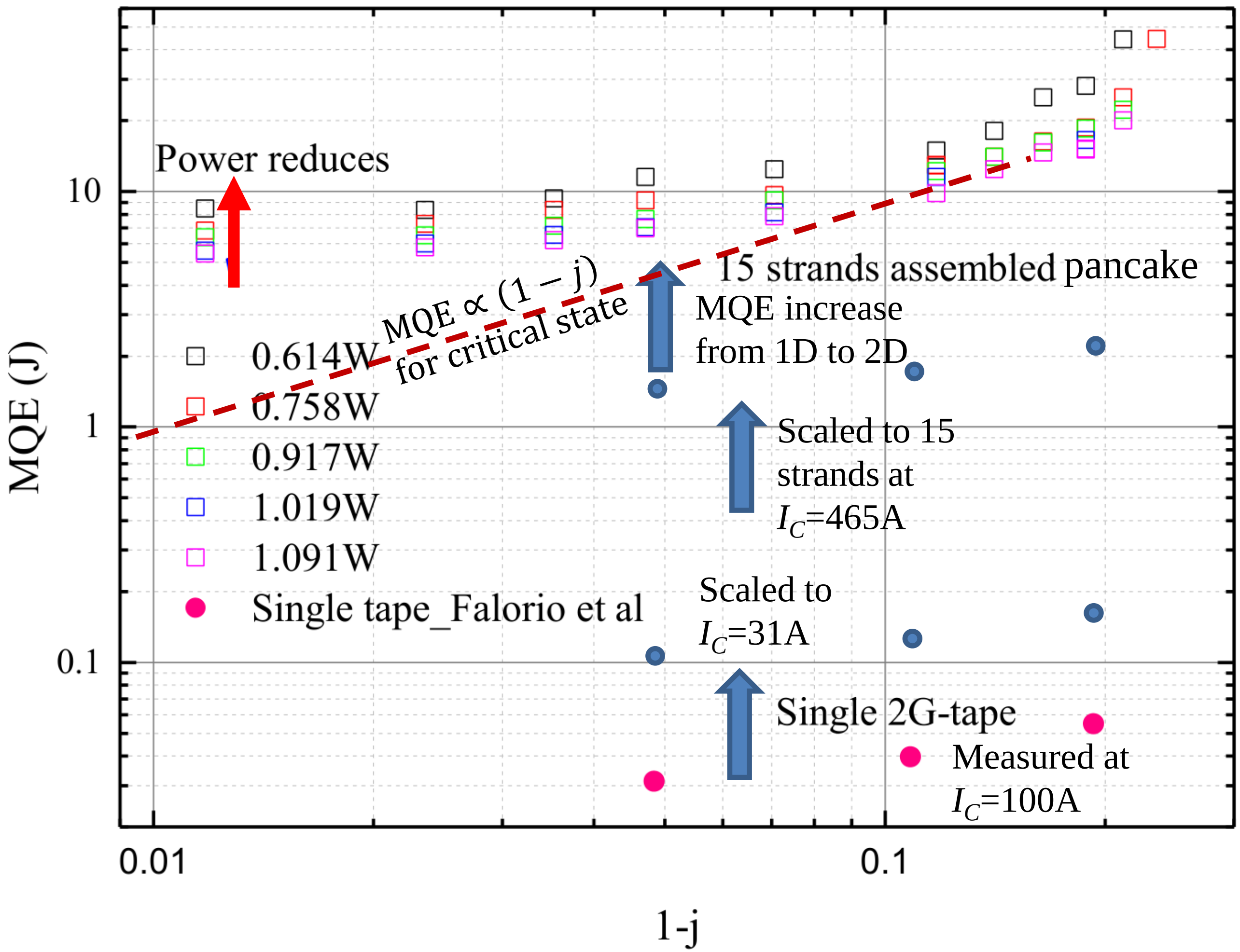
Quench and Stability at 77K with Different Heater Power

- MQE appears independent of heater power *P* for *P*>0.7W
- MQE increases when reducing *P* from 0.8W as longer pulses leads to increase redial heat transfer
- MQE is sharply higher at *P*~0.44W
- T_H decreasing linear with heater power *P*
- Global stability for *P*<0.43W and T_H continue to decrease with same rate

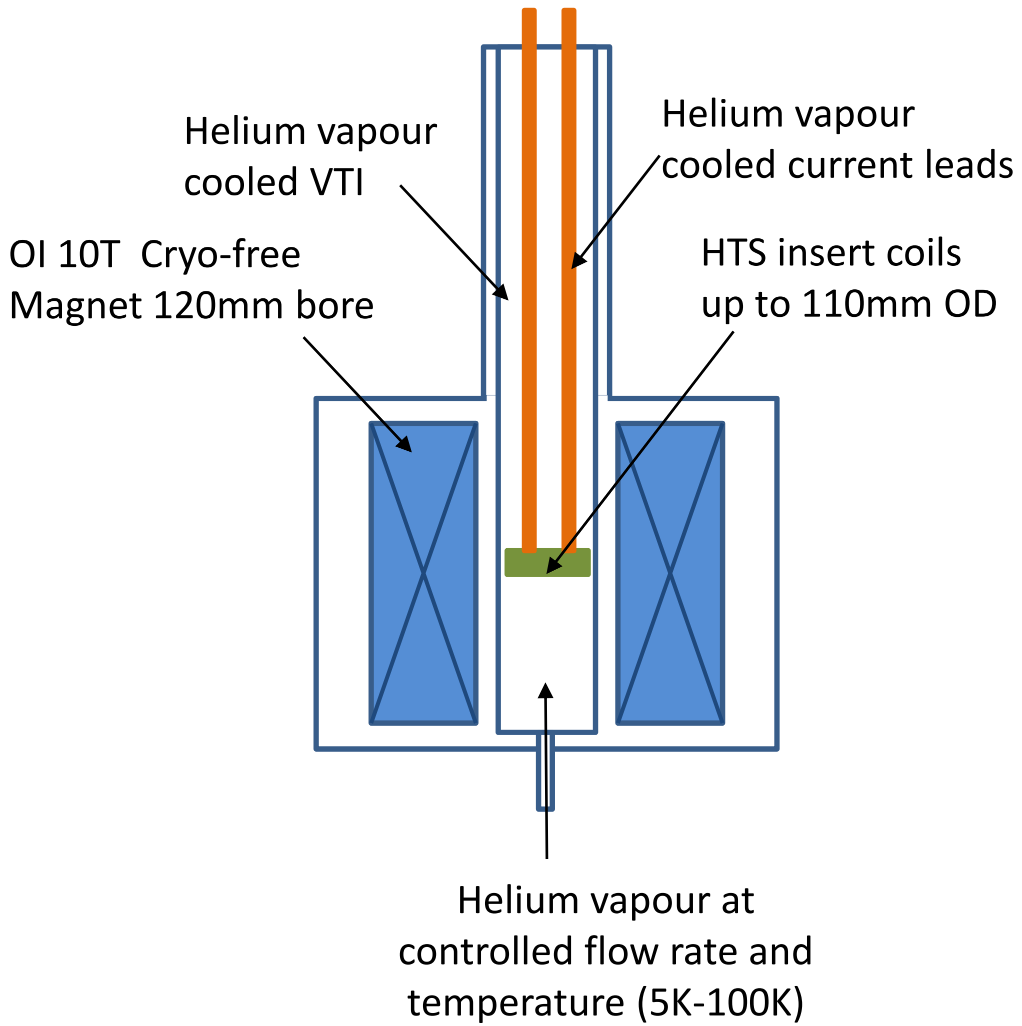


MQE at Different Current

~ 100x single tape's: in line with 2D with coil composite

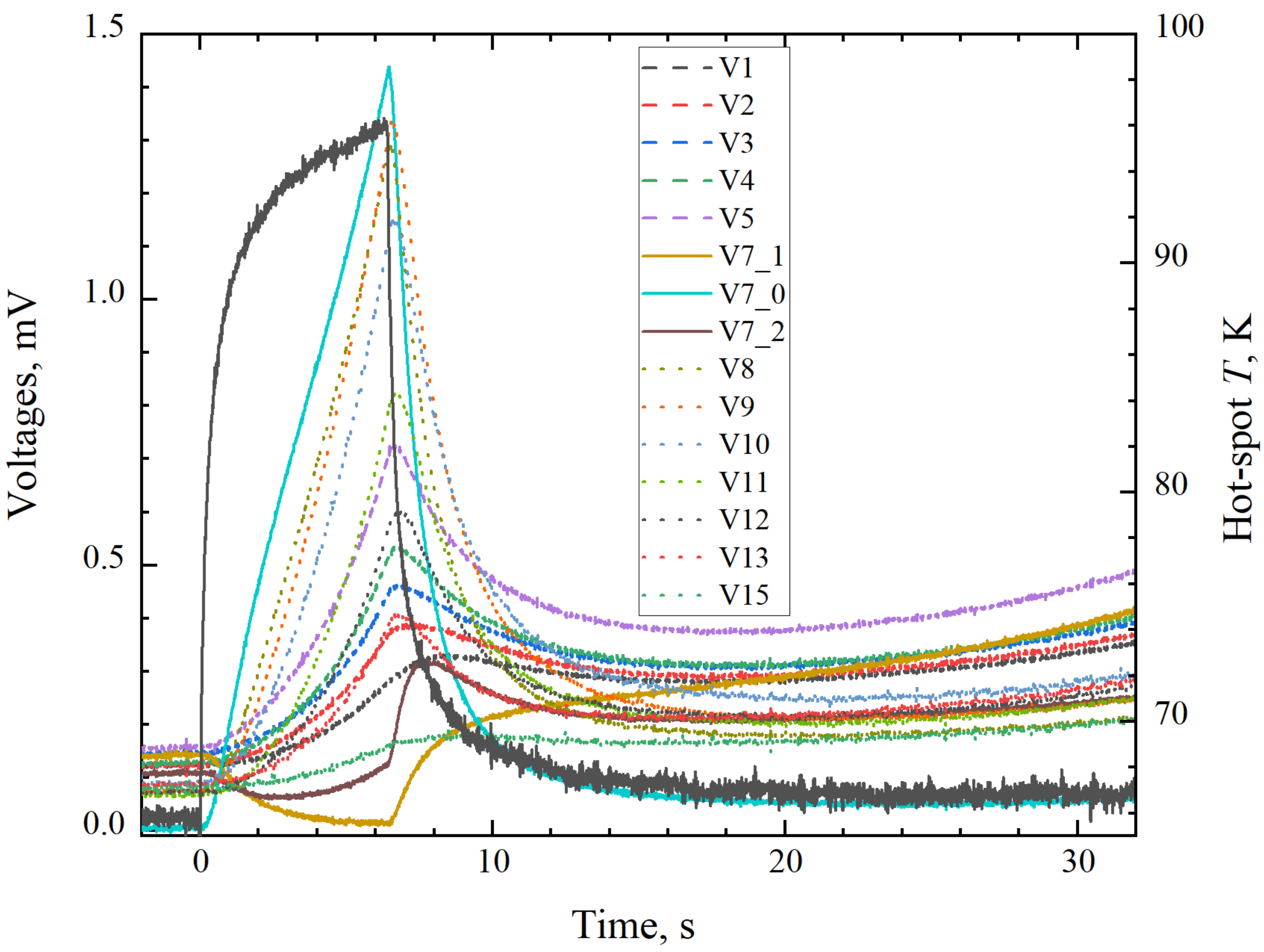


Measurement at Different Temperatures in Helium Vapour in External Fields



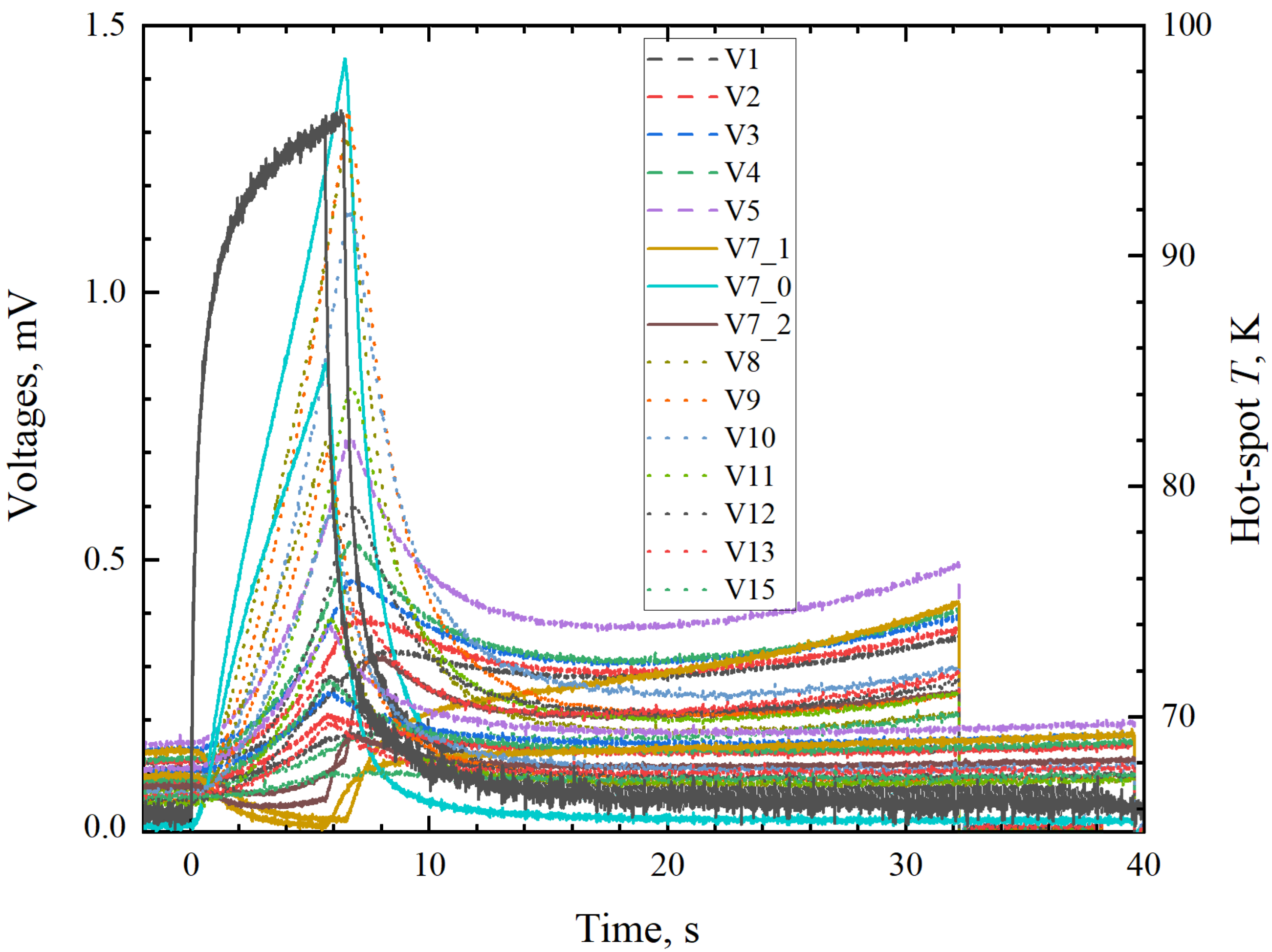
Measurement at Low Temperatures 700A at 66K / 2T

- Critical Current: ~750A on inner turns
- No quench was obtained at 600A with 27J heater energy
- Quench at 700A with 6.5J deposited on strand #7
  - Hot spot reached 96K
  - Hot spot voltage at 1.4mV
  - Current reduced in the heated strand by current sharing
  - All the strands quenched



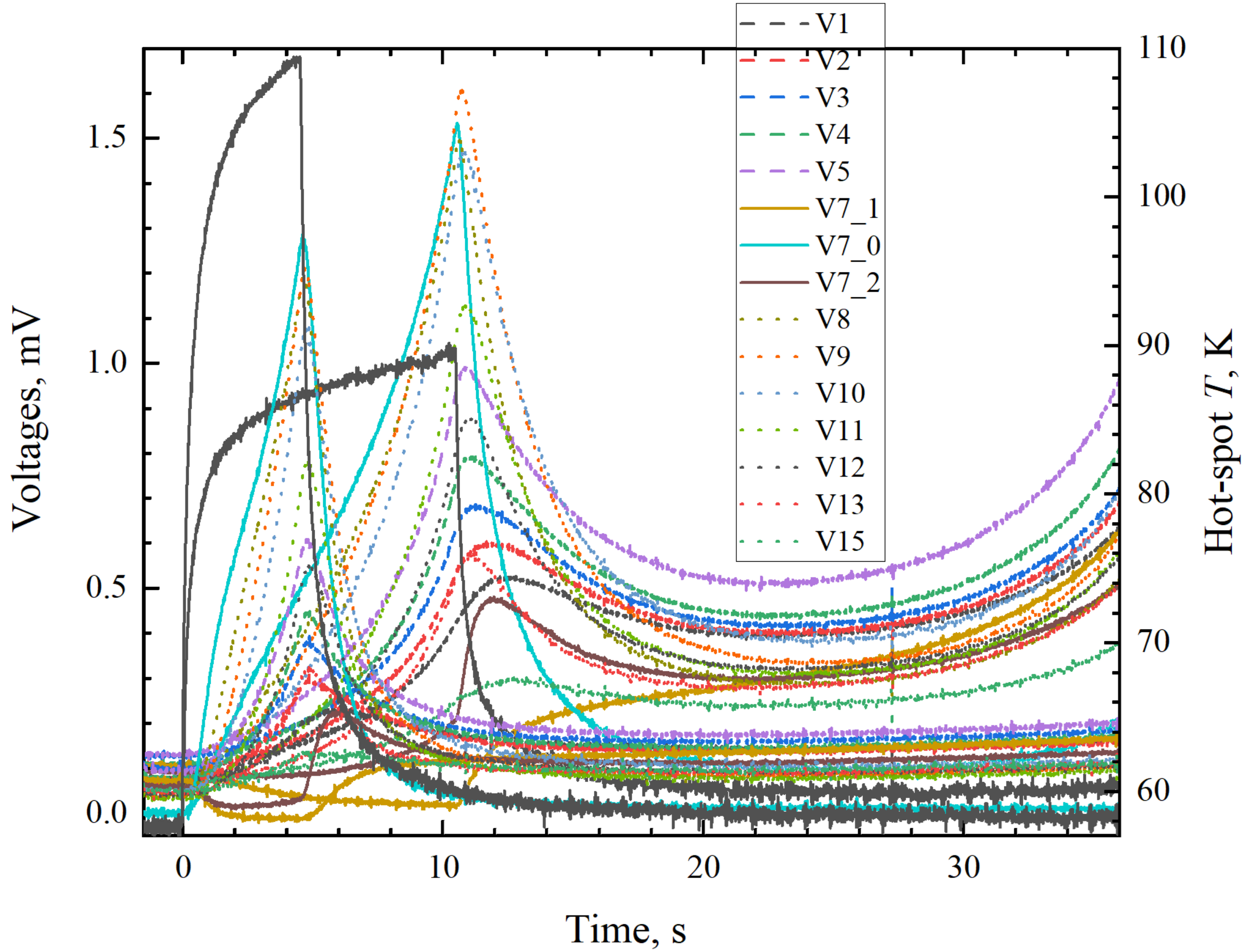
Measurement at Low Temperatures 700A at 66K / 2T

Minimum quench energy (MQE) for 700A at 66K in 2T is ~ 5.5J



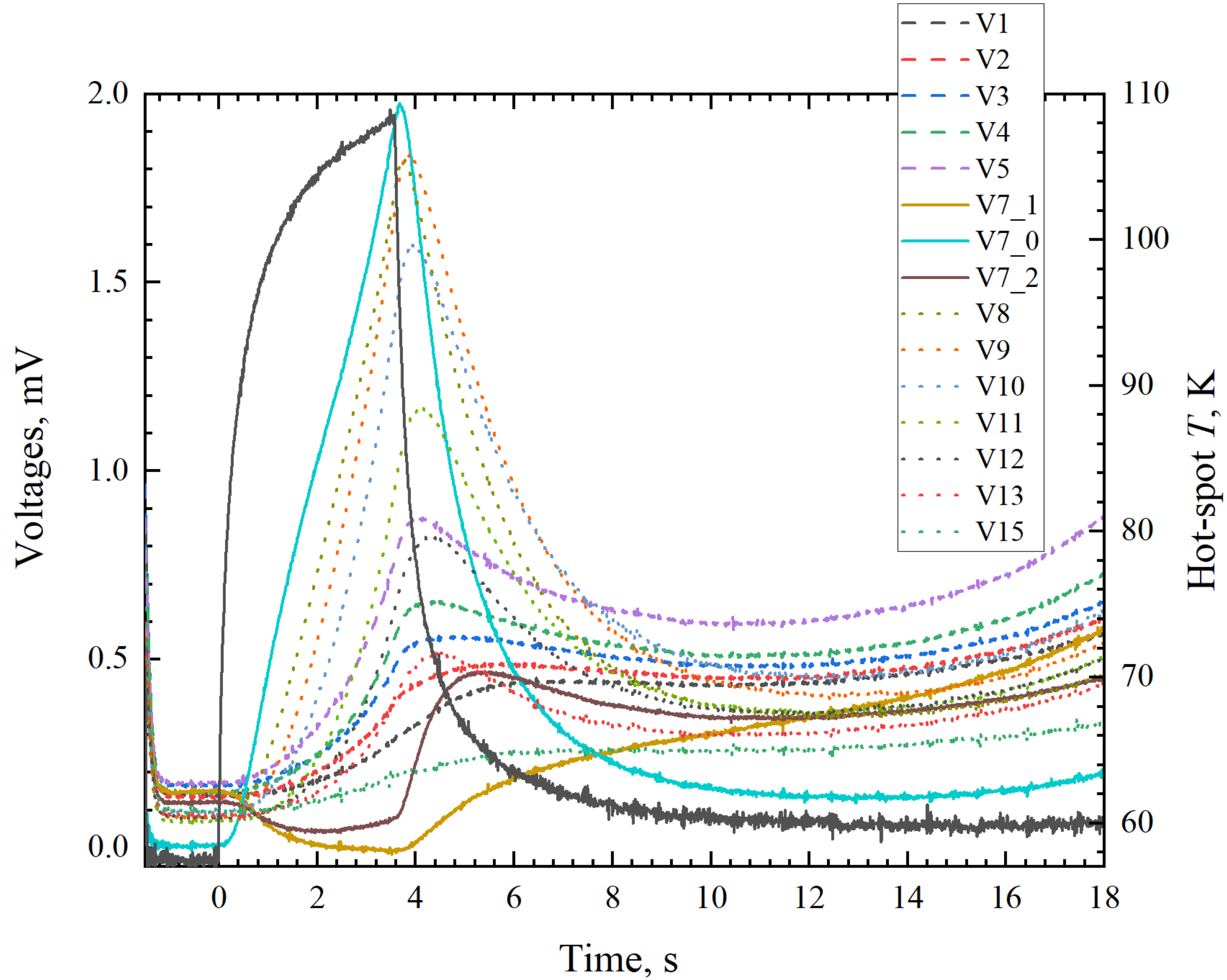
Measurement at Low Temperatures
1100A at 58K / 3T

- ❑ Critical Current: ~1250A or inner turns
- ❑ Quench at 1100A with 10.4J deposited on strand #7 at 1W heat power
  - ➢ Hot spot T_H ~ 90K
  - ➢ Hot spot voltage at 1.5mV
- ❑ Quench at 1100A with 8.5J deposited on strand #7 at 1.8W heat power
  - ➢ Hot spot above 110K
  - ➢ Hot spot voltage at 1.3mV
  - ➢ Almost at MQE



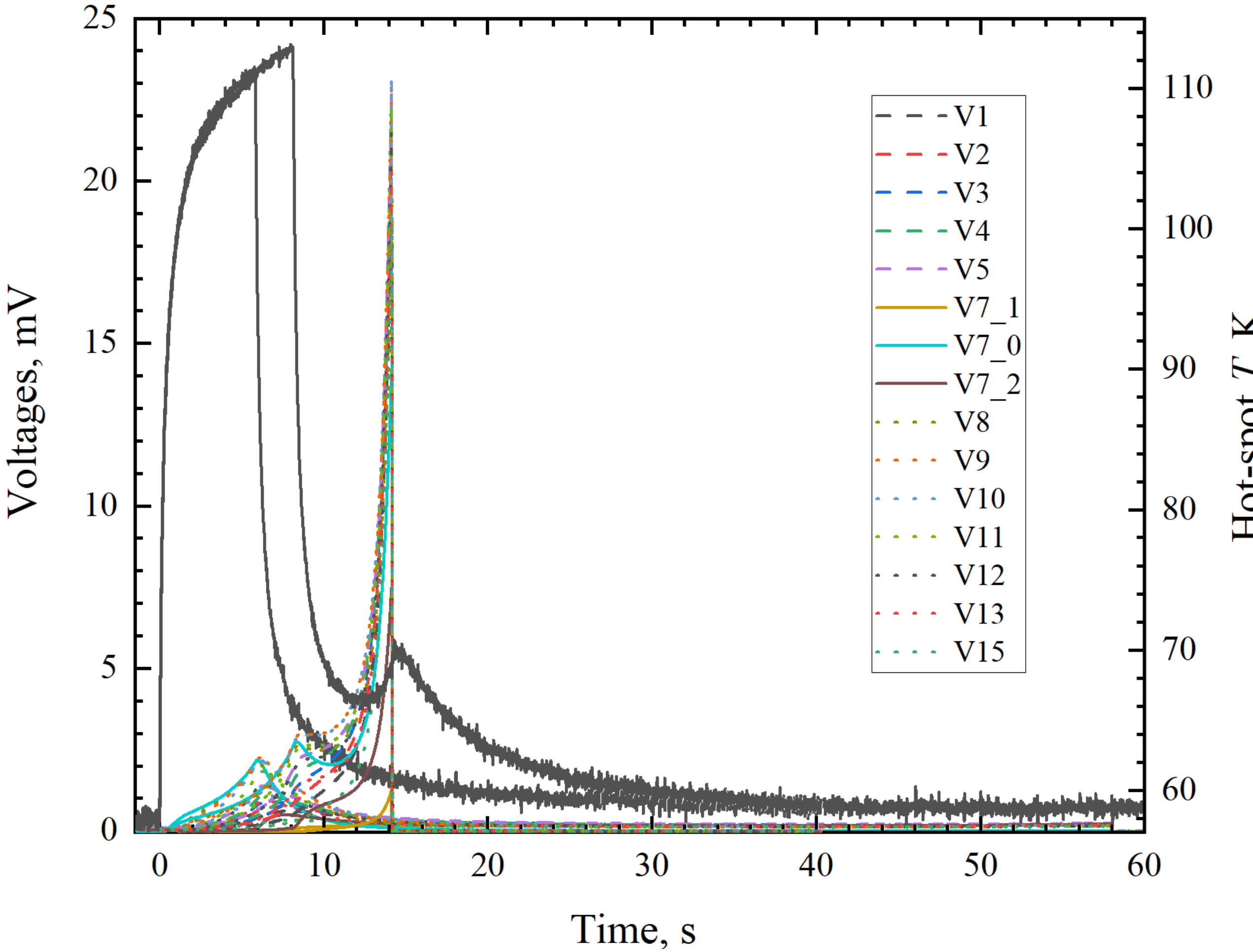
Measurement at Low Temperatures
1200A at 58K / 3T

- ❑ Critical Current: ~1250A on inner turns
- ❑ Quench at 1200A with 6.3J deposited on strand #7 at 1.8W heat power
  - ➢ Hot spot above 108K
  - ➢ Hot spot voltage at 1.3mV



Measurement at Low Temperatures 1000A at 58K / 3T

- Quench at 1000A with 12.1J deposited on strand #7 at 1.8W heat power
  - Hot spot at 110K
  - Hot spot voltage at 2.3mV
  - Close to MQE
- Quench at 1000A with 14.4J deposited on strand #7 at 1.8W heat power
  - Hot spot above 110K
  - Hot spot voltage at 3.5mV
  - Fast quench ensued and with strands reaching 25mV per pitch length in less that 6s

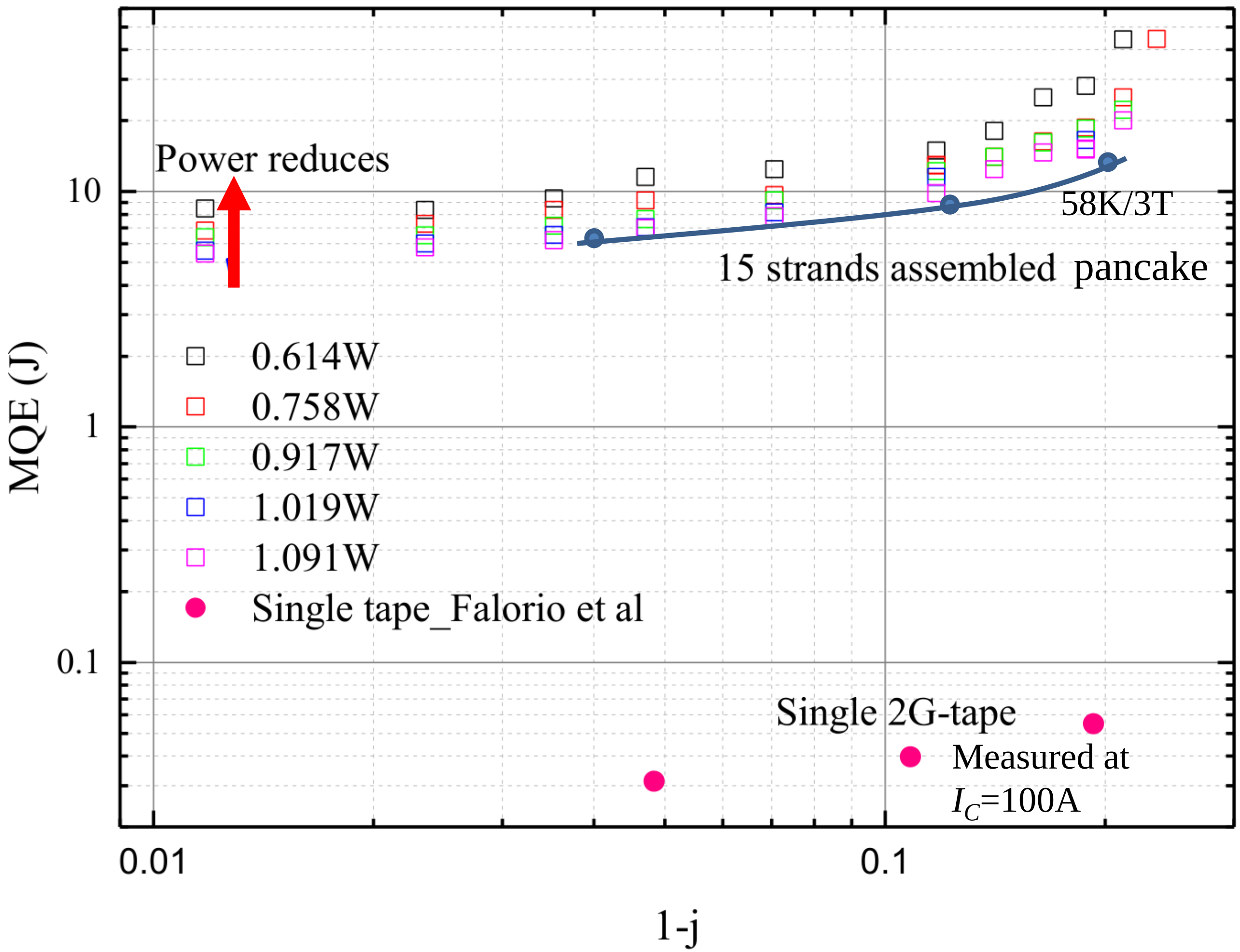


8T/50K

1. Critical current ~> 1600A
2. Minimum quench energy show unexpected large increase (31J @1500A)
3. Quench dynamics changed significantly too with a fast propagation (5m/s) and more difficult to catch "quasi-stable" MPZ

MQE at Different Current

~ 100x single tape's: in line with 2D with coil composite



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Learn More Using Modelling

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Quench in a pancake coil wound with REBCO Roebel cable: model and validation

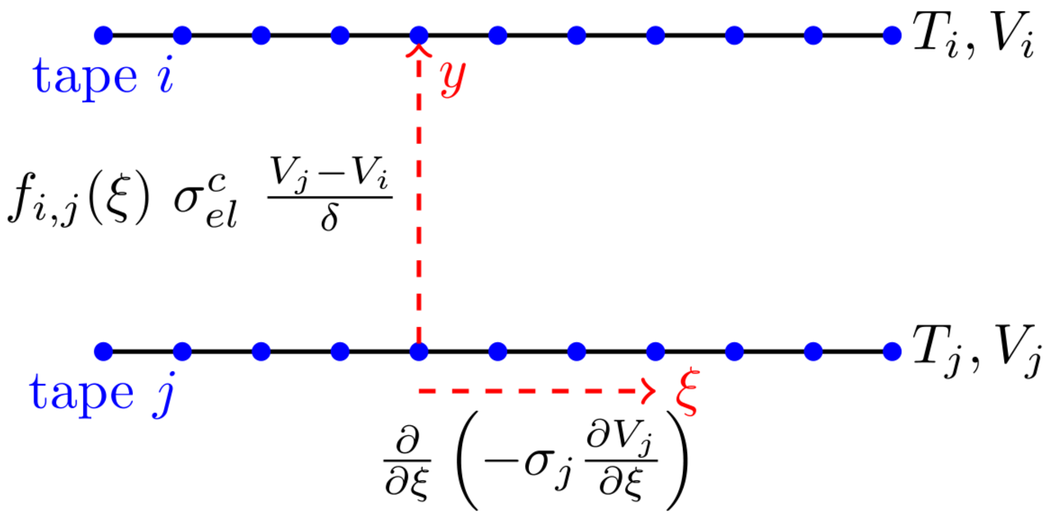
Lorenzo Cavallucci[1,*], **Marco Breschi**[1], **Pier Luigi Ribani**[1], **Qingbo Zhang**[2] **and Yifeng Yang**[2]

[1] Department of Electrical, Electronic, and Information Engineering, University of Bologna, 40136 Bologna, Italy
[2] Institute of Cryogenics, Faculty of Engineering and the Environment, University of Southampton, SO18 Southampton, United Kingdom

1. Accounts for individual transposed strands
2. Efficient 1D thermal-electrical model with lateral current and heat conduction
   - Allowing continuous electrical and thermal contacts for current sharing according to transposition and thermal distribution
   - Enabling turn-to-turn pancake model with thermal contacts to co-wound insulation instead homogenised coil composites
3. Only two adjustable parameters: thermal and electrical contact resistivity

Electrical Model

$$\nabla \cdot \mathbf{J}_j = \frac{\partial J_{\xi.j}}{\partial \xi} + \frac{\partial J_{y.j}}{\partial y} = 0$$



Longitudinal: $$\frac{\partial J_{\xi.j}}{\partial \xi} = \frac{\partial}{\partial \xi}\left(-\sigma_j \frac{\partial V_j}{\partial \xi}\right)$$

power-law in parallel with normal matrix $\sigma_j = \lambda \frac{J_c(T_j, B_j)}{E_c}\left(\frac{|E_j|}{E_c}\right)^{1-n^{-1}} + (1-\lambda)\sigma_{\mathrm{nc}}$

Normal: $$\frac{\partial J_{\xi,j}}{\partial \xi} = \sum_{k=1, k\neq j}^{N} f_{j,k}(\xi)\sigma^c_{\mathrm{el}} \frac{V_j - V_k}{\delta}$$

with a contact function $f_{j,k}(\xi)$ and contact resistance σ^c_{el}

Boundary: $$\sum_{i=1}^{N} j_j(\xi = 0) = \sum_{i=1}^{N} j_j(\xi = L) = I_{op}$$

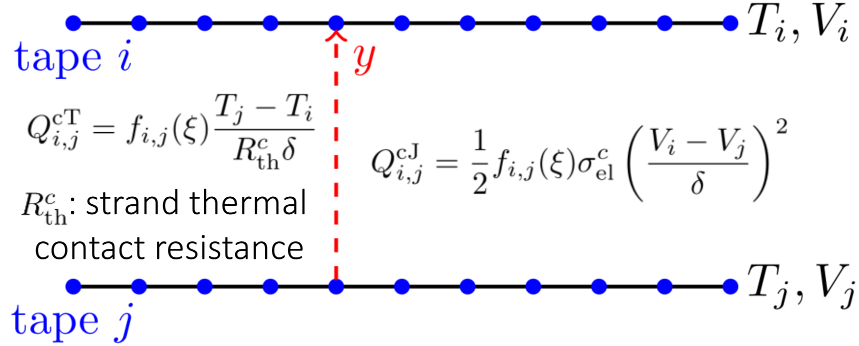
Thermal Model with Turn-by-Turn Winding

$$\rho c_p(T_i(\xi,t))\frac{\partial T_i(\xi,t)}{\partial t} - \frac{\partial}{\partial \xi}\left(k(T_i(\xi,t))\frac{\partial T_i(\xi,t)}{\partial \xi}\right)$$

$$= \sigma_i(T_i,t)\left(\frac{\partial V_i(T_i,t)}{\partial \xi}\right)^2 + \sum_{j=1,j\neq i}^{N}\left(Q_{i,j}^{\mathrm{cJ}} + Q_{i,j}^{\mathrm{cT}}\right)$$

$$+ Q_i^{\mathrm{in}} + Q_i^{\mathrm{out}}$$

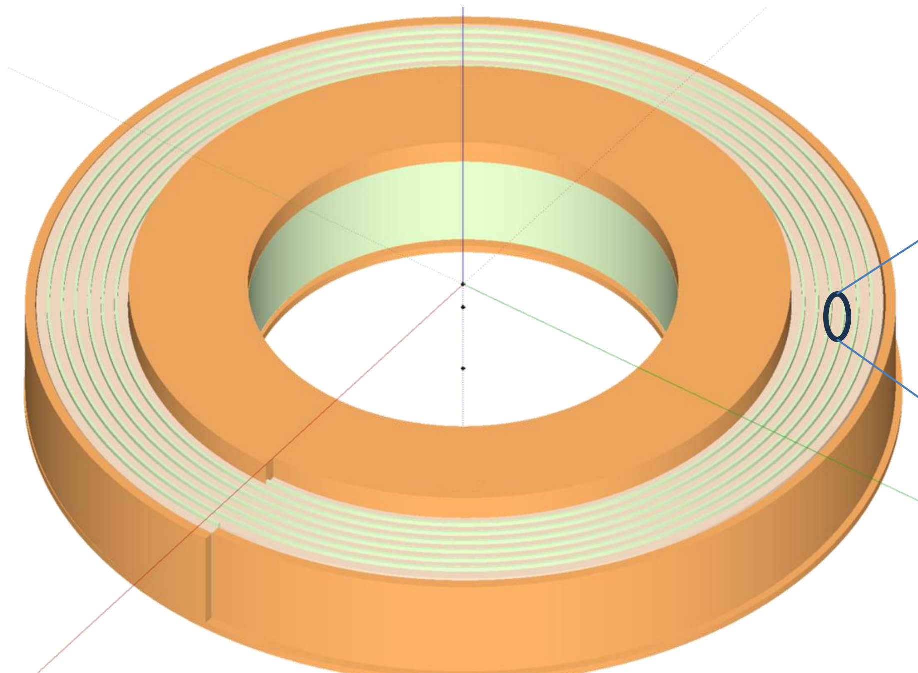
$$+ Q_i^{\mathrm{heater}}$$



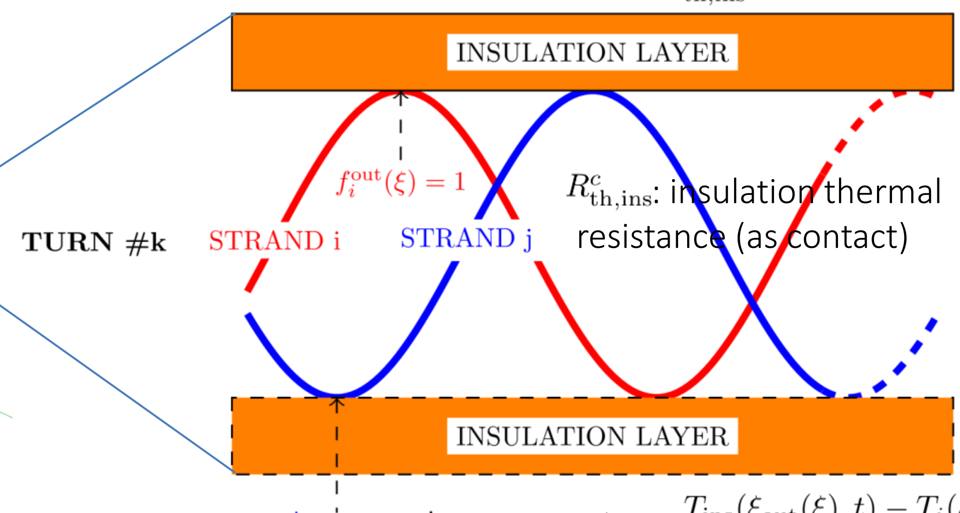
$$Q_{i,j}^{\mathrm{cT}} = f_{i,j}(\xi)\frac{T_j - T_i}{R_{\mathrm{th}}^c \delta}$$

R_{th}^c: strand thermal contact resistance

$$Q_{i,j}^{\mathrm{cJ}} = \frac{1}{2} f_{i,j}(\xi)\sigma_{\mathrm{el}}^c\left(\frac{V_i - V_j}{\delta}\right)^2$$



$$Q_i^{\mathrm{ii}}(\xi,t) = f_i^{\mathrm{in}}(\xi,t)\frac{T_{\mathrm{ins}}(\xi_{\mathrm{in}}(\xi),t) - T_i(\xi,t)}{R_{\mathrm{th,ins}}^c \delta}$$



$R_{\mathrm{th,ins}}^c$: insulation thermal resistance (as contact)

$$Q_i^{\mathrm{io}}(\xi,t) = f_i^{\mathrm{out}}(\xi,t)\frac{T_{\mathrm{ins}}(\xi_{\mathrm{out}}(\xi),t) - T_i(\xi,t)}{R_{\mathrm{th,ins}}^c \delta}$$

Parameters

Fixed parameters

Tape geometrical parameters		
Thickness	Copper	50 μm
	YBCO	1 μm
	Buffer layer	0.2 μm
	Stainless steel	100 μm
Width		5.8 mm
Copper RRR		30
Tape critical current parameters		
Ic_0		57.2
n-value		20

Roebel cable	
Transposition pitch T_p	226 mm
Transposition angle T_θ	50°
Cable width	12 mm
Strands number	15

Pancake geometry

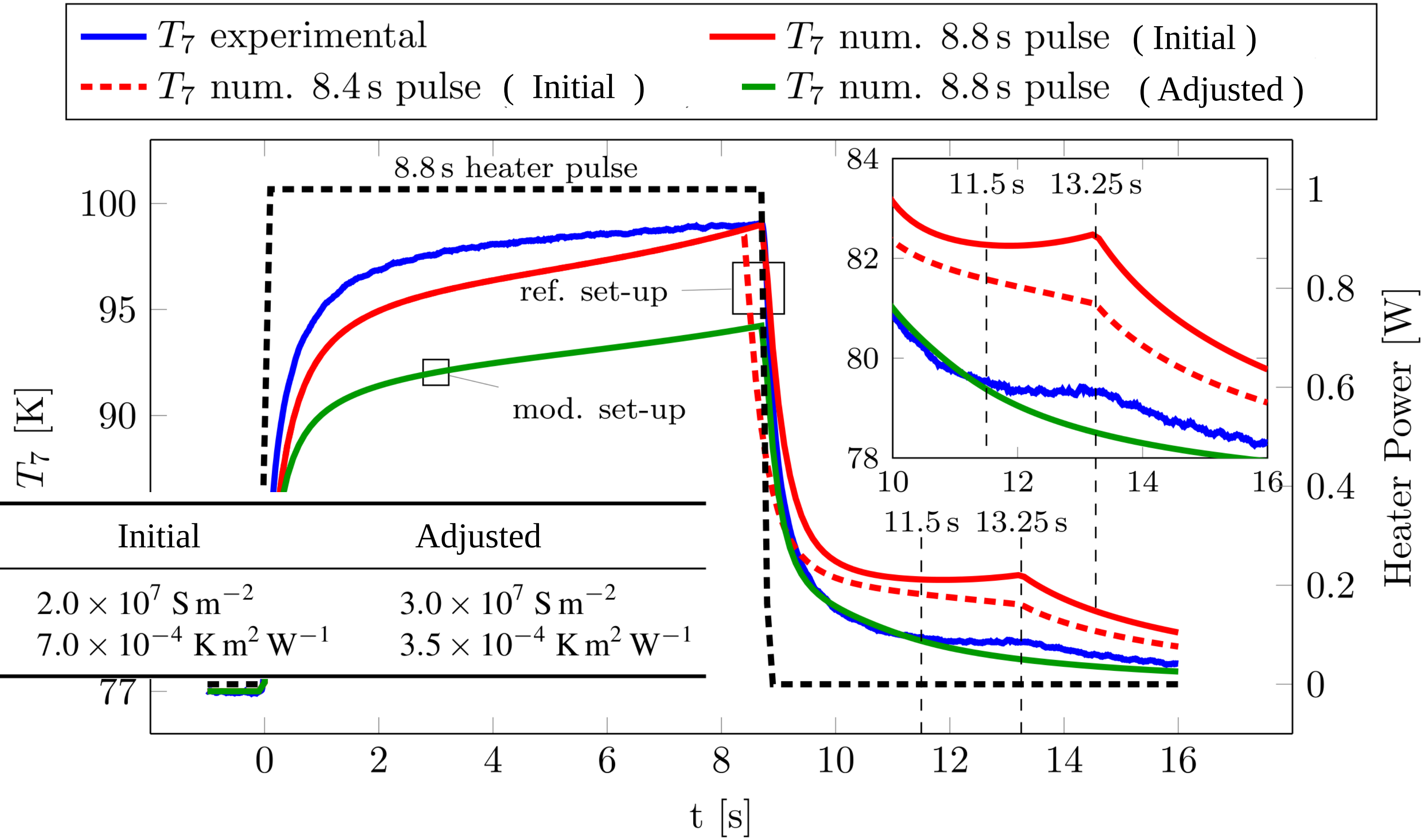
Pancake Coil	
Turns number	7
Inner radius	72 mm
Inter-strand insulation layer δ_{ins}	200 μm
Top pancake insulation layer $\delta_{ins,s}$	500 μm

Adjustable parameters

Initial guess		
σ_{el}^c	2.0×10^7 S m^{-2}	0.1% sporadic point contacts
R_{th}^c	7.0×10^{-4} K m^2 W^{-1}	0.1mm epoxy

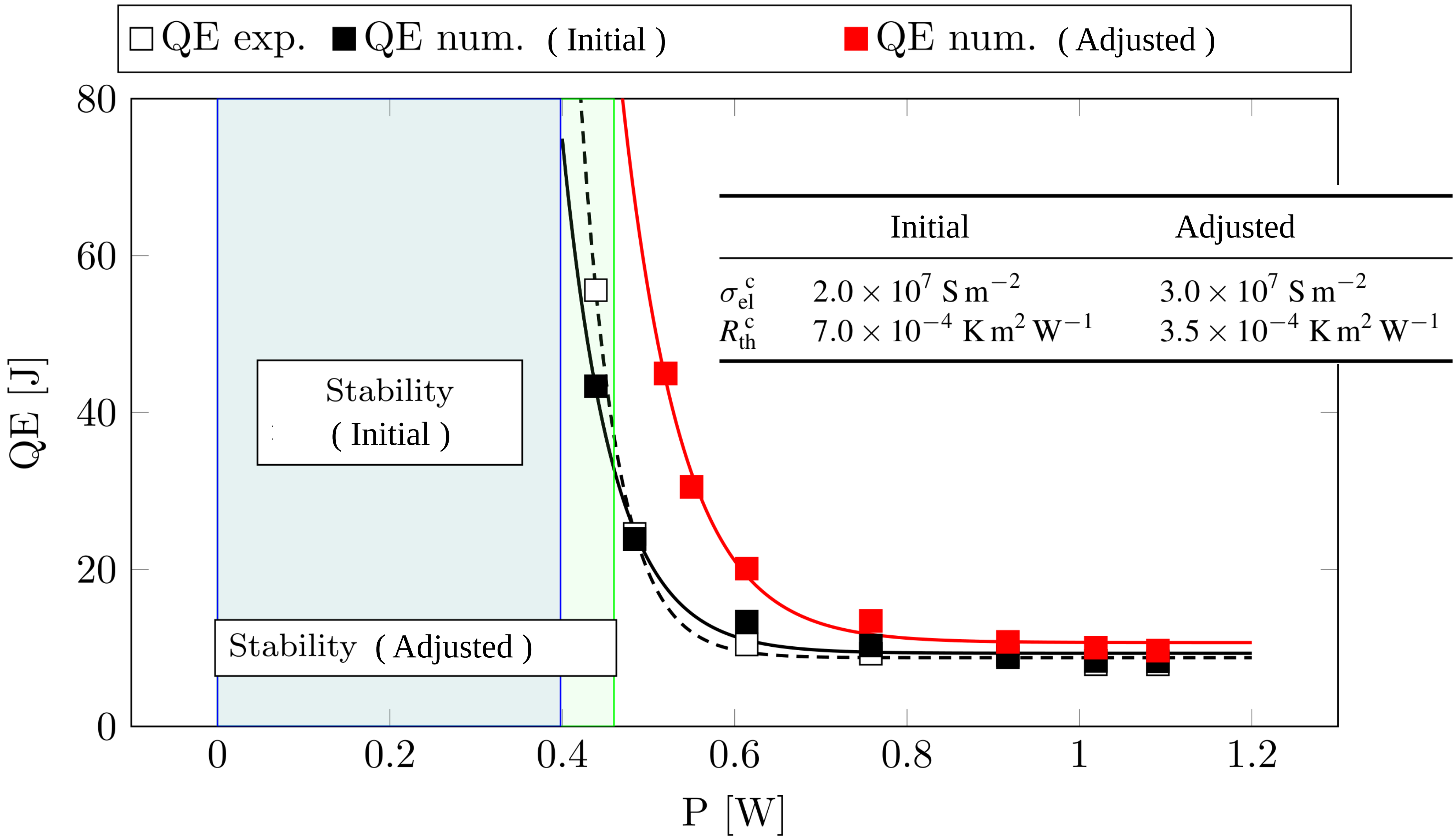
Clean copper contacts: $\sigma_{el}^c \sim 10^{11}\text{Sm}^{-2}$
Ambient oxidised: $\sigma_{el}^c \sim 3 \times 10^{10}\text{Sm}^{-2}$

Quench at I_{OP}=444A in LN_2

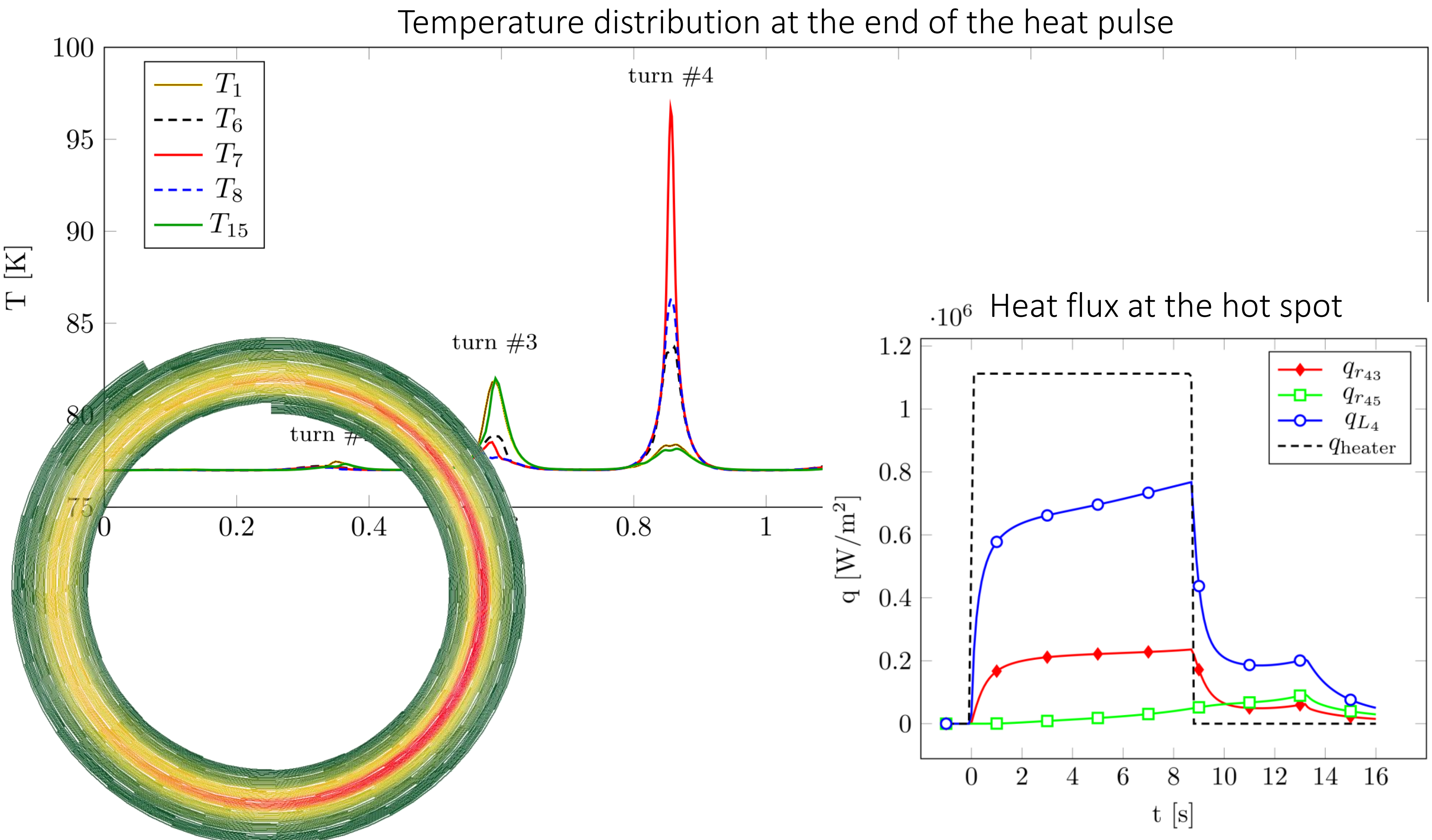


	Initial	Adjusted
σ_{el}^{c}	2.0×10^{7} S m^{-2}	3.0×10^{7} S m^{-2}
R_{th}^{c}	7.0×10^{-4} K m^{2} W^{-1}	3.5×10^{-4} K m^{2} W^{-1}

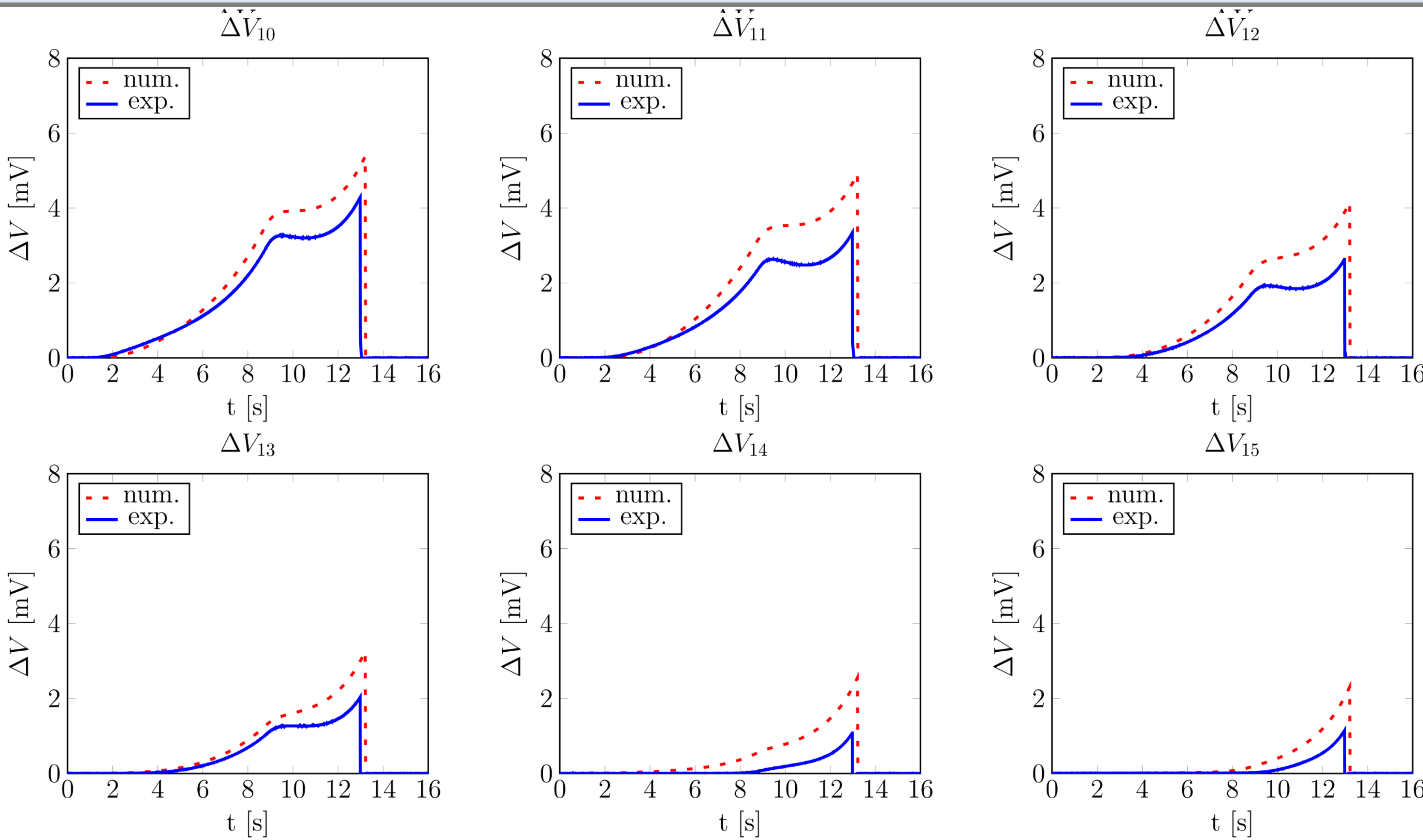
Quench at Different Heater Power and Global Stability



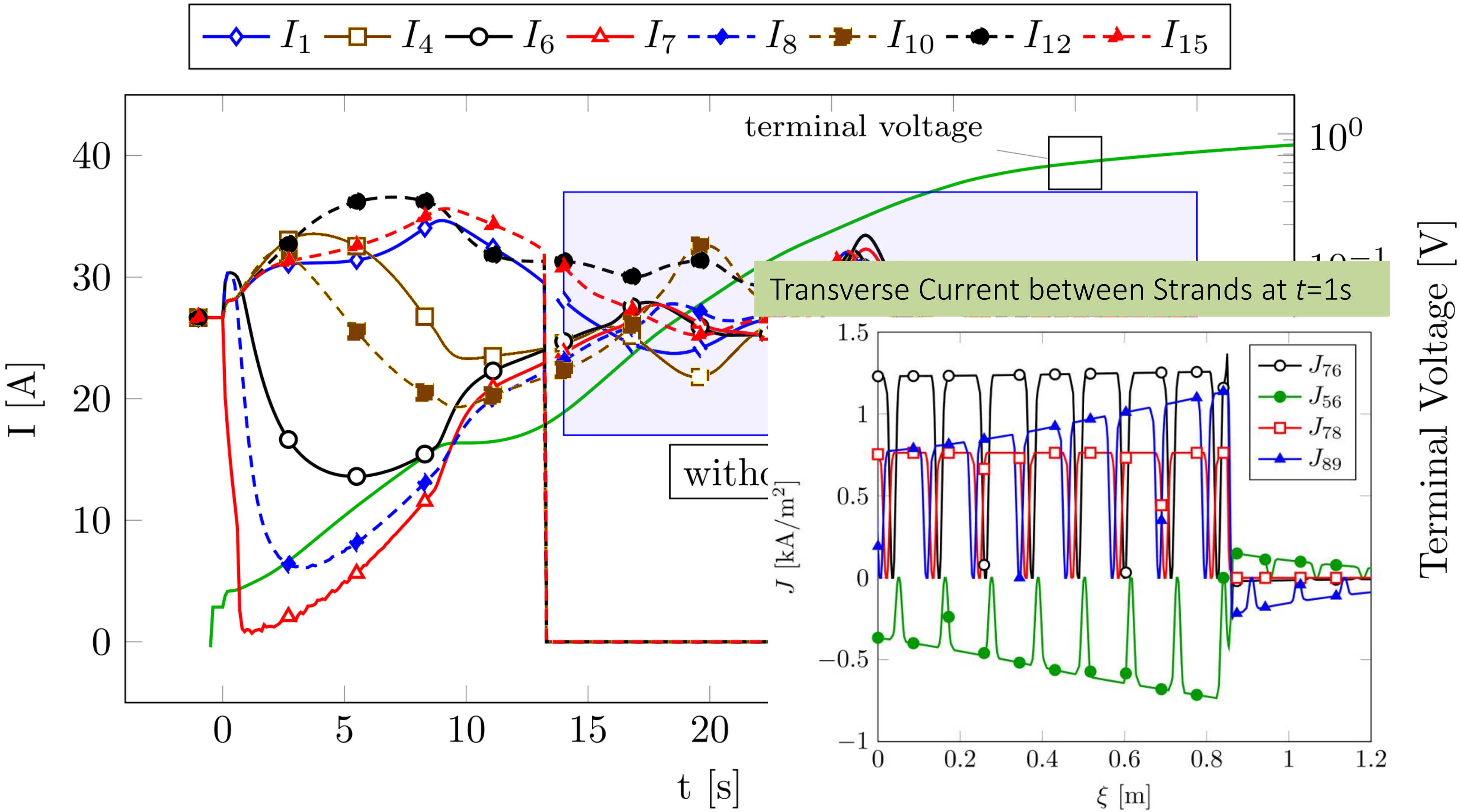
Temperature Distribution and the Effect of Transposition



Strands' Voltages



Current Sharing during Heater Pulse



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Conclusions

- Robust pancake coil construction
- 2D adiabatic quench realised
- Roebel quenches with higher MQE of increased number of tapes and 2D effect
- A strand-by-strand and turn-by-turn cable/coil model for quench