Qualified Analysis of Unmitigated Quench Integrated ANSYS modelling

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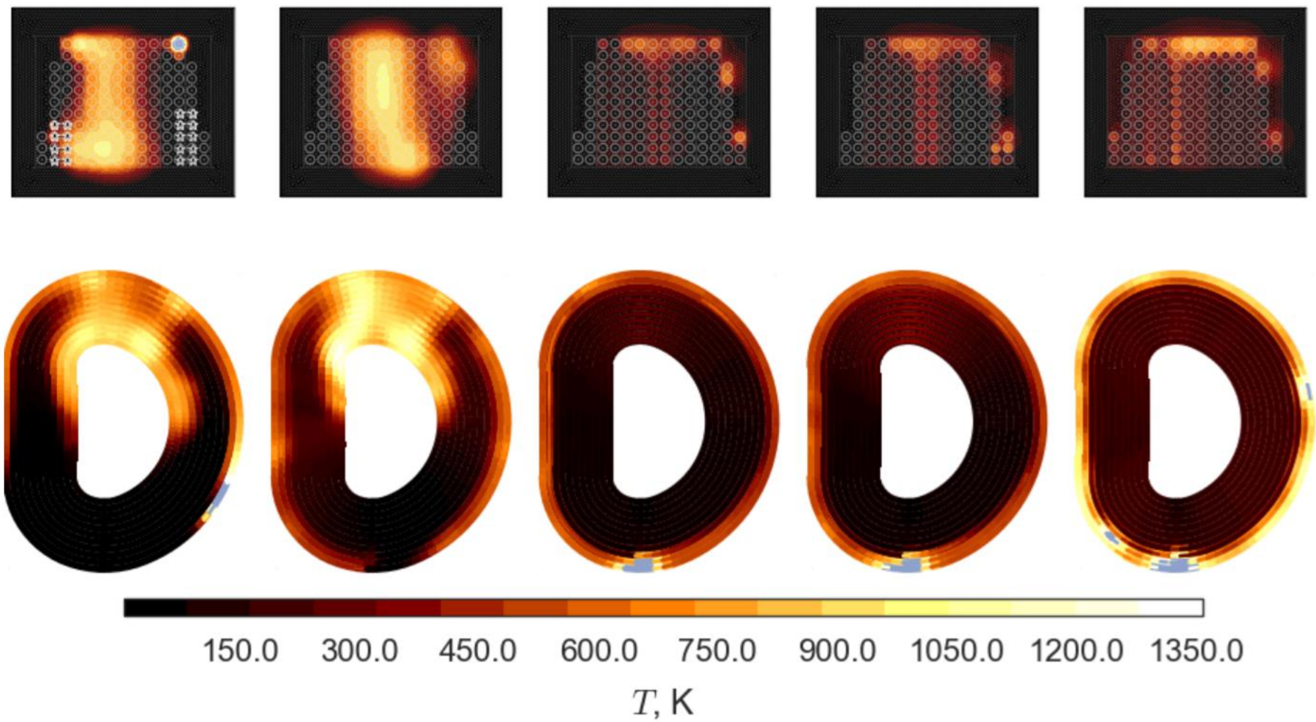

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Topic Introduction

- **Safety concerns**
  - Magnetic energy stored in coils: **~40GJ (TFC)** and **~10GJ (CS/PFC)**
  - Localisation of stored energy in fault coil.
  - Consequences of damage to magnets or adjacent components

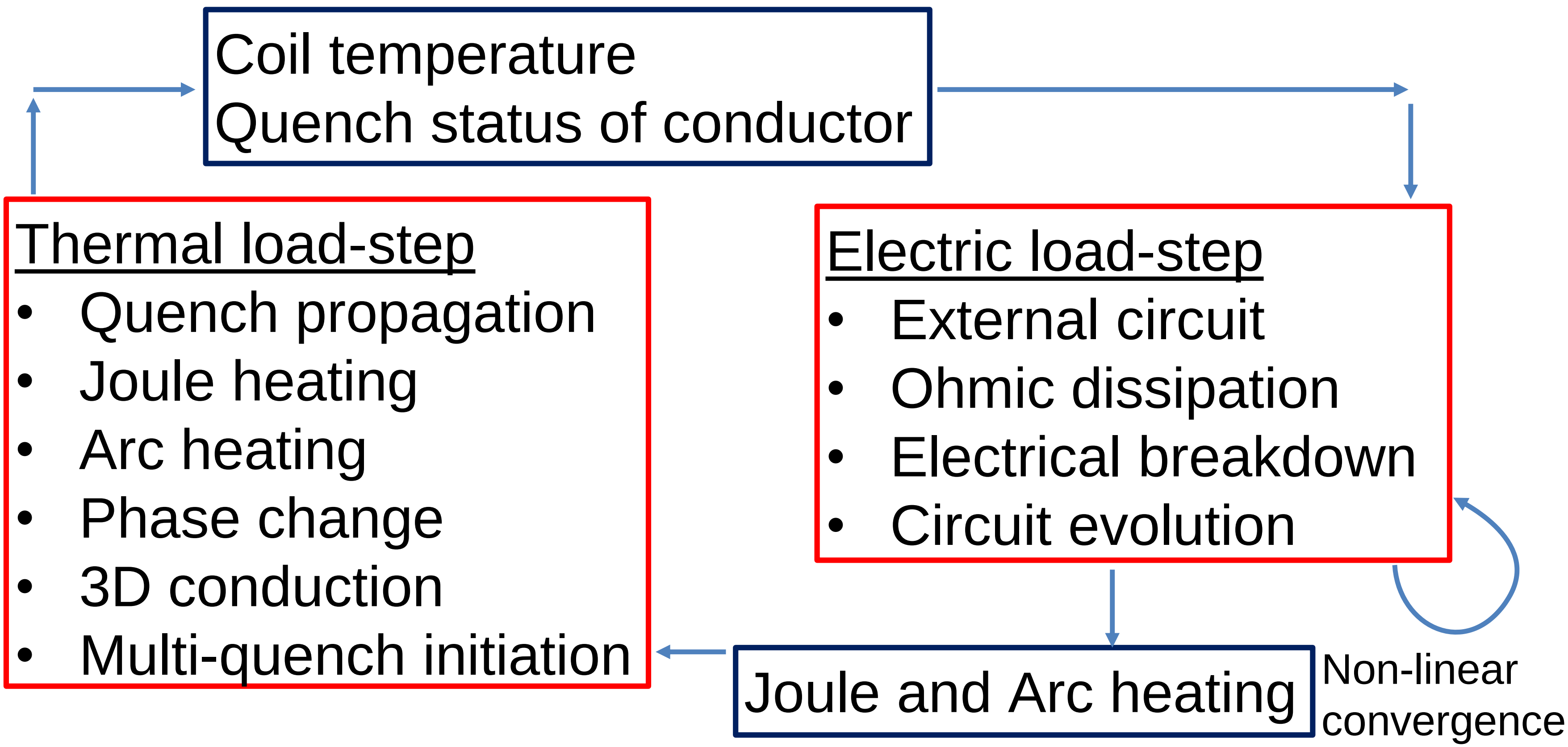
- **Integrated ANSYS model provides qualified analyses**
  - Python and APDL scripts
    - Build geometry
    - Implement quench and construct arc element network
    - Post-process results
  - Quench in superconductor
  - Time evolution of electrical circuit
  - Non-linear arc models and melt short-circuits
  - Thermal damage assessment

Model Introduction

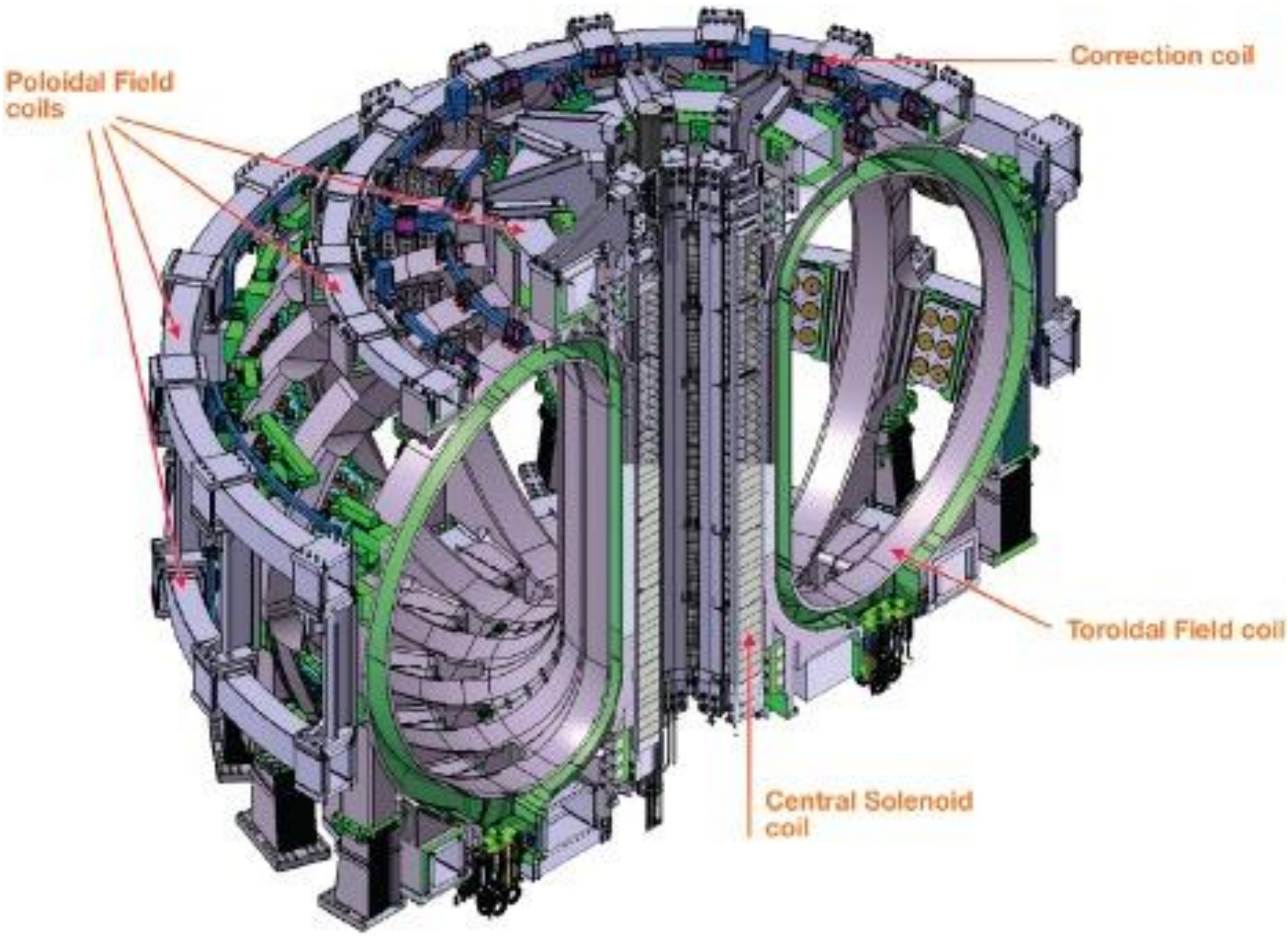
- **Methodology**
- **Geometry and finite element mesh**
- **Quench**
- **Thermal Model**
- **Electrical Model**
  - External driving circuit
  - Electrical connections
  - Electrical arcs (inline and turn-turn / pancake)
- **Material Properties**
- **Reference Simulations**
- **Conclusions**
- Meetings
  - Benchmark with MagArc code
  - Integrated model Results for qualified analysis of ITER unmitigated quench

Methodology

- Thermal and Electrical physics environments created
- Physics environments coupled at each load-step
- Model launched from workbench but written in APDL



Geometry



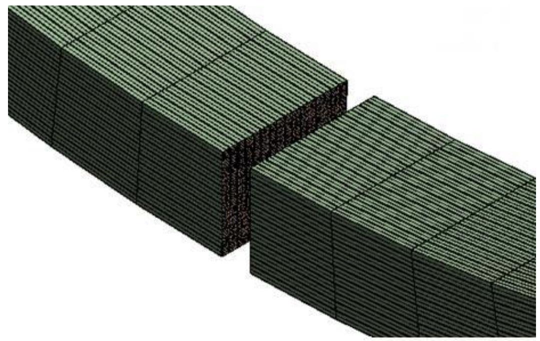
Poloidal Field coils
Correction coil
Toroidal Field coil
Central Solenoid coil

Geometry

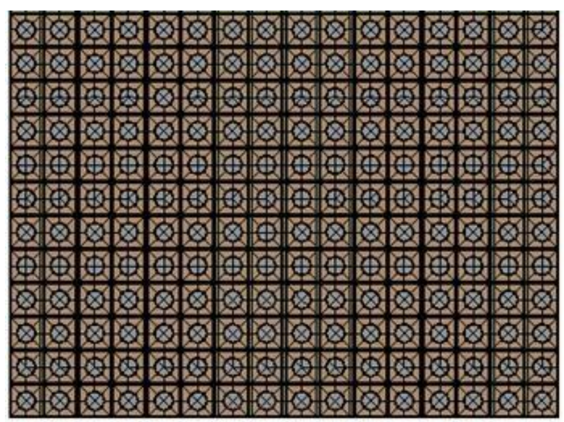
Fault coils resolved using 3D Finite Elements

- models typically comprise ~1.5M elements
- same mesh used for electrical and thermal models
- TF and PF geometries both modelled as circular

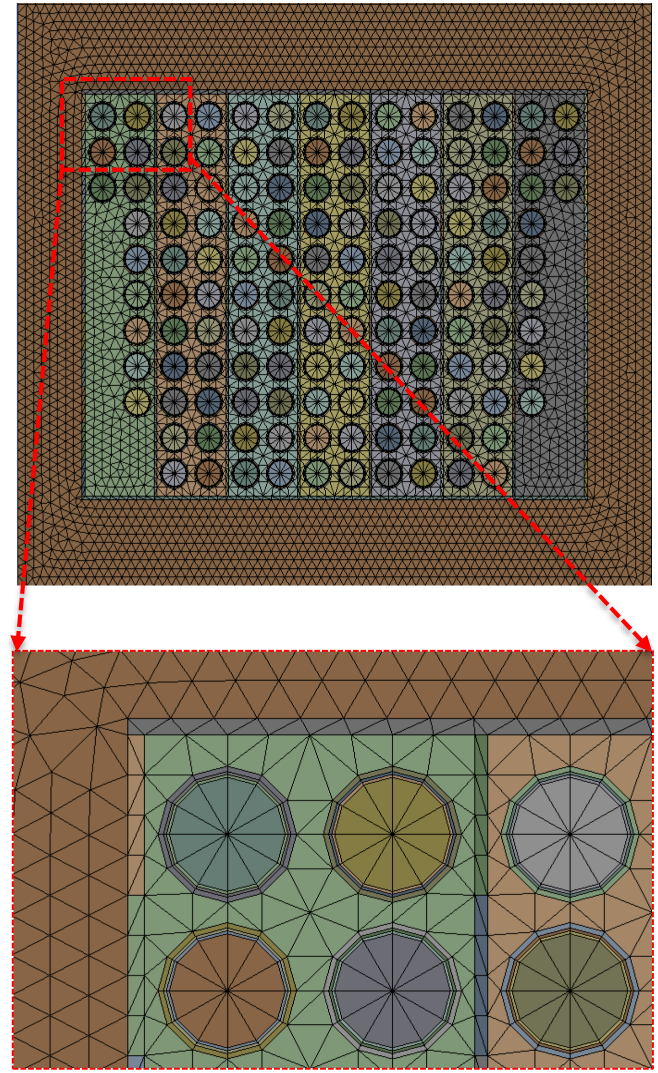
D-shape TF coil



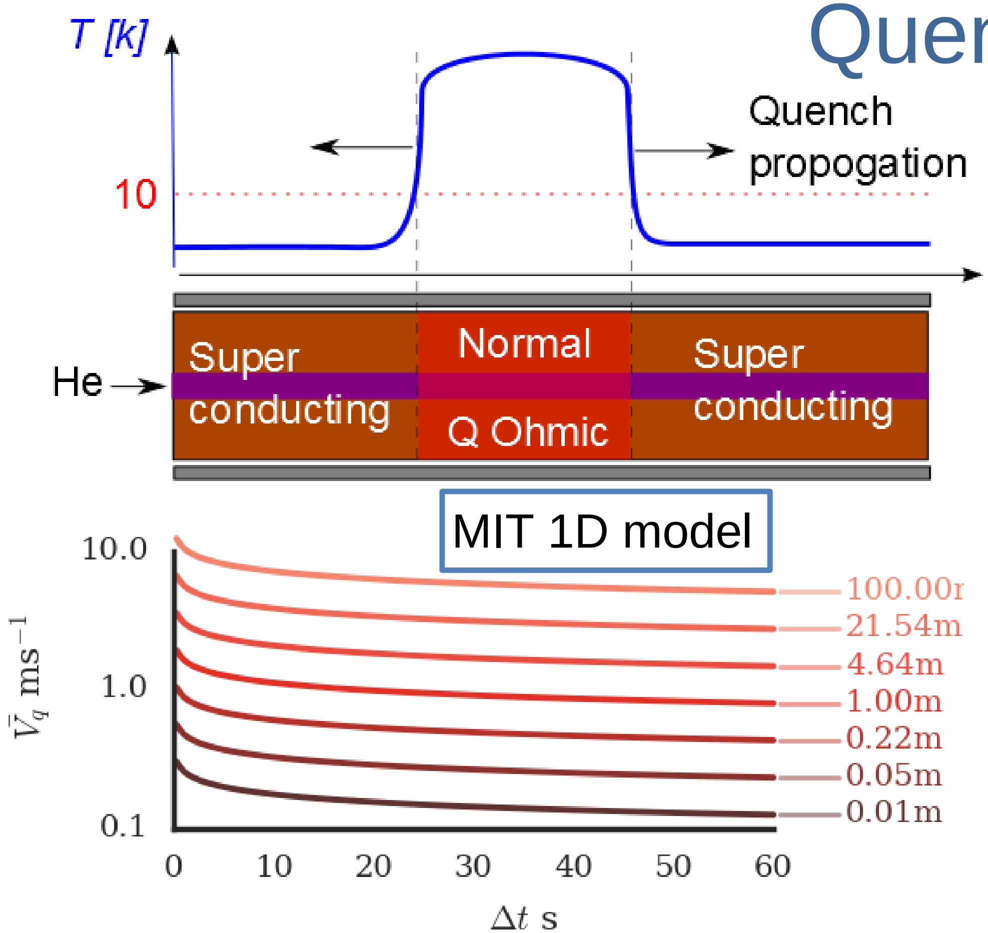
PF coil cross-section

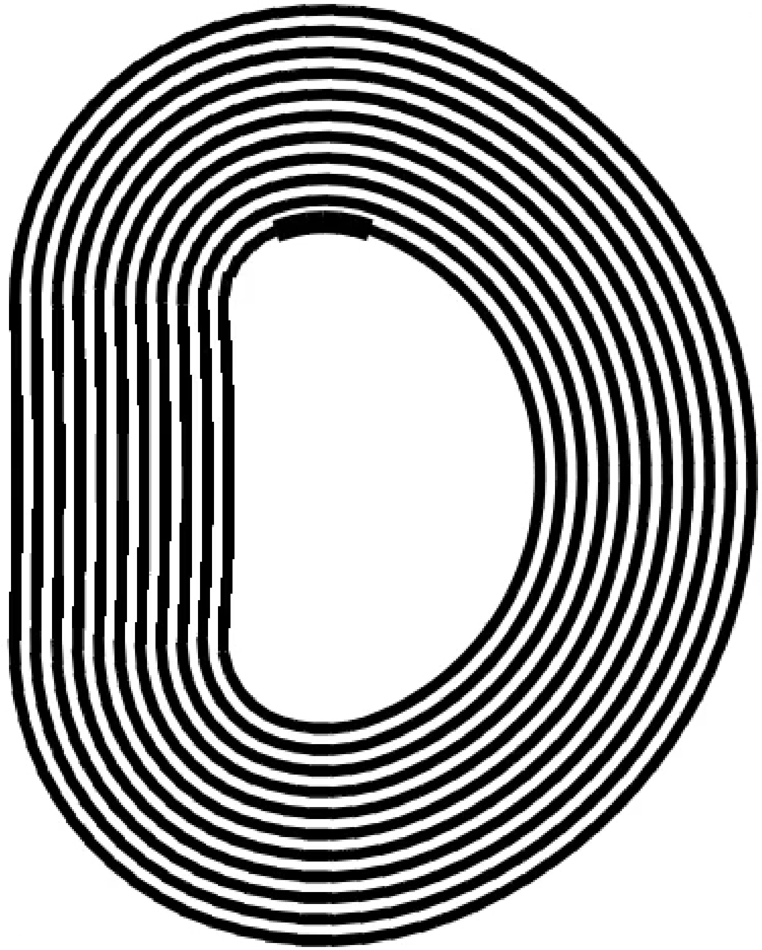


TF coil cross-section



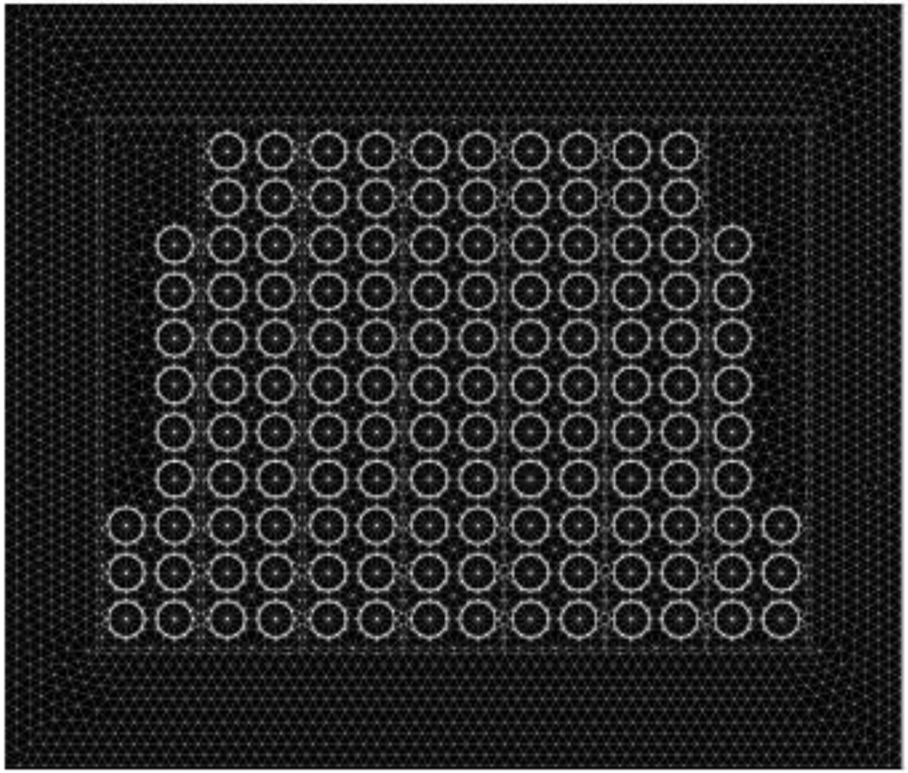
Quench

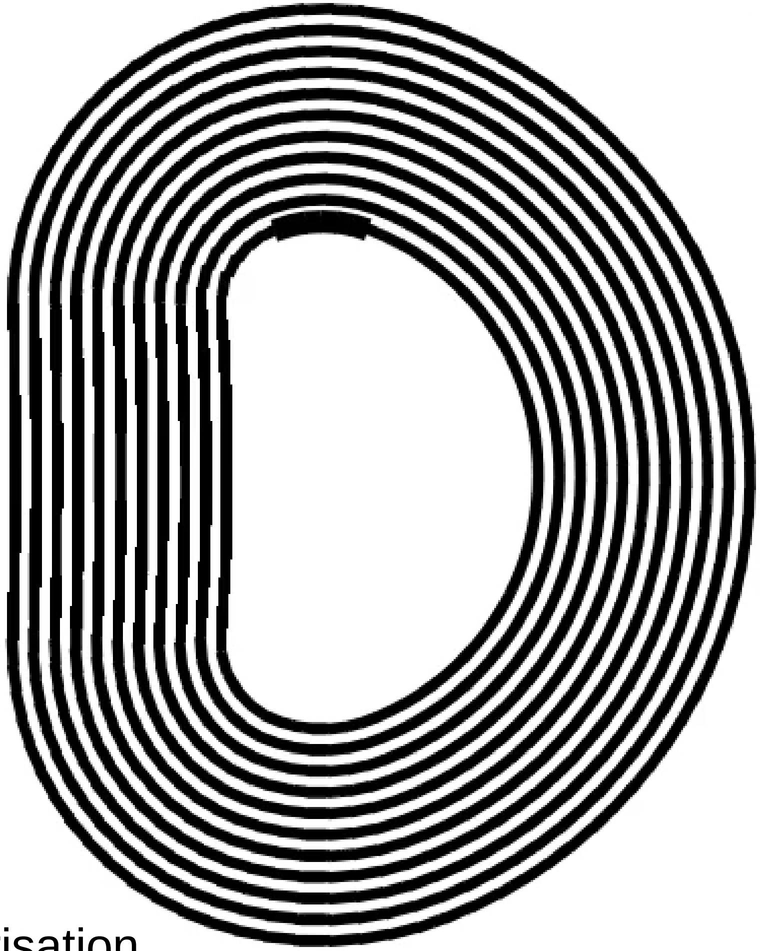




- 1D model sets quench propagation speed
- speed a function of initiating length and duration
- additional quench sites triggered by 3 mechanisms:
  3D heat conduction, electrical arcing and pancake heating

Thermal model

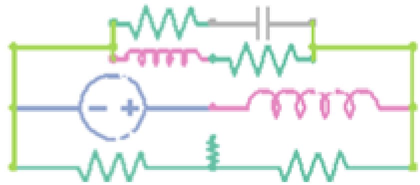




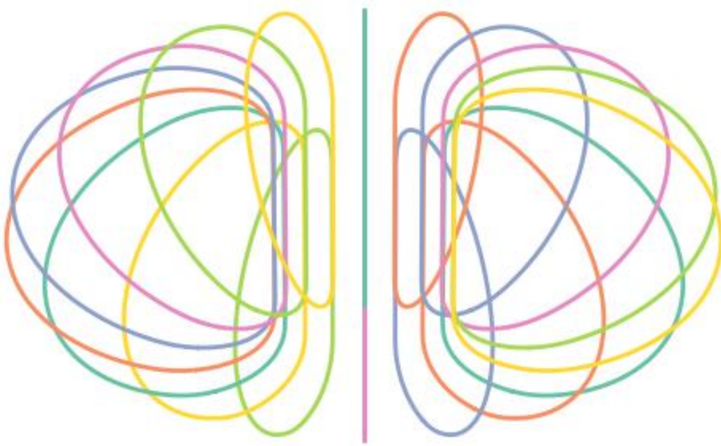
- Power deposited from electrical model
- Conductor Ohmic heating and electrical arcs
- Enthalpy steps capture latent heats of melt /vaporisation
- 3D thermal conduction model diffuses heat through coil (triggering additional quench)
- Radiation boundary on coil case exterior transports heat away from magnet

Electrical - external driving circuit

Single coil's circuit
(circu124 elements)



$$[V] = [\mathrm{M}]\left[\frac{dI}{dt}\right]$$

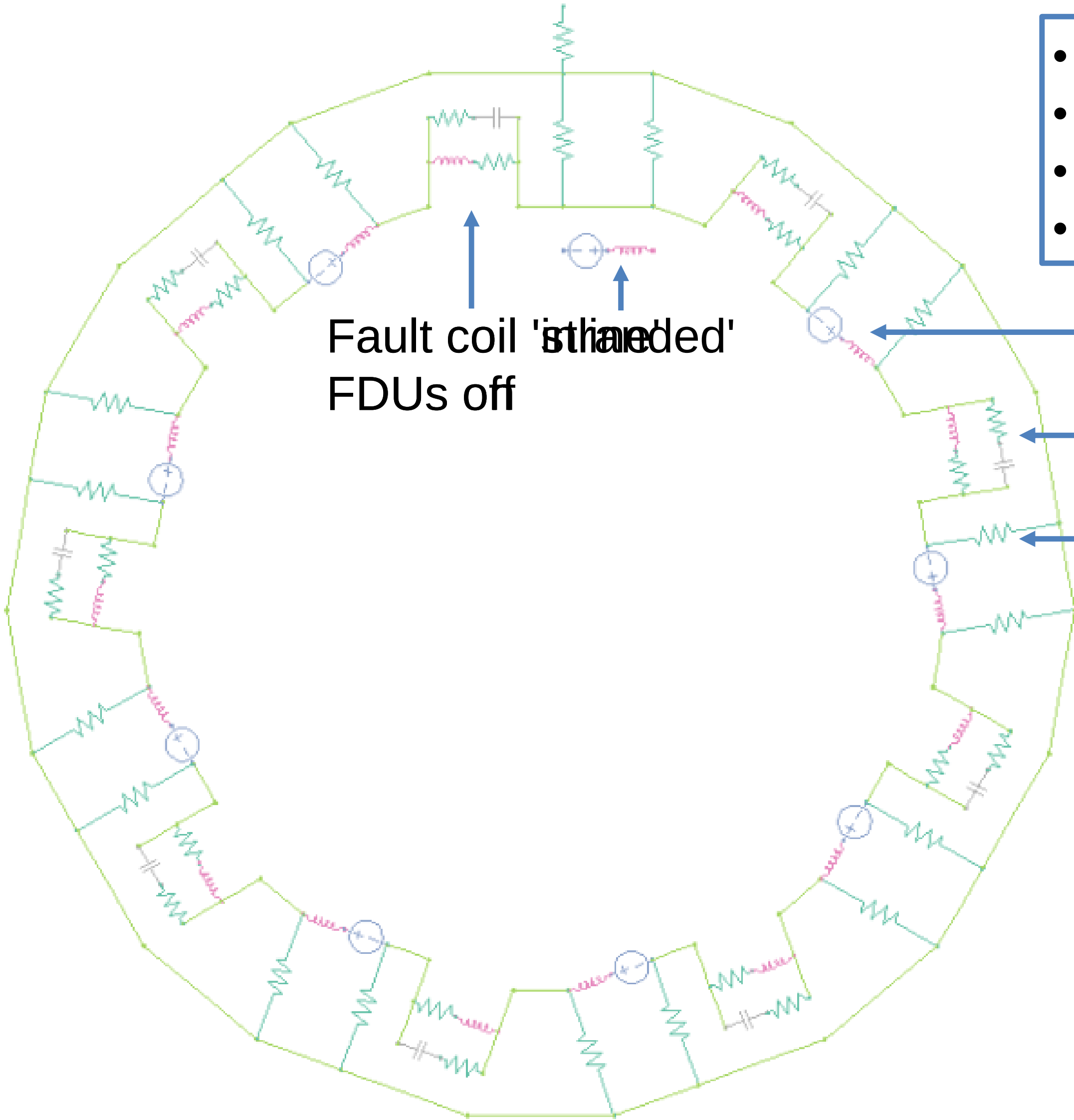


Lumped inductance matrix (18x18)

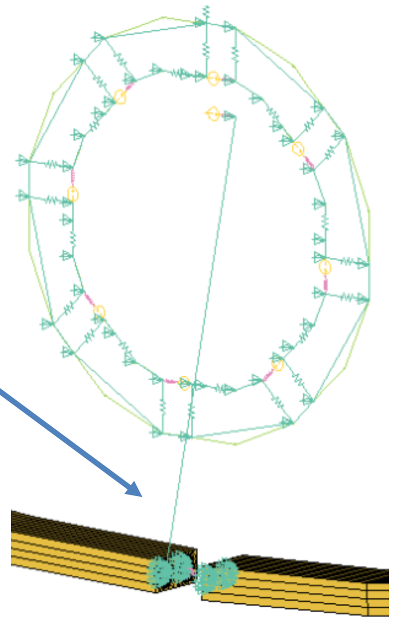
```
[[ 0.345  0.132  0.066  0.038  0.023 ...,  0.016  0.023  0.038  0.066  0.132]
 [ 0.132  0.345  0.132  0.066  0.038 ...,  0.011  0.016  0.023  0.038  0.066]
 [ 0.066  0.132  0.345  0.132  0.066 ...,  0.009  0.011  0.016  0.023  0.038]
 [ 0.038  0.066  0.132  0.345  0.132 ...,  0.007  0.009  0.011  0.016  0.023]
 [ 0.023  0.038  0.066  0.132  0.345 ...,  0.007  0.007  0.009  0.011  0.016]
 ...,
 [ 0.016  0.011  0.009  0.007  0.007 ...,  0.345  0.132  0.066  0.038  0.023]
 [ 0.023  0.016  0.011  0.009  0.007 ...,  0.132  0.345  0.132  0.066  0.038]
 [ 0.038  0.023  0.016  0.011  0.009 ...,  0.066  0.132  0.345  0.132  0.066]
 [ 0.066  0.038  0.023  0.016  0.011 ...,  0.038  0.066  0.132  0.345  0.132]
 [ 0.132  0.066  0.038  0.023  0.016 ...,  0.023  0.038  0.066  0.132  0.345]]
```

Electrical - external driving circuit

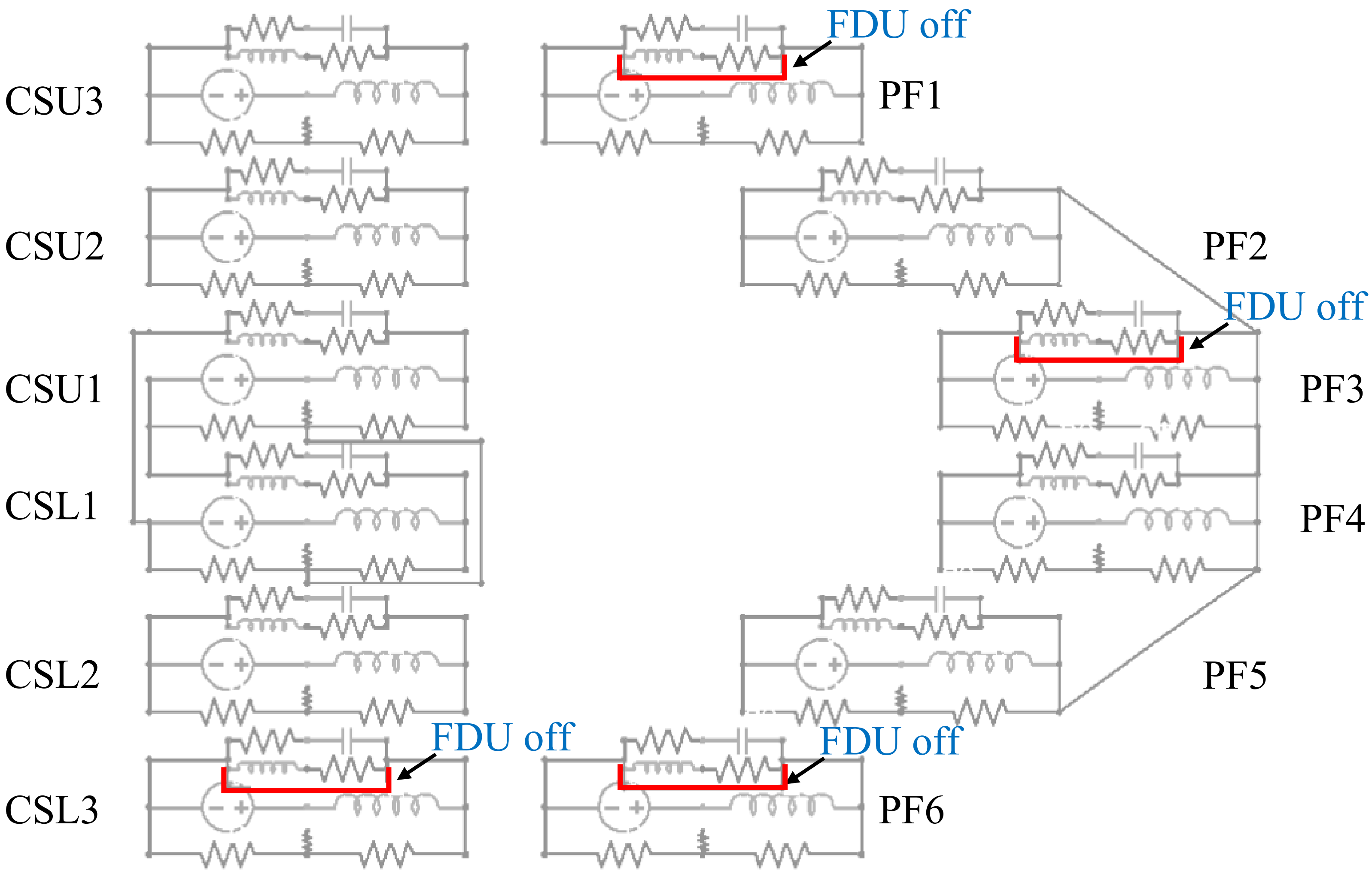
- 18 TF coils arranged in pairs
- Coils connected in series
- Coils pairs separated by 9 FDUs
- Multiple paths to ground



Driving circuit connected to 'brick' FE model



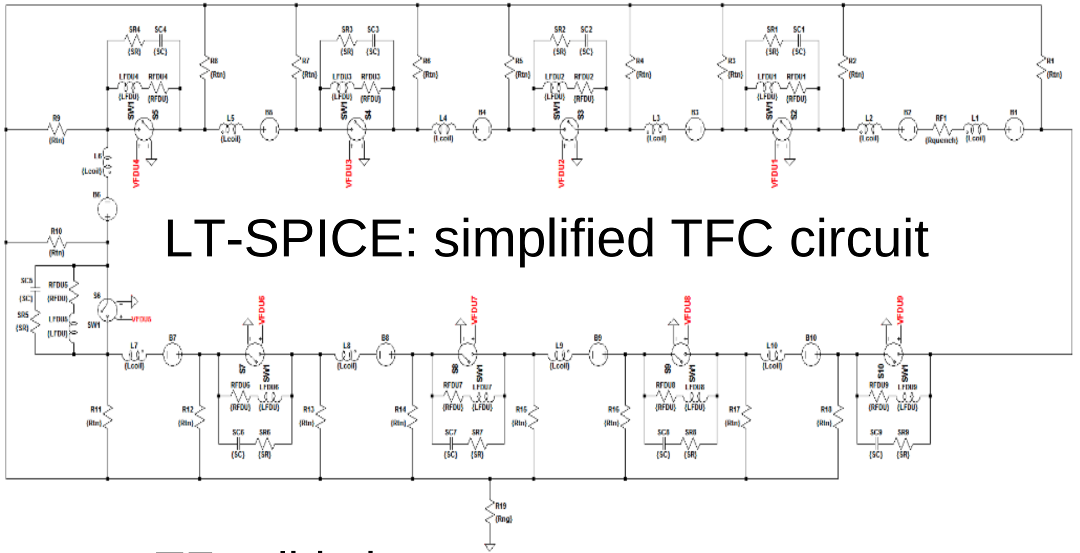
Electrical - external driving circuit



Electrical - external driving circuit

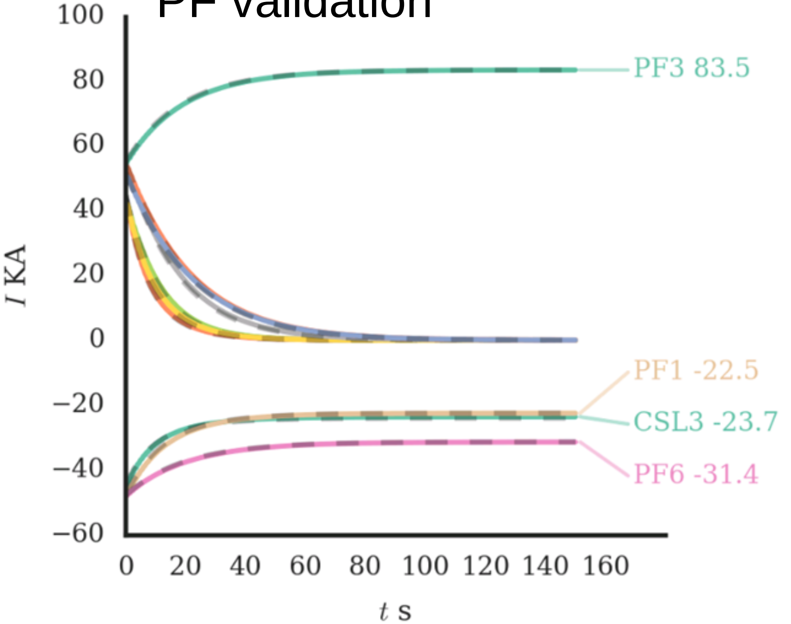
ANSYS driving electrical circuit validated with LT-SPICE

- Zero resistance fault coil
- Fault coil 'stranded'
- Energy transferred to fault coil
- Good agreement between models

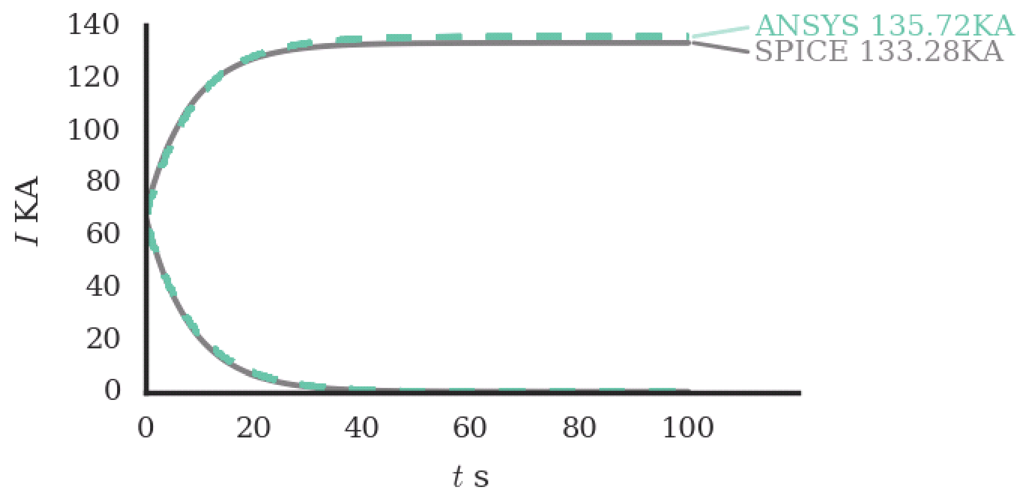


LT-SPICE: simplified TFC circuit

PF validation

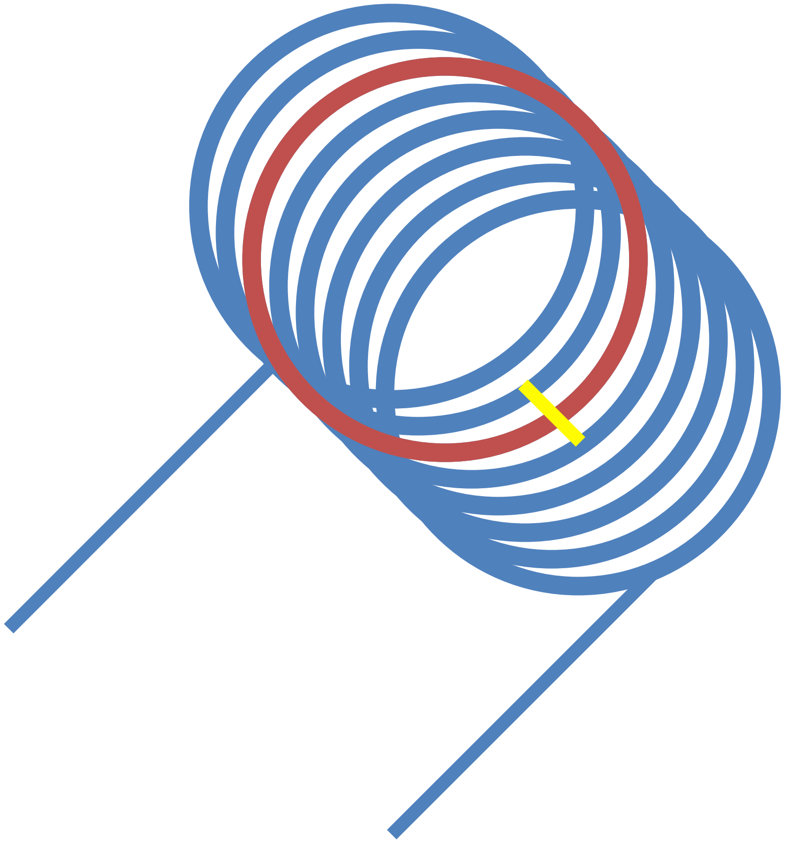


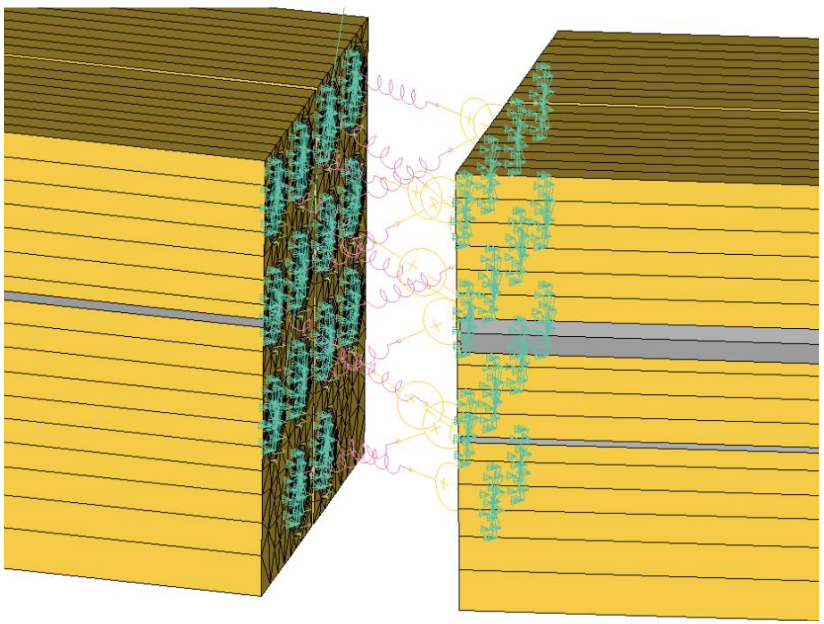
TF validation



Electrical - distributed inductance

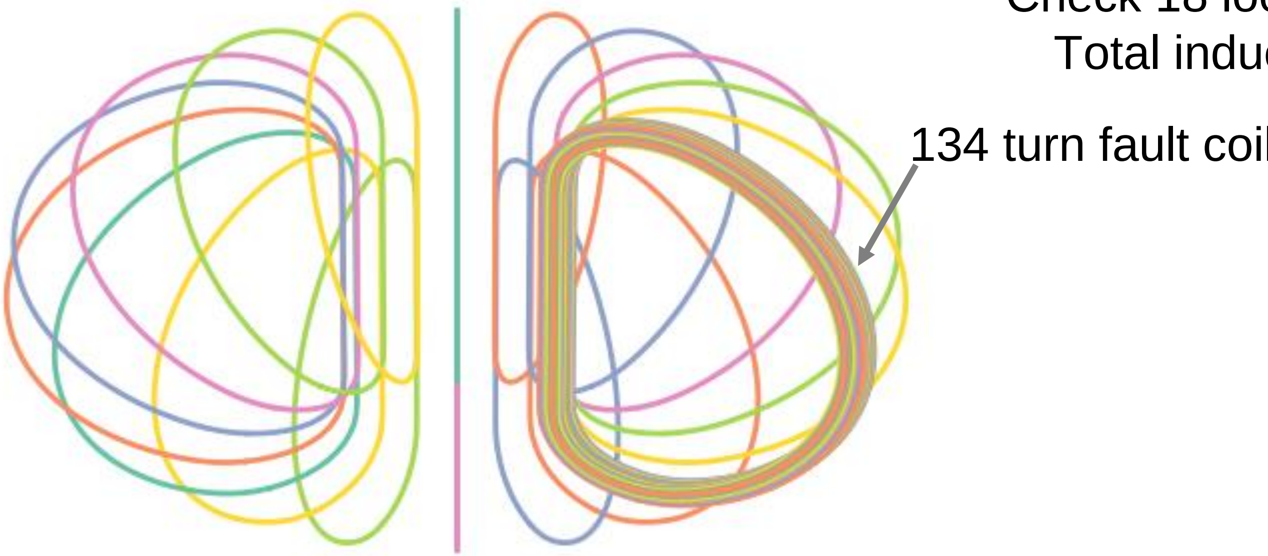
- Electrical shorts / arcs modify current path
- New current path alters the fault coil's inductance





Fault coil inductance distributed 'per-turn'

Check 18 loop calculation against DDD
Total inductance 17.2H (DDD 17.7H)



	calculated	DDD
Coil 1-1	0.345	0.349
Coil 1-2	0.132	0.133
Coil 1-3	0.066	0.066
Coil 1-4	0.038	0.038
Coil 1-5	0.023	0.023
Coil 1-6	0.016	0.016
Coil 1-7	0.011	0.011
Coil 1-8	0.009	0.009
Coil 1-9	0.007	0.007
Coil 1-10	0.007	0.007

Calculate inductance using Neumann integral

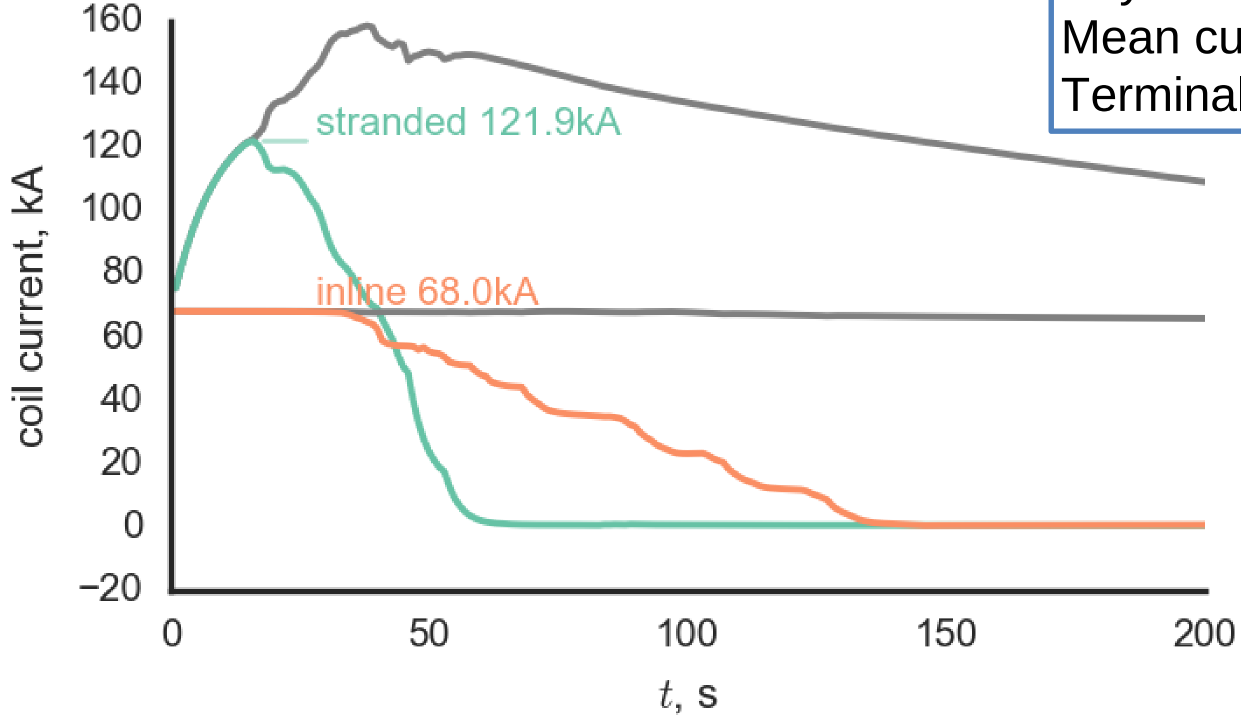
$$M_{ij} = \frac{\mu_0}{4\pi} \oint_{C_i} \oint_{C_j} \frac{\mathbf{ds}_i \cdot \mathbf{ds}_j}{|\mathbf{R}_{ij}|}$$

Distributed inductance matrix (151x151)

```
[[  3.453e-01   1.320e-01   6.598e-02   3.756e-02   2.327e-02 ...,   2.250e-03   2.153e-03   2.066e-03   2.148e-03   2.223e-03]
 [  1.320e-01   3.453e-01   1.320e-01   6.598e-02   3.756e-02 ...,   1.083e-03   1.056e-03   1.086e-03   1.115e-03   1.143e-03]
 [  6.598e-02   1.320e-01   3.453e-01   1.320e-01   6.598e-02 ...,   5.159e-04   5.037e-04   5.147e-04   5.273e-04   5.397e-04]
 [  3.756e-02   6.598e-02   1.320e-01   3.453e-01   1.320e-01 ...,   2.839e-04   2.760e-04   2.812e-04   2.893e-04   2.973e-04]
 [  2.327e-02   3.756e-02   6.598e-02   1.320e-01   3.453e-01 ...,   1.701e-04   1.644e-04   1.671e-04   1.729e-04   1.788e-04]
 ...,
 [  2.250e-03   1.083e-03   5.159e-04   2.839e-04   1.701e-04 ...,   7.405e-05   3.510e-05   2.954e-05   3.568e-05   3.042e-05]
 [  2.153e-03   1.056e-03   5.037e-04   2.760e-04   1.644e-04 ...,   3.510e-05   7.363e-05   3.508e-05   2.994e-05   2.519e-05]
 [  2.066e-03   1.086e-03   5.147e-04   2.812e-04   1.671e-04 ...,   2.954e-05   3.508e-05   7.363e-05   3.551e-05   2.630e-05]
 [  2.148e-03   1.115e-03   5.273e-04   2.893e-04   1.729e-04 ...,   3.568e-05   2.994e-05   3.551e-05   7.405e-05   3.612e-05]
 [  2.223e-03   1.143e-03   5.397e-04   2.973e-04   1.788e-04 ...,   3.042e-05   2.519e-05   2.630e-05   3.612e-05   7.447e-05]]
```

Electrical - TF driving circuit

Effect of TF driving circuit type (stranded vs inline) on coil current

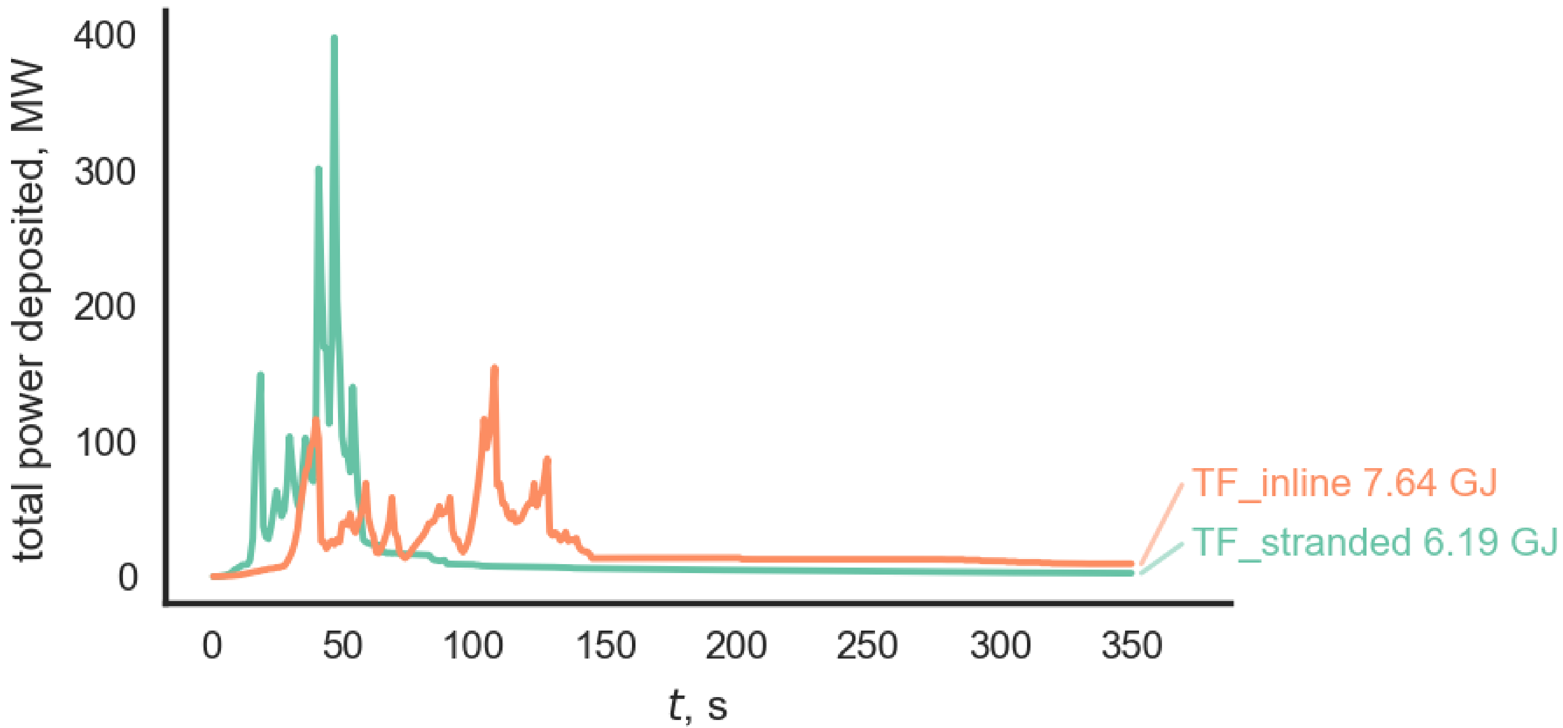


Key:
Mean current: colour
Terminal current: grey

- Discharge of un-faulted coils couples energy into stranded circuit
- Further increase in turn currents due to distributed inductance

Electrical - TF driving circuit

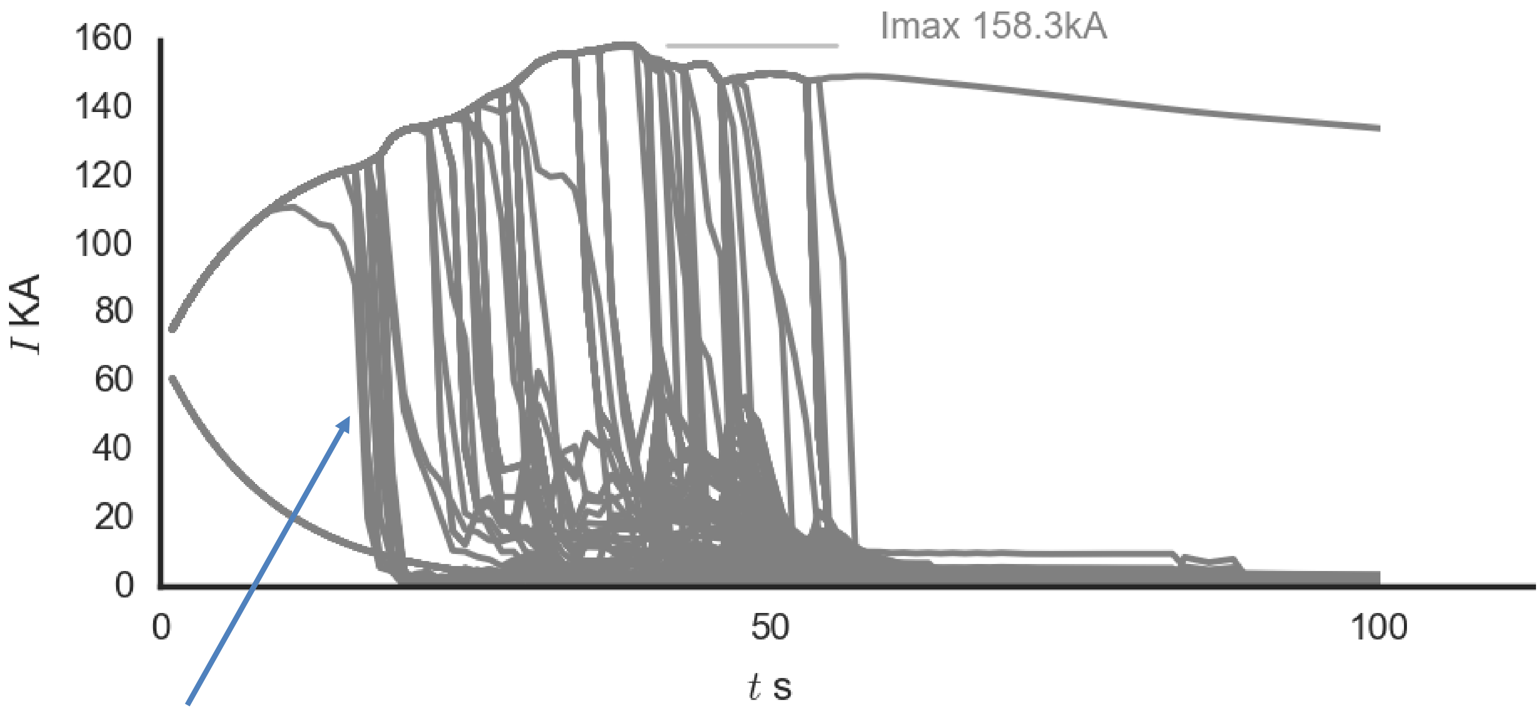
Influence of driving circuit type (inline vs stranded) on total energy deposited



- Much greater stored energy in inline circuit (41GJ vs 8GJ)
- However, similar total power deposition (short-circuits exclude inline coil)
- ~ 4 times higher peak power for stranded coil (higher terminal currents)

Electrical - distributed inductance

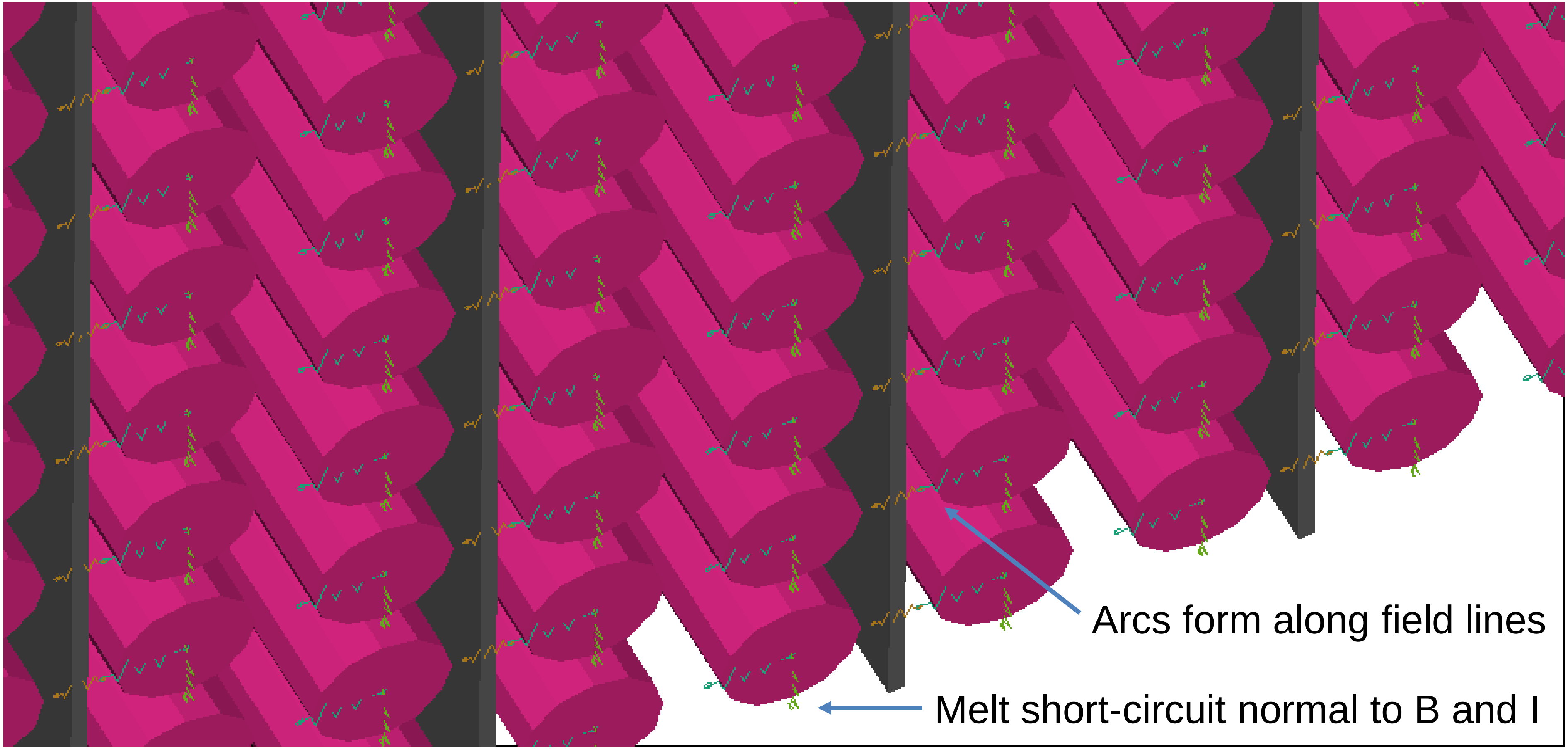
Current development for stranded TF simulation showing currents in all turns



Distributed inductance ensures conservation of energy
Discharge of single turns (arcs, short-circuits) couple energy back into circuit
High peak currents attained

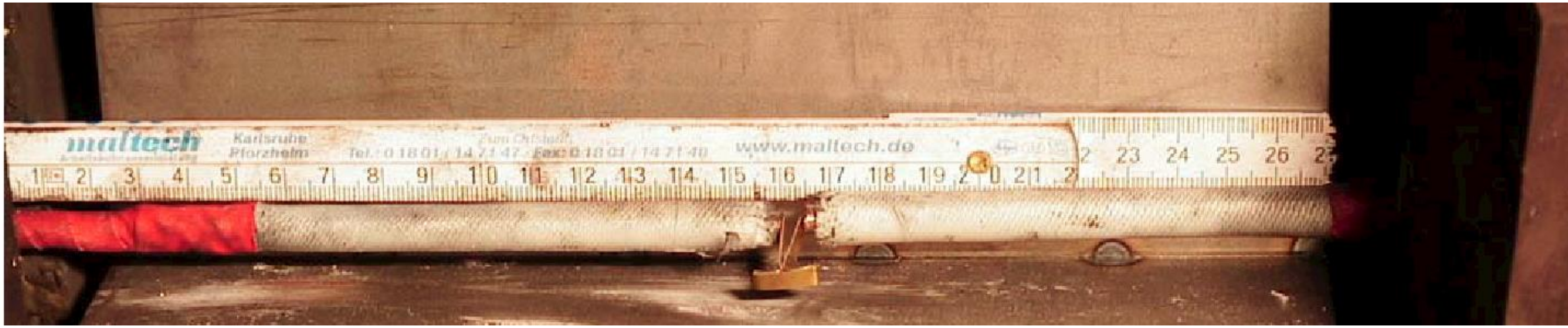
Electrical - arcs and short-circuits

Time evolving electrical network implemented with a network of resistors linking elements
Resistance adjusted during simulation to capture effects of arcing and electrical shorts



Panel of potential electrical connections repeated around coil (3300 connections for TF)

Electrical - inline arcs

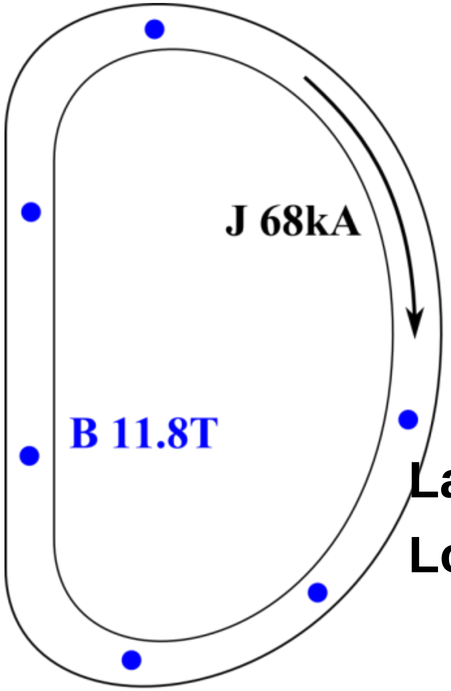


Experiments performed at KIT

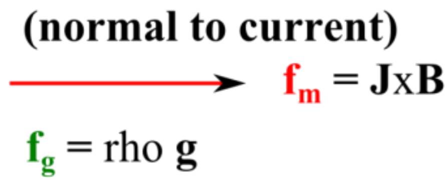
a) RB0303, 45kW for 30s

b) RB0508, 102kW for 20s

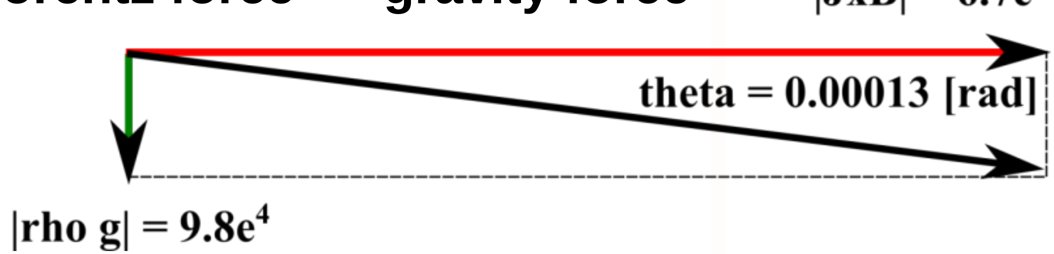
Electrical - inline arcs



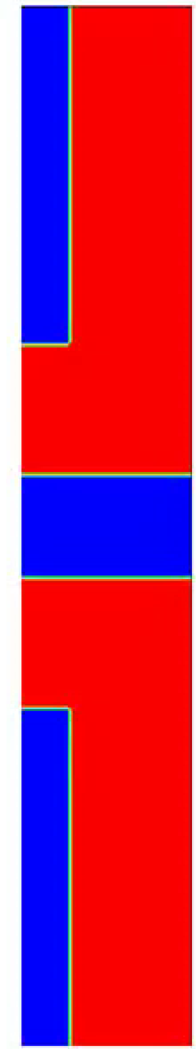
Gap connection time ~ 2ms
Gap vaporisation time ~ 38ms



Large magnetic field → Lorentz force >> gravity force



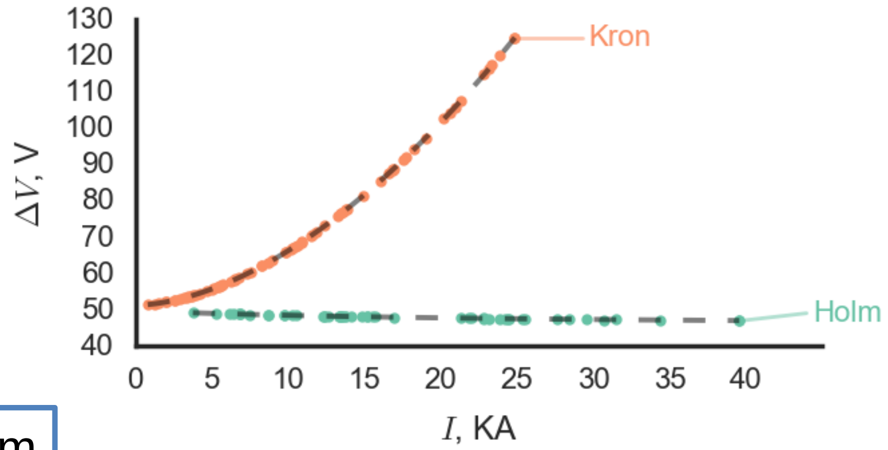
- large bursting forces stabilise molten conductor sections
- In-line gaps/arcs self-extinguish in high magnetic fields
- molten sections modelled as continuous conductors



Red: Copper
Blue: Helium

Electrical - turn-turn and pancake arcs

- Non-linear voltage-current characteristic
- VI characteristic determines current sharing between arc and structure
- Resistive circuit elements linking turns
- **Conditions to initiate arcs**
  - *T* > 600°C
  - Δ*V* > 40V
- **Conditions to initiate melt**
  - *T Jacket* > 1400°C
  - melt resistor 'latching'

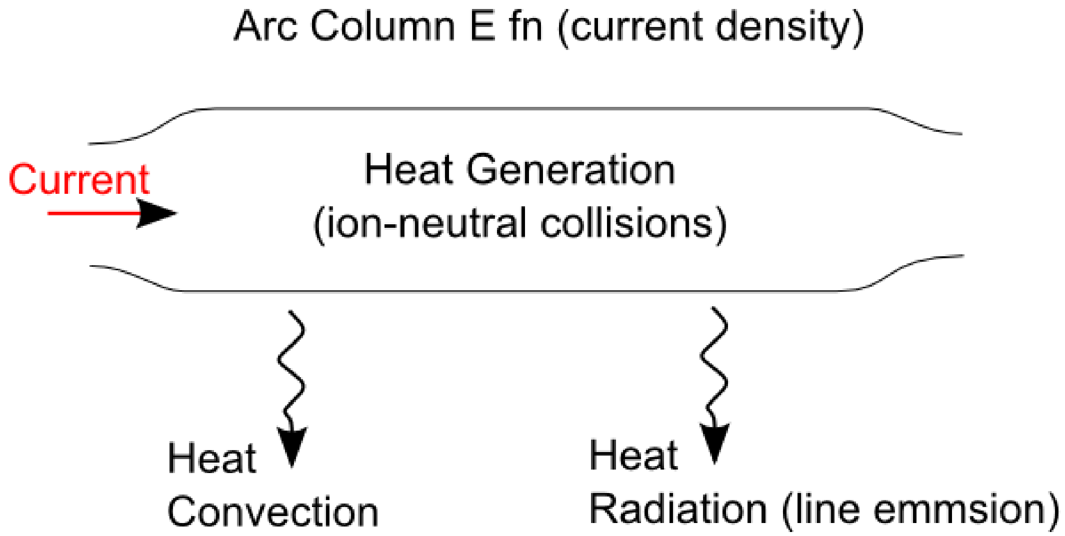


Arc algorithm

1. Arcs placed at the **edges of all viable zones** at the start of each time-step
2. Electrical model **iterates to find converged solution**
3. Arcs with a driving **voltage that falls below 40V removed**
4. Arc **volumetric heating** split between to elements contacting each arc node

Electrical - turn-turn and pancake arcs

- **Kronhart arc model** - data fit from experiment (constricted arcs)
- **Holmes arc model** – theoretical model permitting free arcs

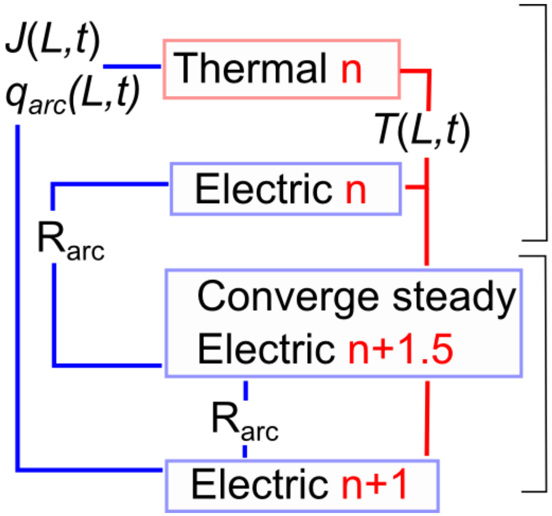


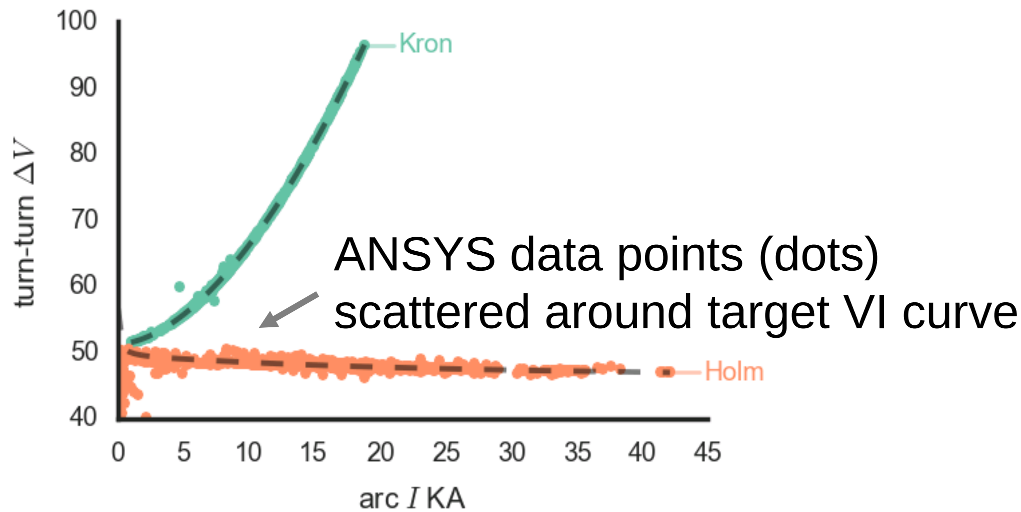
Column potential an implicit function of temperature
Numerical solution necessary
Solution Implemented using relaxed Newton-Rapson method
Holmes VI characteristic tabulated and passed to ANSYS

ANSYS model can accept any VI curve to represent different arc characteristics

Electrical - turn-turn and pancake arcs

Early versions of code struggled with **arc convergence**:





Convergence issue fixed with improved iteration scheme:

$$f(I_{arc}) = \Delta V_{arc} - \Delta V_{coil}$$

Arc dV balances Coil dV

$$I_{arc}: f(I_{arc}) = 0$$

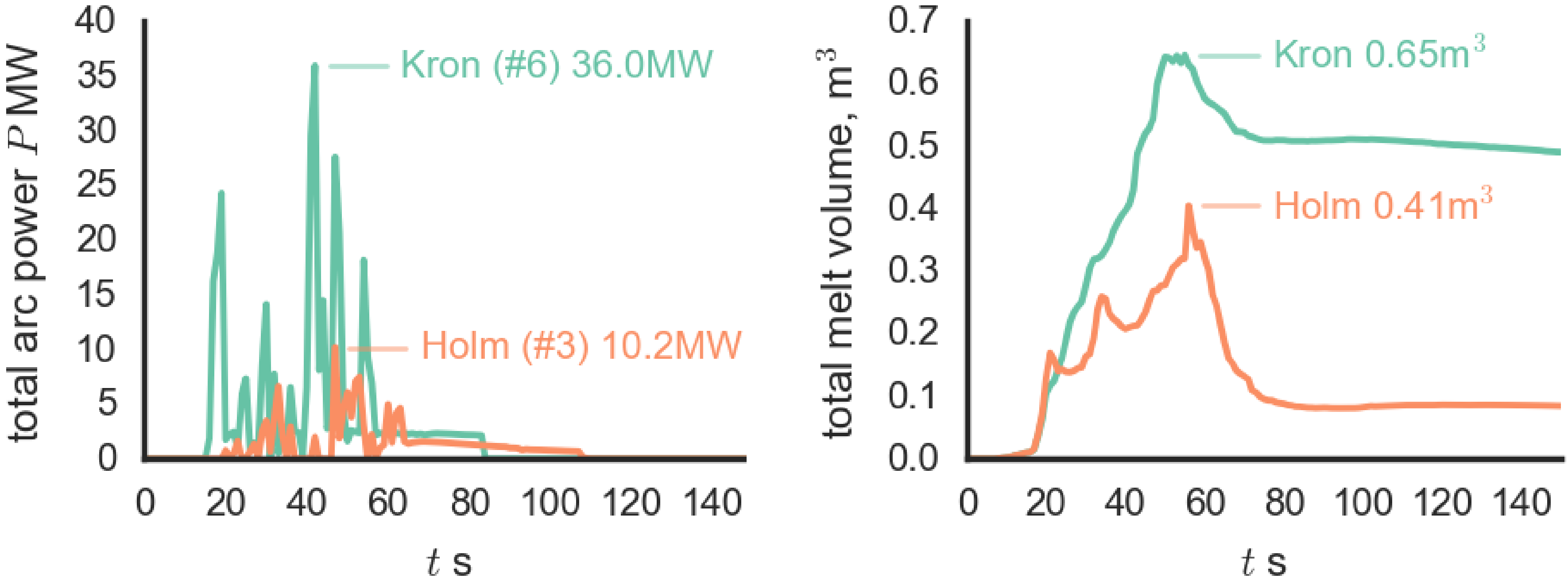
Solve for arc current (VI)

$$R_{arc} = \frac{\Delta V_{arc}}{I_{arc}}$$

Update arc resistance, iterate…

Electrical - turn-turn and pancake arcs

Influence of arc model on coil damage (ITER TF reference)

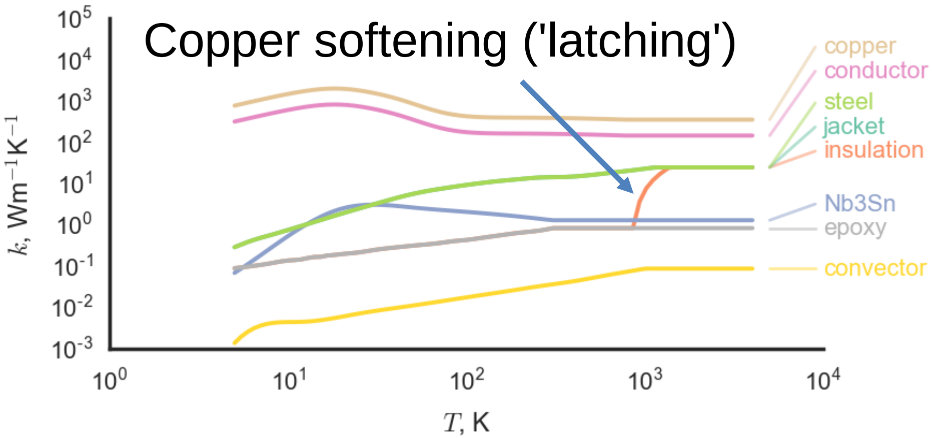


Kronhardt model produces:

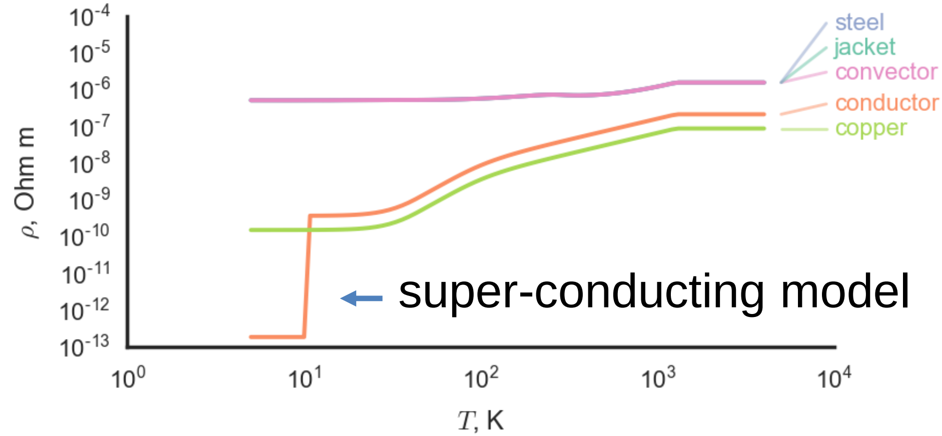
- the highest total arc power (36MW)
- largest total melt volume (0.65m3)

Material Properties

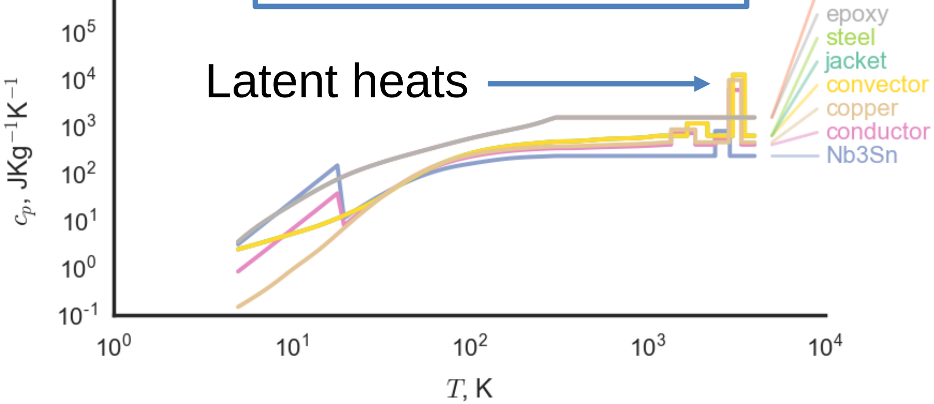
Thermal conductivity



Electrical resistivity



Specific heat capacity



Temperature dependant materials

- composite materials developed for conductor (copper + Nb3Sn) and convector (convective resistance + steel)
- anisotropic thermal conduction in conductor (perp x10 parallel)

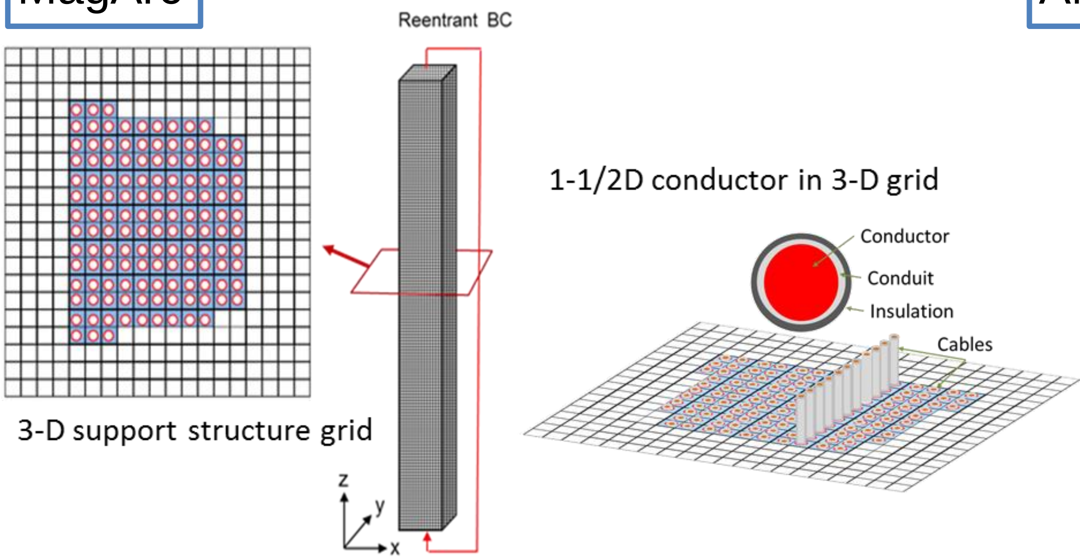
Benchmark with MagArc Code

#	Coil	Initiating length	Quench model	Initiating location	Arc model	Driving circuit	Melt short-circuits
1	TF	34cm	$5ms^{-1}$	Outer turn	Kronhardt	Inline	No
2	TF	34cm	$5ms^{-1}$	Outer turn	Kronhardt	Inline	Yes

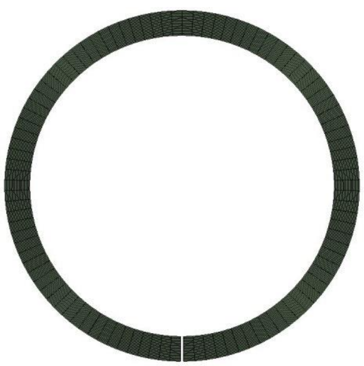
Benchmark with MagArc Code

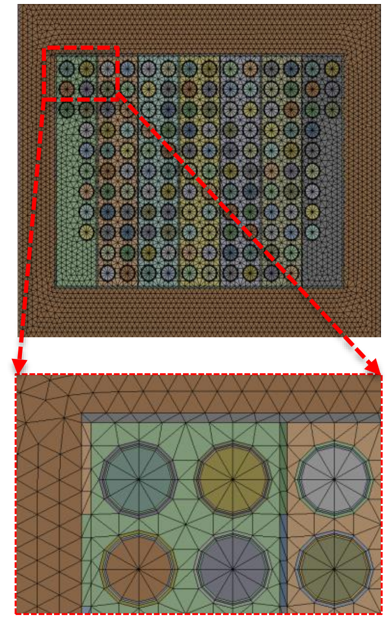
- Comparison of preliminary calculations (INL collaboration)
- Differences with MAGARC
  - Model geometry and numerical solution **(minor impact)**
  - quench propagation modelling **(minor impact)**
  - Heat conduction and thermal material properties **(minor impact)**
  - Arc modelling and assumptions **(significant impact)**

MagArc



ANSYS model





Benchmark with MagArc Code

Integrated ANSYS model benchmarked with MagArc code developed by Brad Merrill at Idaho National Labs

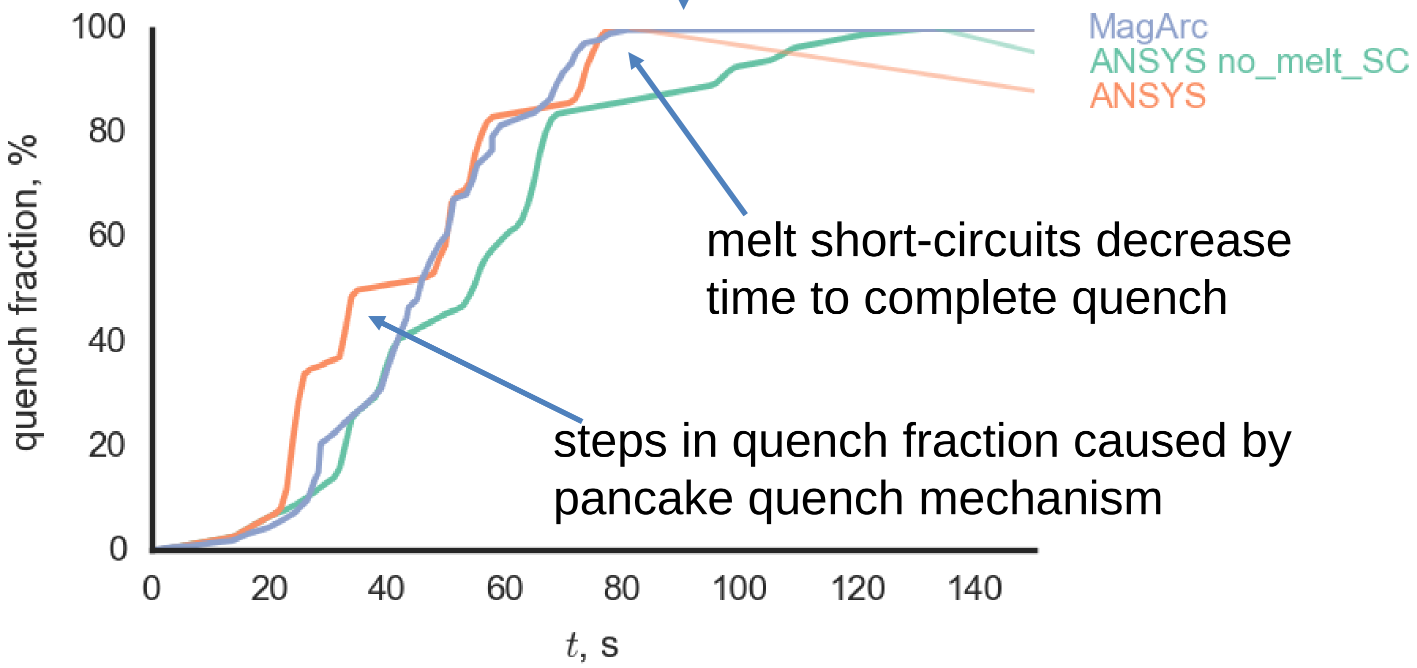
	ANSYS	**MagArc**
Quench speed	Variable: based on MIT model	Fixed: 5 m/s
Molten conductor	Treat as conducting: Inline breaks 'self repair'	Treat as break: Inline arc carries current across break in conductor
Molten jacket	Treat as mobile: molten material short-circuits turns in radial direction	Treat as static:

Adjustments in input to ANSYS code to facilitate comparison:

- quench speed set to a constant (5m/s)
- No special treatment for molten conductor (behaviour already similar)
- impact of melt short-circuits investigated with two simulations (disabled/enabled)

Benchmark with MagArc Code

time to complete quench similar for both codes

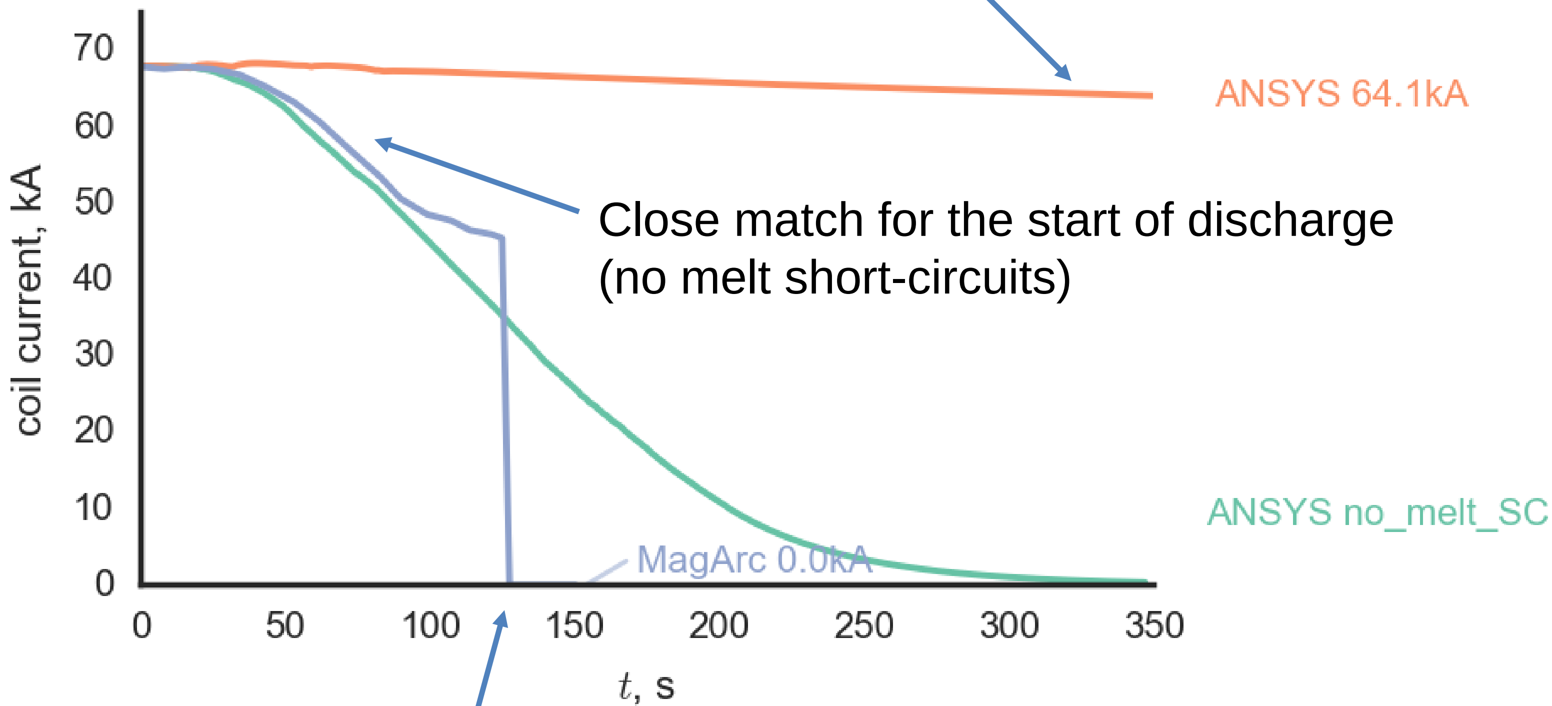


melt short-circuits decrease time to complete quench

steps in quench fraction caused by pancake quench mechanism

Benchmark with MagArc Code

Fault coil discharge lower with melt short-circuits enabled

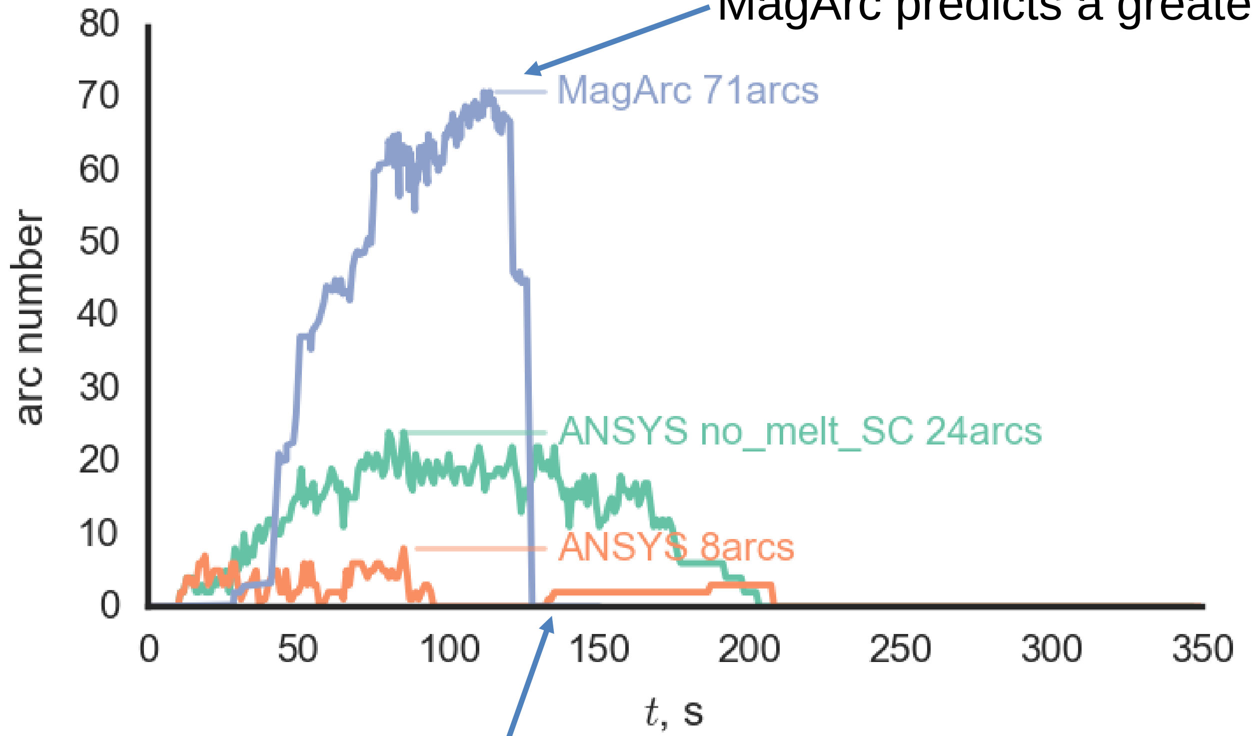


Close match for the start of discharge (no melt short-circuits)

MagArc predicts electrical short across terminals

Benchmark with MagArc Code

MagArc predicts a greater number of arcs

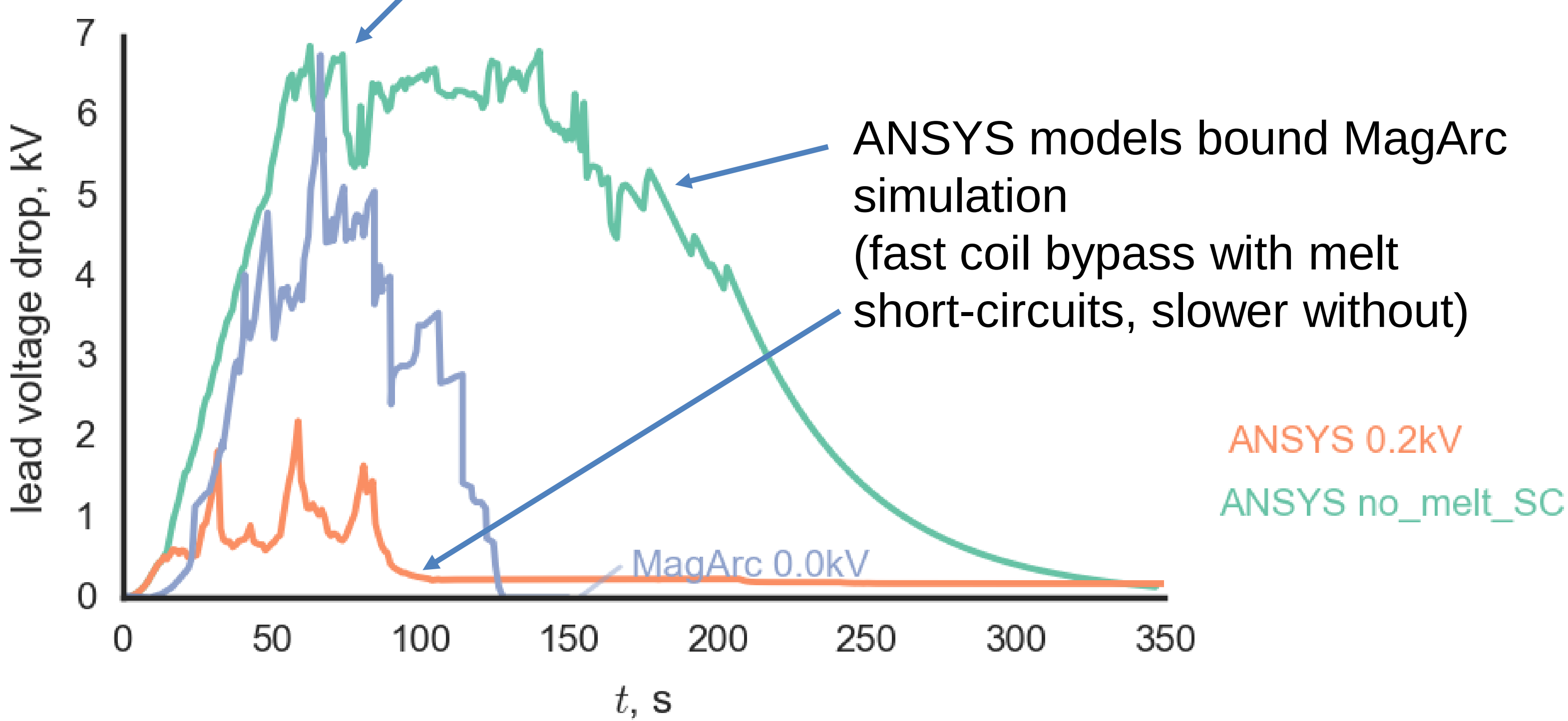


Melt short-circuits restrict arc number (decrease driving potential across turns)

Benchmark with MagArc Code

Similar maximum voltage drop developed across coil terminals

ANSYS models bound MagArc simulation
(fast coil bypass with melt short-circuits, slower without)



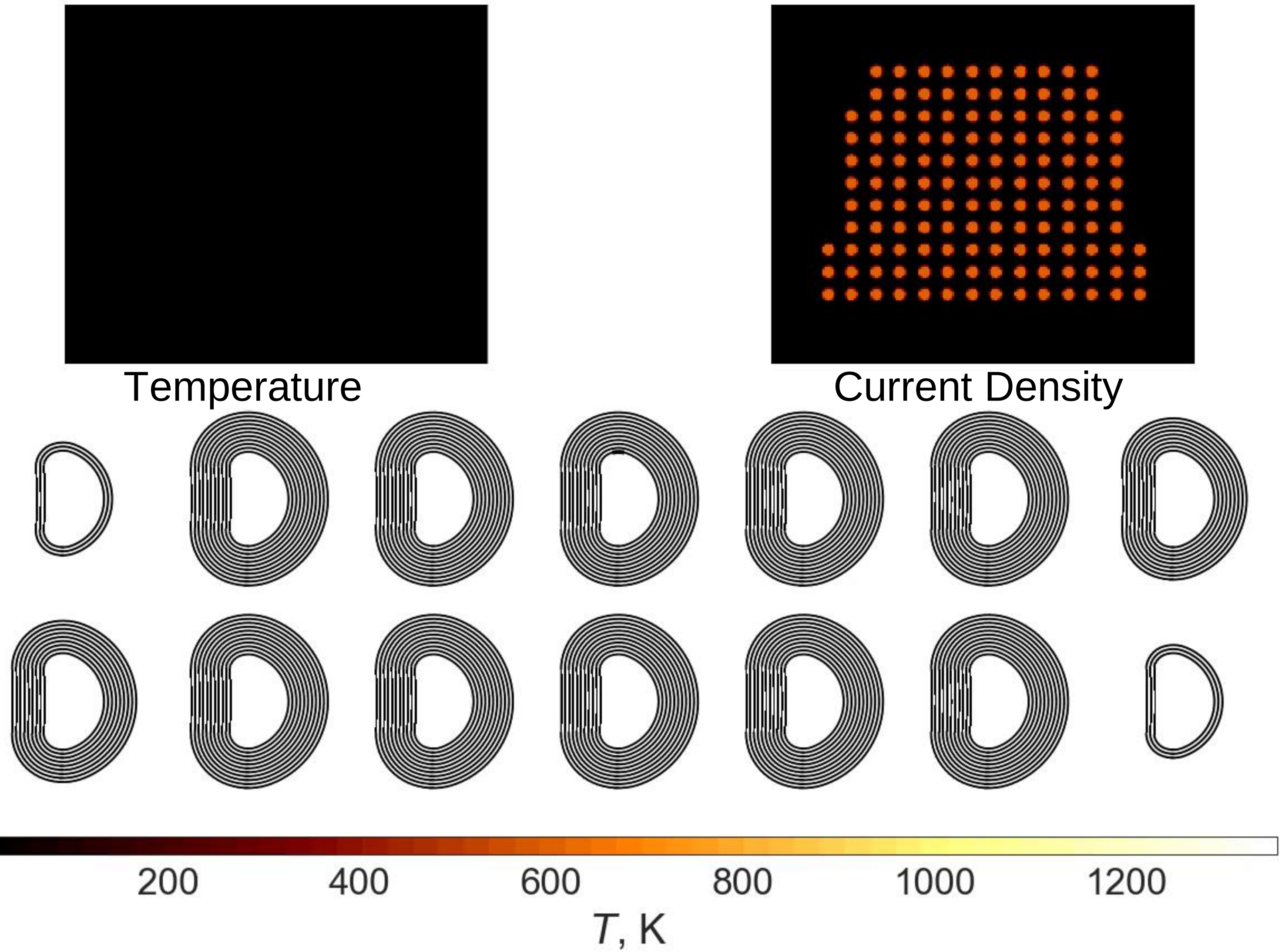
Selected Results of Qualified Analysis

Simulations run on the Freia compute cluster at CCFE, total CPU time = 2.5 years

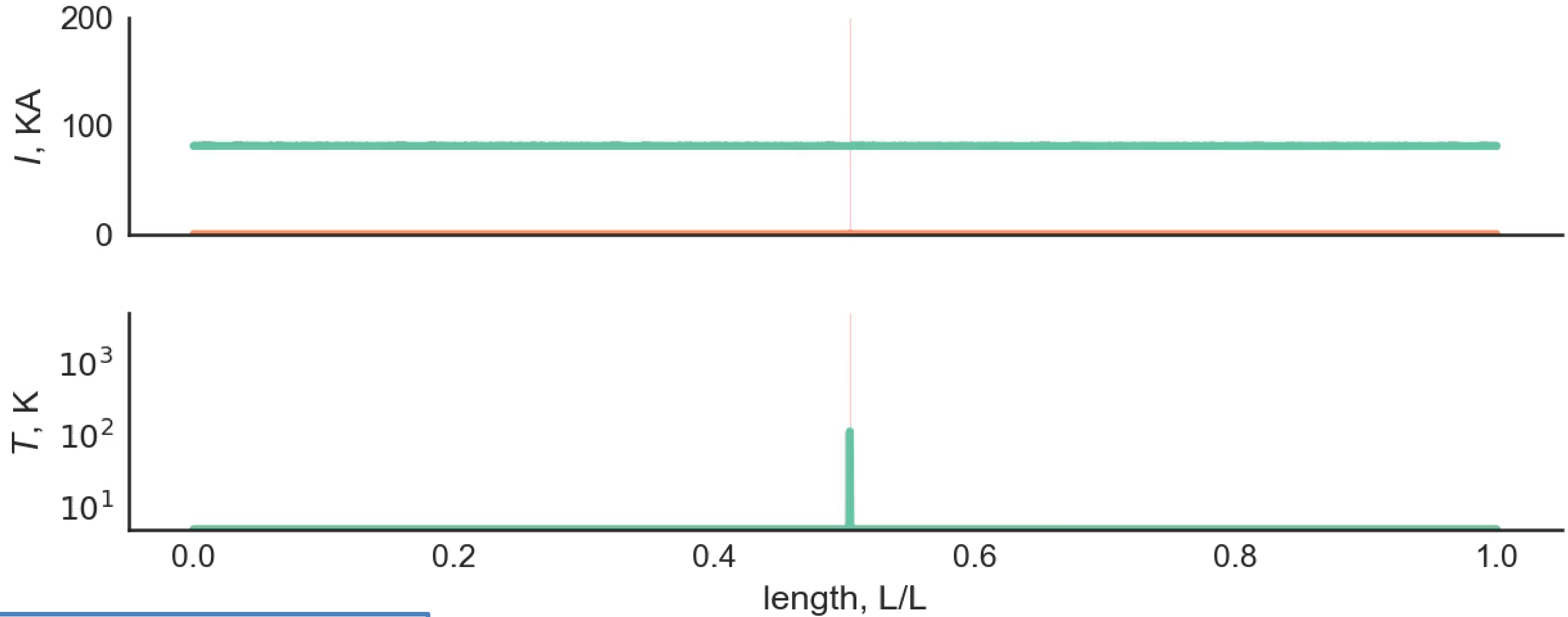
#	Coil	I_o kA	I_{max} kA	Tex_{max} K	m_{cond} m^3	m_{steel} m^3	m_{total} m^3	V_{max} kV	E_{arc} GJ	E_{total} GJ
3	**TF**	**68**	**121.9**	**722**	**0.421**	**0.277**	**0.647**	**2.08**	**0.39**	**6.19**
4	TF	68	122.0	167	0.359	0.051	0.0405	3.06	0.15	7.27
5	TF	68	122.2	1088	0.317	0.223	0.524	1.34	0.46	6.87
6	TF	68	68	90	0.081	0.043	0.117	2.10	0.47	7.64
7	**PF3**	**44.0**	**52.3**	**1720**	**0.019**	**0.005**	**0.022**	**0.69**	**0.08**	**3.19**
8	PF3	44.0	51.5	1602	0.012	0.002	0.014	0.83	0.00	3.01
9	PF2	3.4	30.0	441	0.000	0.000	0.000	0.10	0.00	0.30
10	**CSU2**	**35.5**	**49.7**	**3074**	**0.015**	**0.006**	**0.022**	**0.43**	**0.22**	**1.51**

- Simulations 1 and 2 used in benchmark exercise with MagArc code
- Reference simulations for TF, PF and CS shown in bold
- Maximum melt volume: TF (0.65 m3)
- Maximum average coil current: TF (121KA)
- Maximum external temperature: CS (3074K) - low melt volume

Reference TF simulation 3



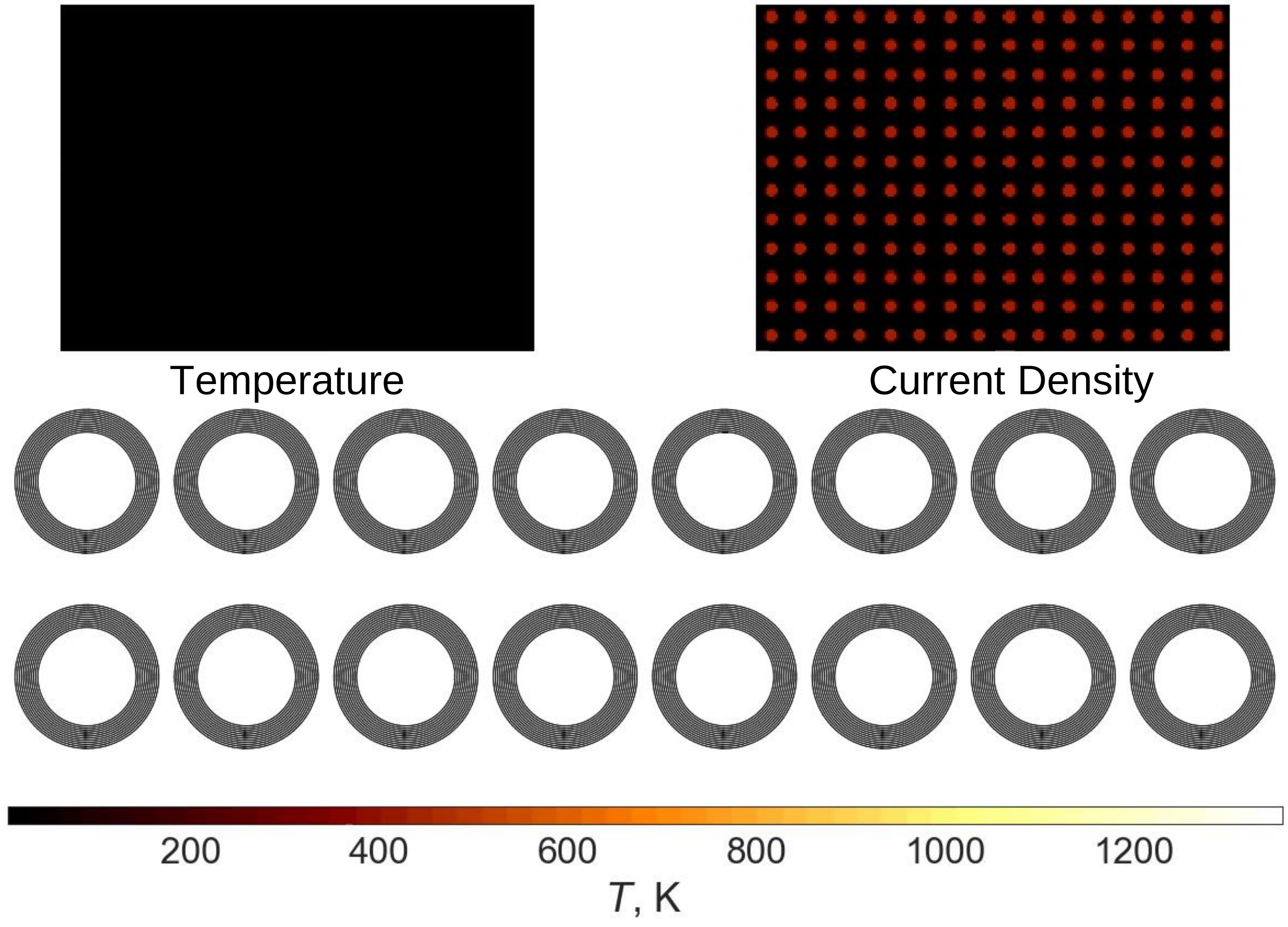
Reference TF simulation 3



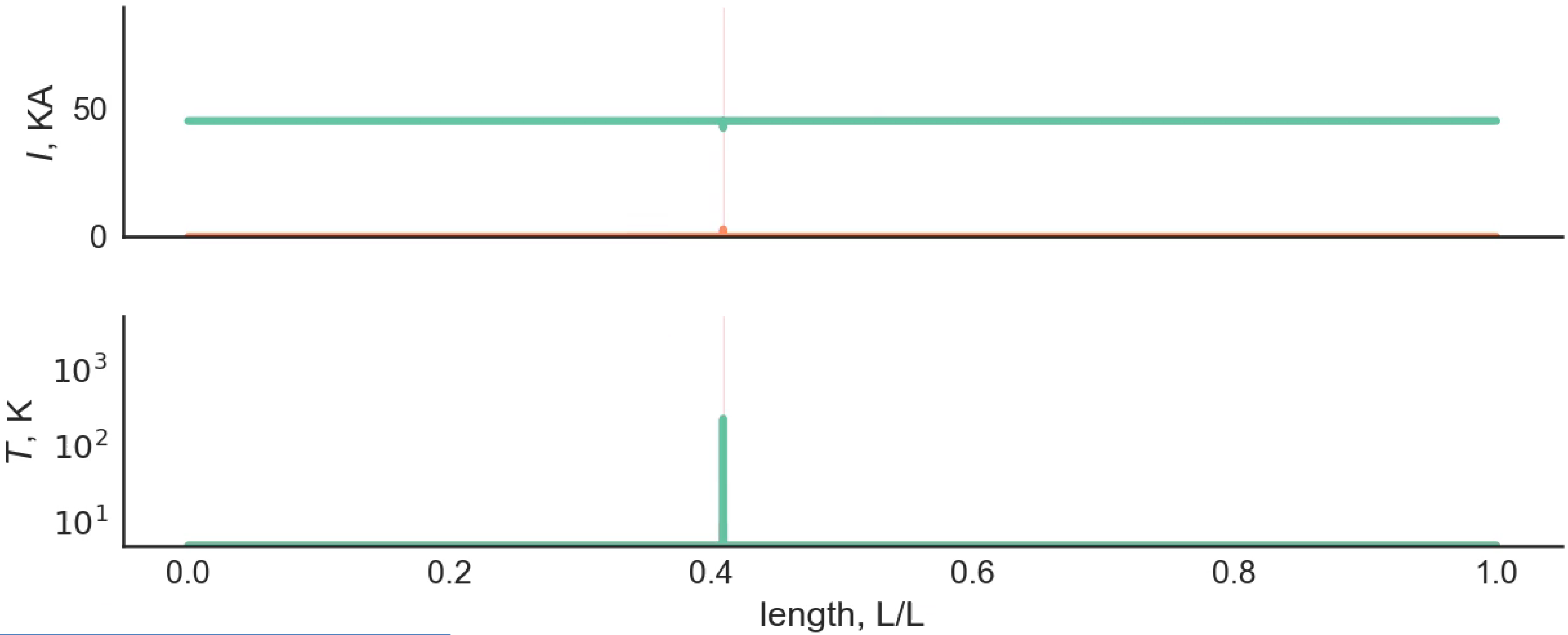
Key:
Green: Conductor
Orange: Jacket
Pink: Quenched rejoins
Red: Electrical Arcs
Grey: Melt short-circuits

- Inductive coupling increases current > starting 68KA
- Pancake quench mechanism clear (orange > green)
- Arcs (red) and melt (grey) short-circuit sections of coil
- First 60 seconds shown

Reference PF simulation 7



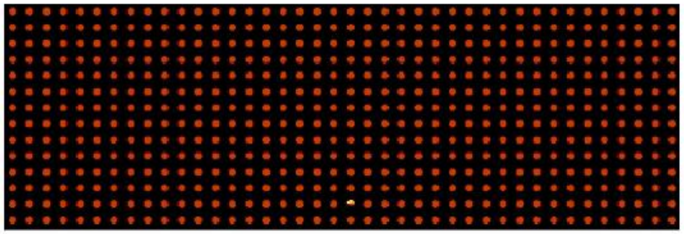
Reference PF simulation 7



Key:
Green: Conductor
Orange: Jacket
Pink: Quenched rejoins
Red: Electrical Arcs
Grey: Melt short-circuits

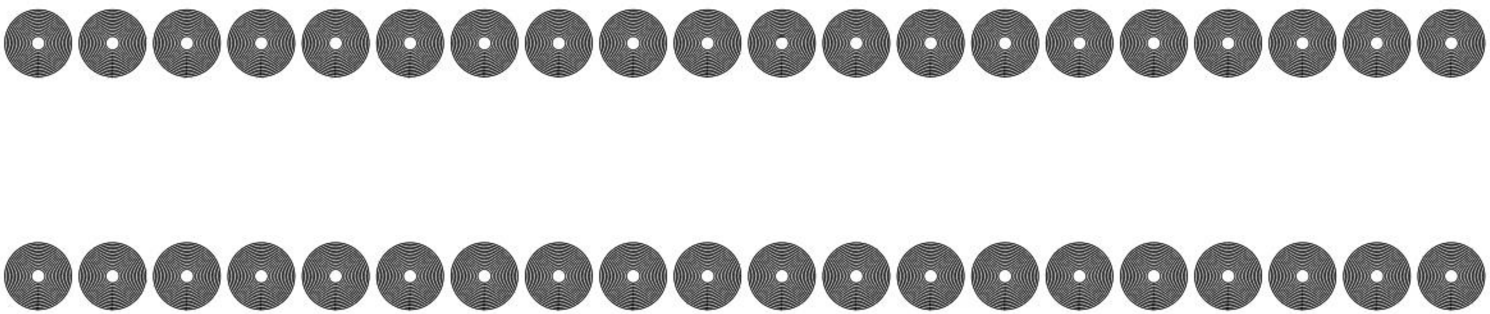
- Lower starting current and stored energy than TF
- Quench slow to propagate due to large coil diameter
- Thick (square) steel jackets limit melt short-circuits
- Arcs extinguish as coil discharges
- First 120 seconds of simulation shown

Reference CS simulation 10

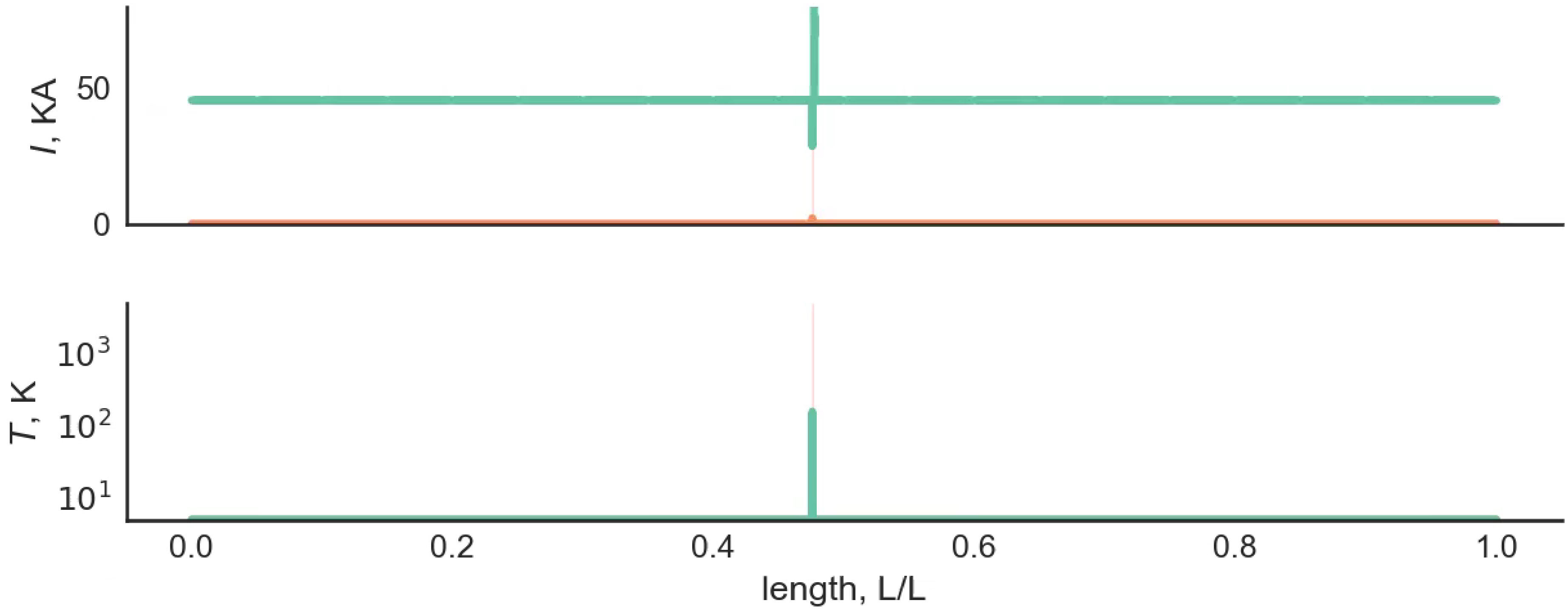


Temperature

Current Density



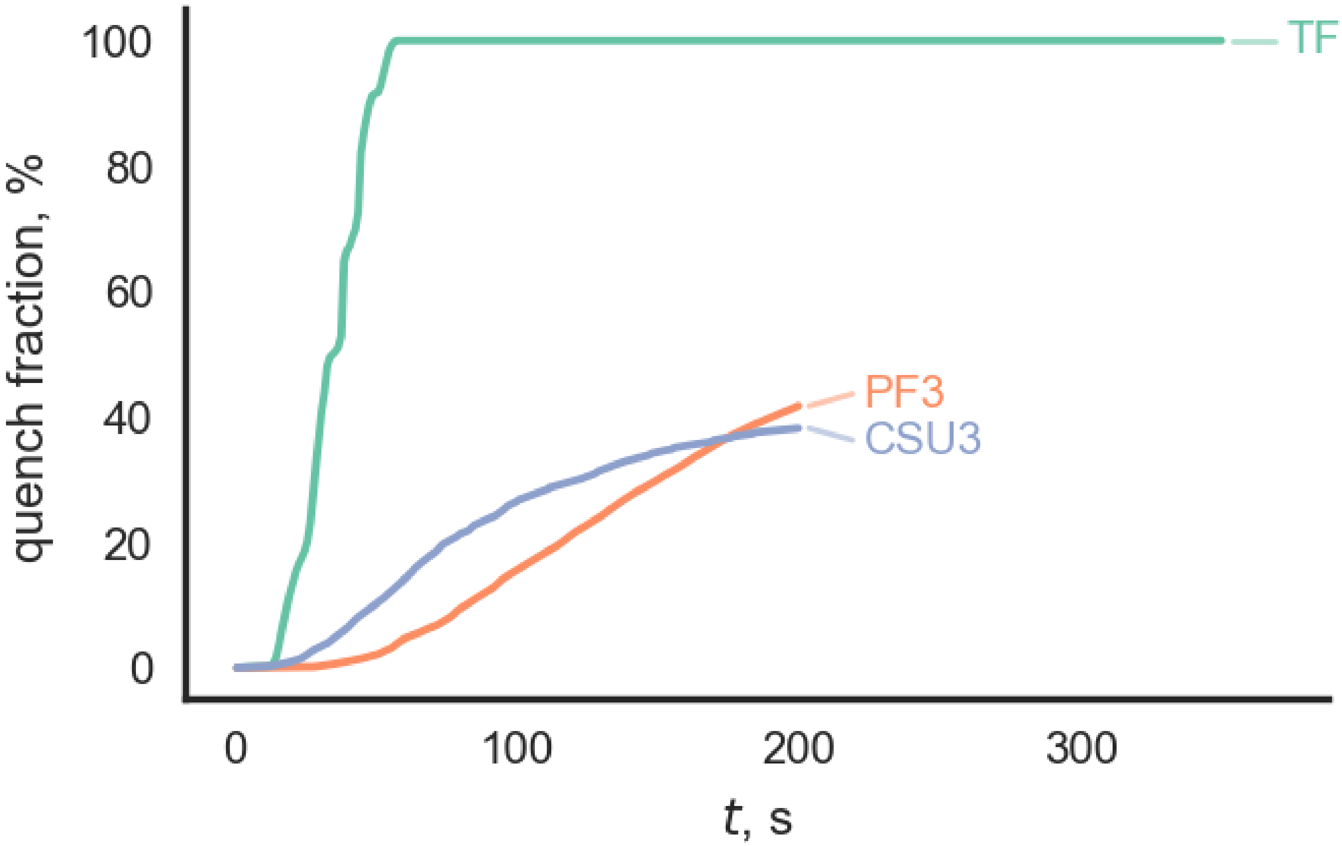
Reference CS simulation 10



Key:
Green: Conductor
Orange: Jacket
Pink: Quenched rejoins
Red: Electrical Arcs
Grey: Melt short-circuits

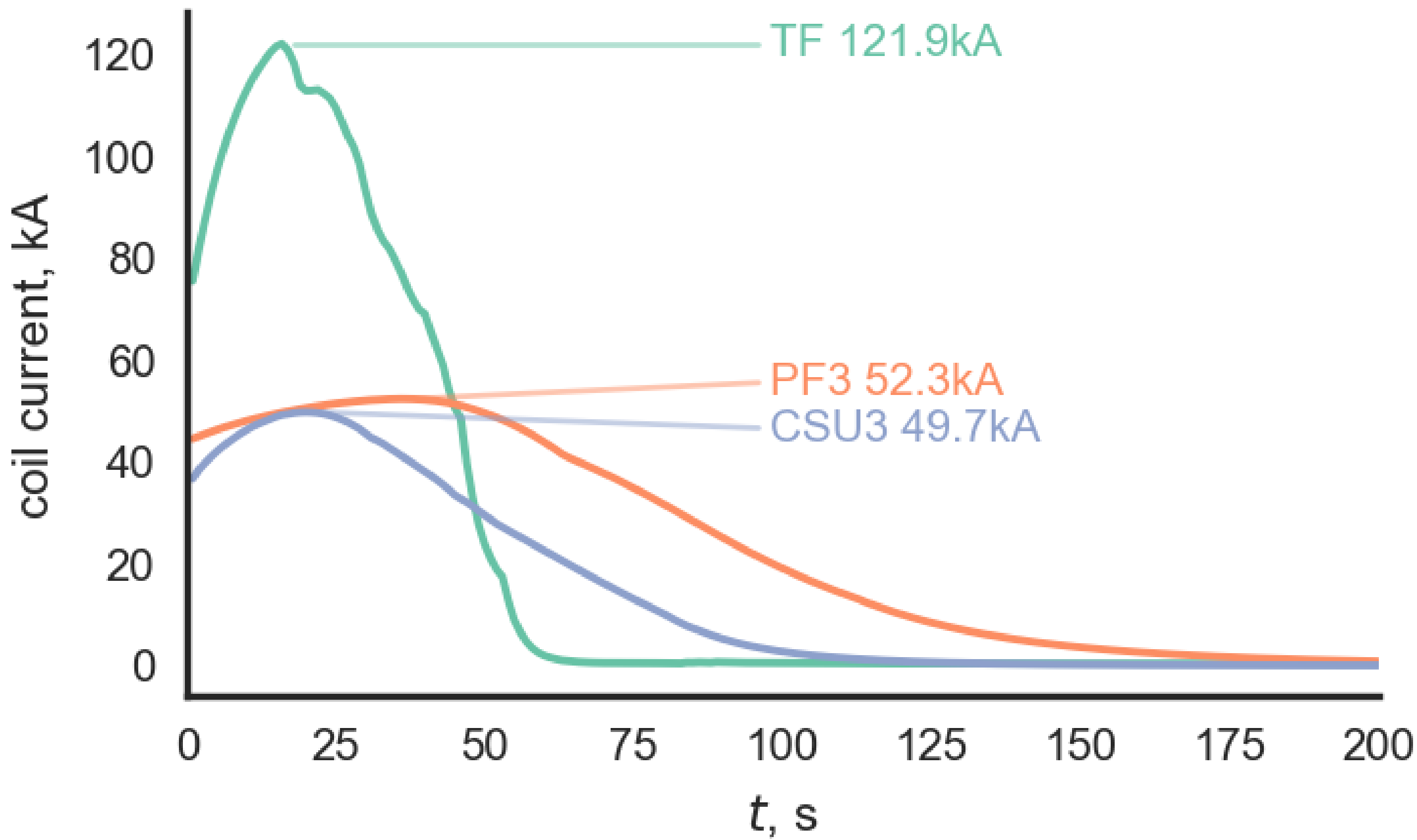
- Lower starting current and stored energy than TF
- Quench slow to propagate due to large conductor length
- Thick (square) steel jackets limit melt short-circuits
- Arcs extinguish as coil discharges
- First 120 seconds of simulation shown

ITER reference simulations - quench fraction



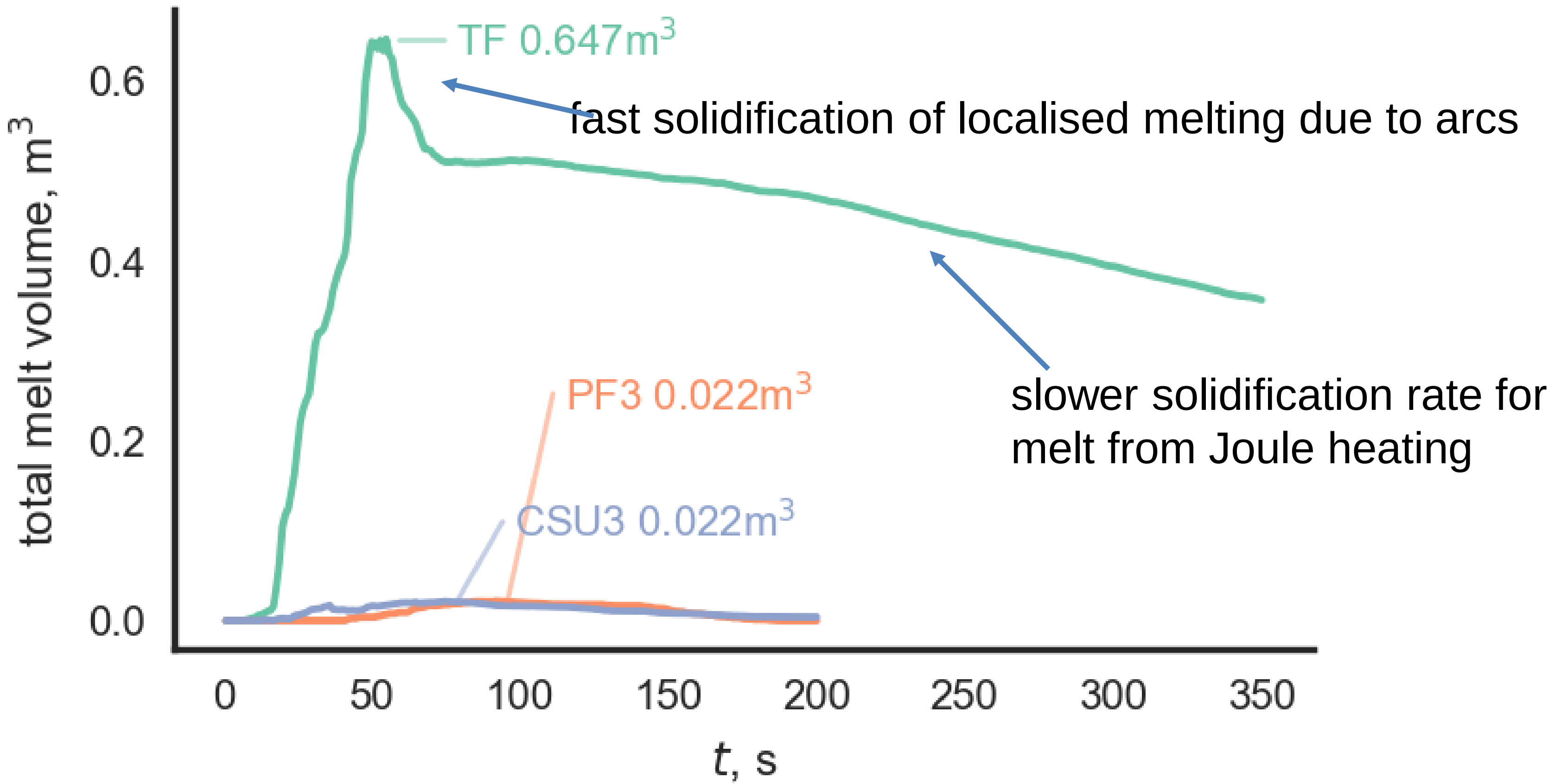
- Double pancake quench mechanism for TF ensures faster quench than CS/PF

ITER reference simulations - average current



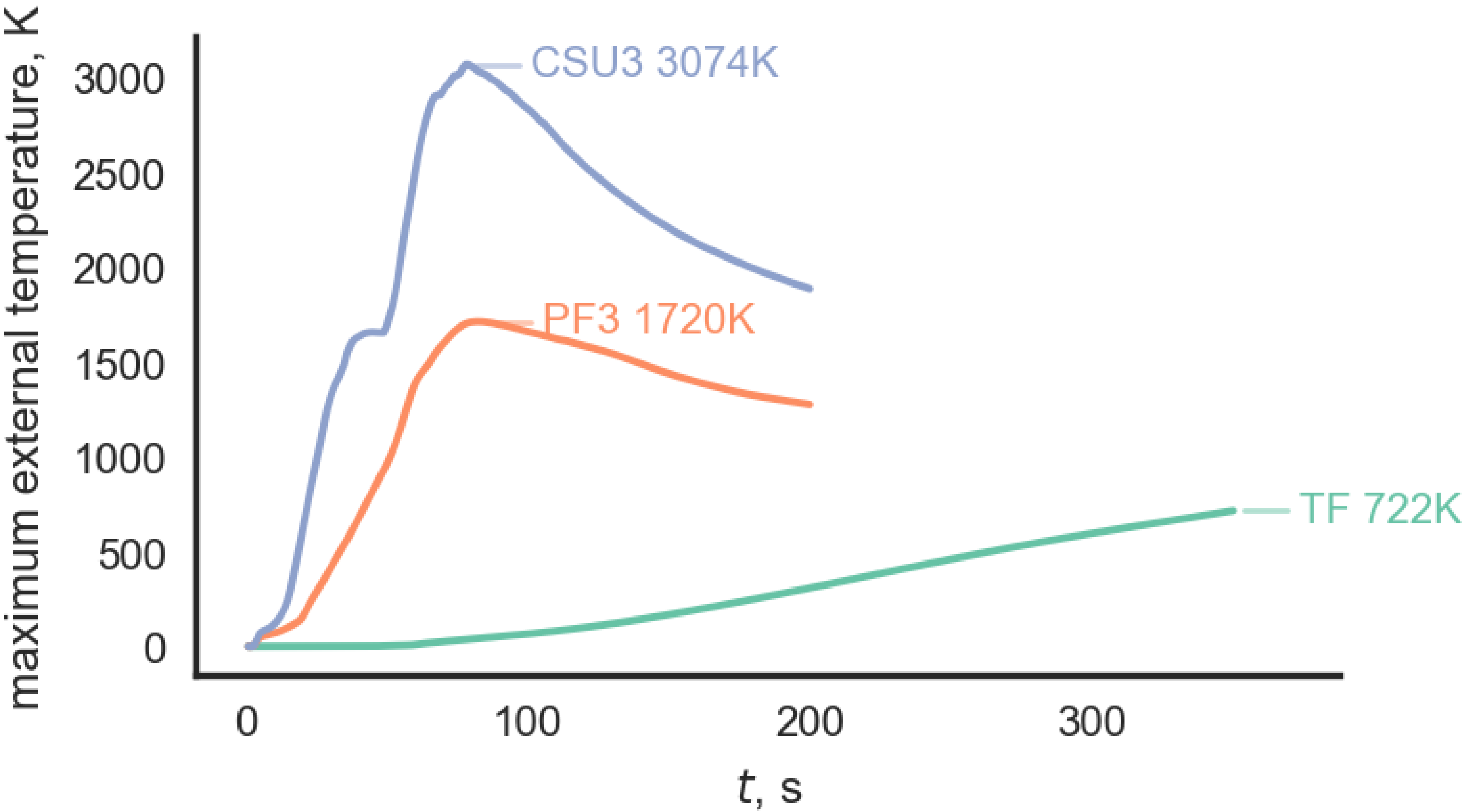
- Stranded TF circuit and high stored energy result in large maximum current
- Maximum current for CS / PF similar
- Smaller stored energy in CS results in faster discharge compared to PF

ITER reference simulations - total melt volume



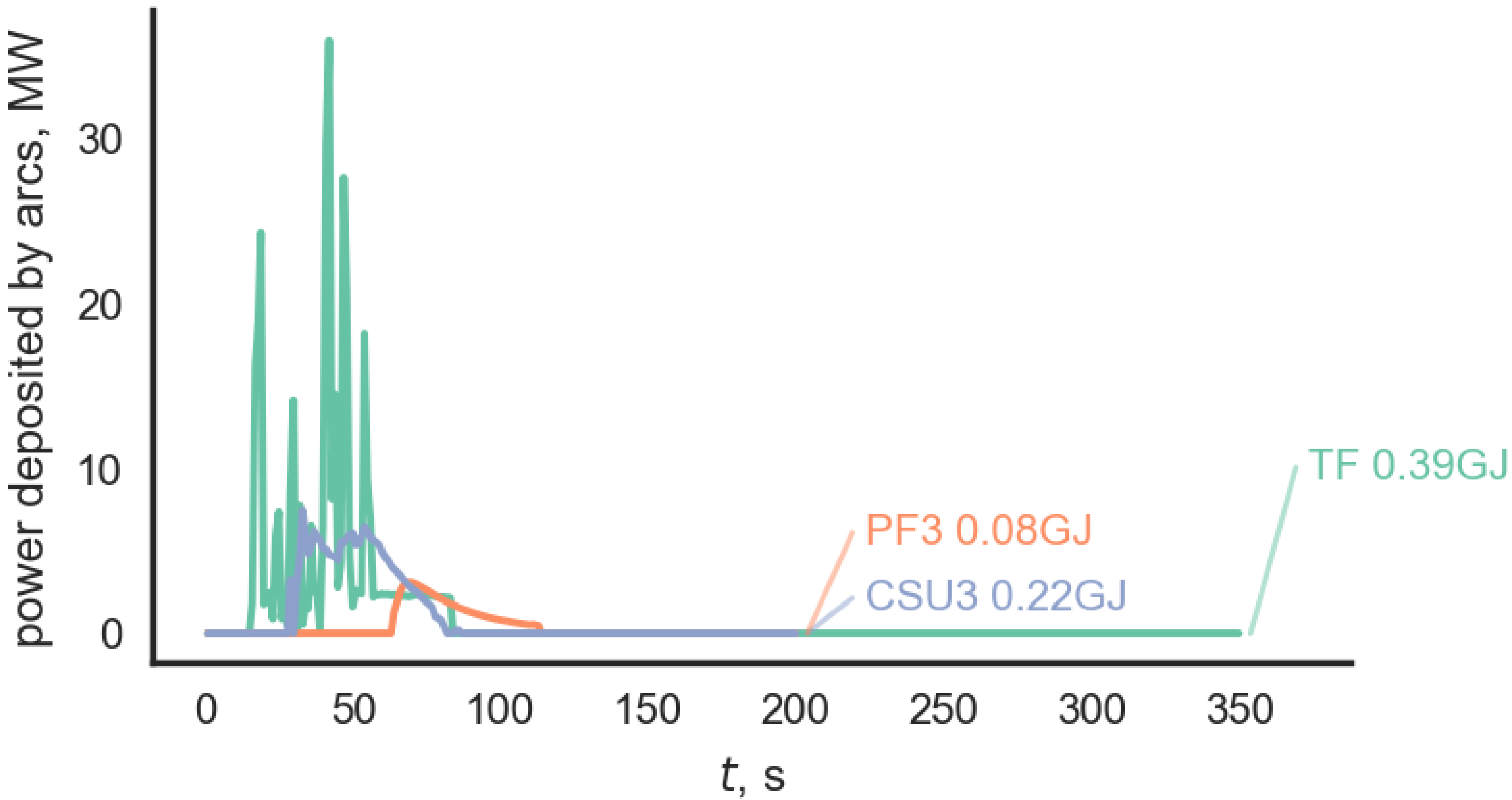
- TF generates much larger melt volume than CS / PF
- CS / PF melt volumes similar

ITER reference simulations - external temperature



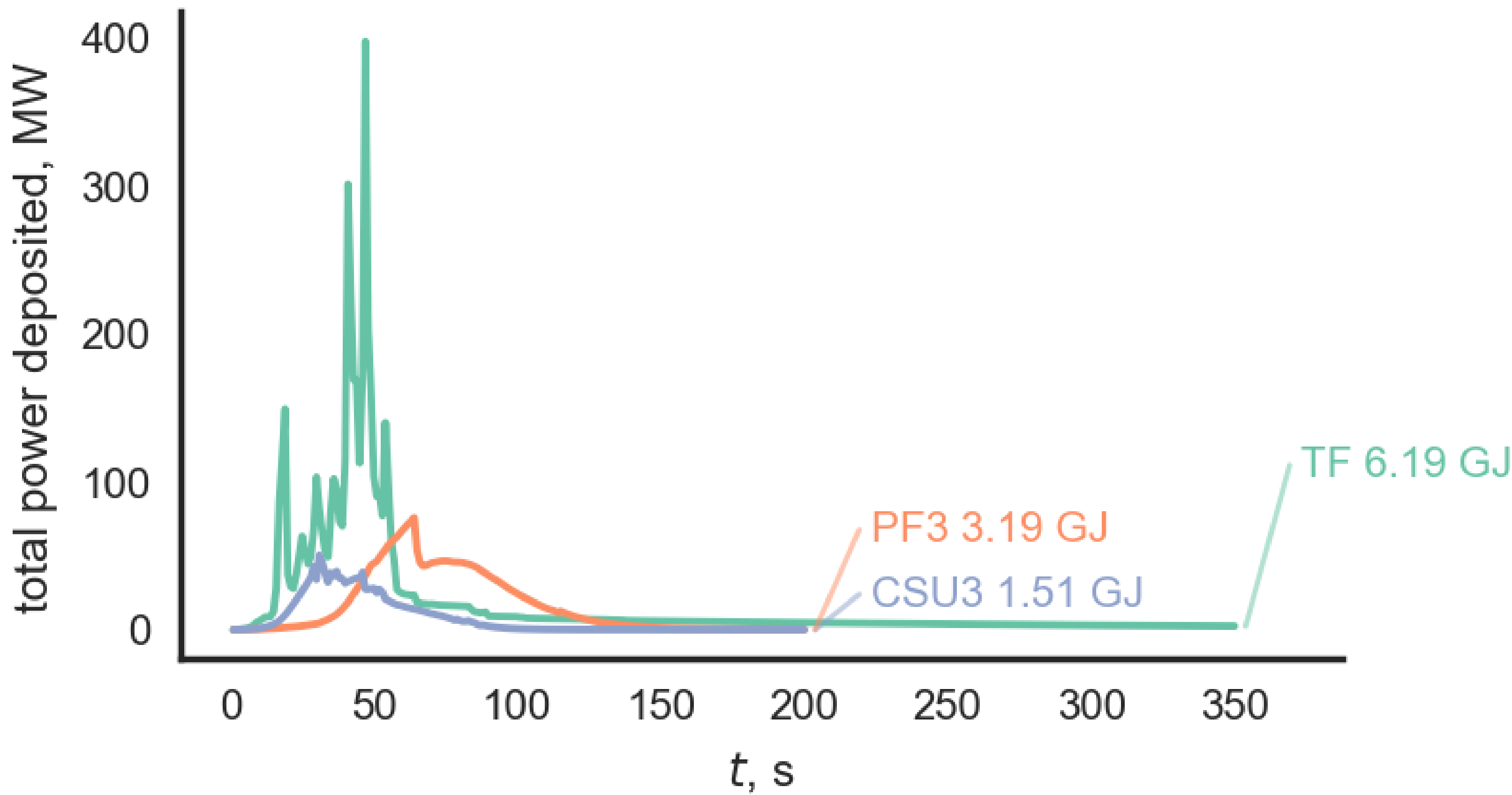
- Steel case surrounding TF winding pack keeps external temperature low
- Highest external temperature for CS simulation
- Both CS and PF temperature exceed melt however volume is small (0.022m3)
- Maximum PF temperature lower than CS due to 'two in hand' winding

ITER reference simulations - arc power



- Largest maximum arc power in TF simulation
- TF jacket thin - fast jacket melting and the extinguishing of arcs (spikes in arc power)
- Thicker square section jacket of CS and PF ensure that arcs remain 'on' for longer

ITER reference simulations - total power



- Total power deposited - sum of Joule heating and arc power
- TF coil only discharges twice as much energy than PF (stored energy much higher)
- PF discharges twice as much energy as CS but similar melt volumes (PF two in hand)

Summary

- **Integrated ANSYS model developed for TFC & PFC**
  - Model couples: quench / electrical / evolving arc network / thermal
  - Model produces a thermal damage assessment
  - Arc models would benefit from verification/improvement, e.g. conditions dependency; movement in a magnetic field
- **Simulation results**
  - the driving **circuit type**, **thermal model** and the **location of the initiating quench** are all shown to have a significant impact on the accident's evolution
  - The **length of the initiating quench** and the **arc model type** are considered to exert a smaller influence
  - Melt short circuits bypass zones with high energy deposition - spreading fault energy across larger volume
- **Comparison with MagArc**
  - MagArc compared to inline discharge with outer turn fault initiation
  - Ability of melt pool to short circuit magnet found to have significant effect
  - Similar trends between codes captured with melt short circuits disabled

Detailed Results

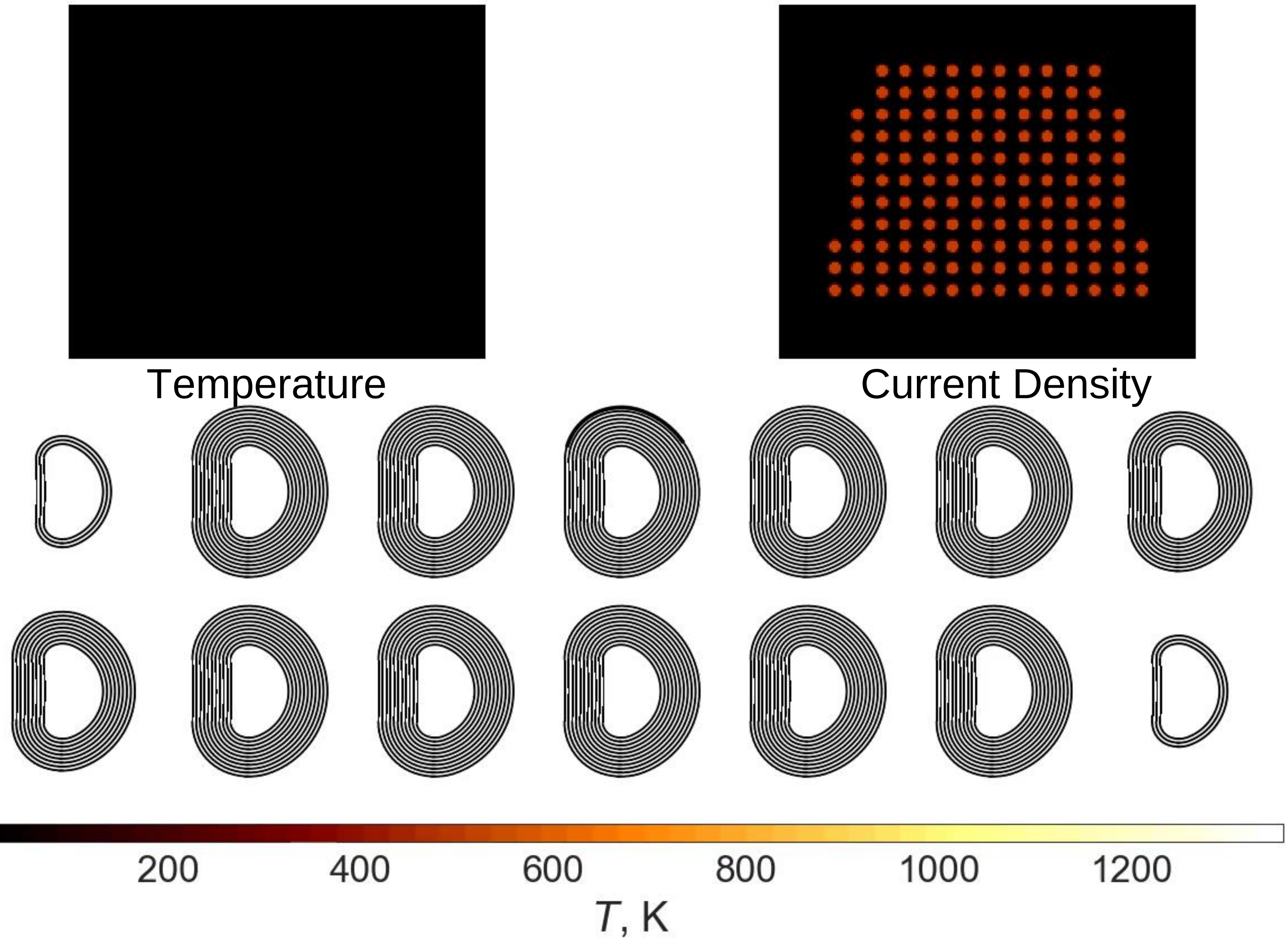
Detailed Results

Ten simulation test matrix for full TF, PF and CS models

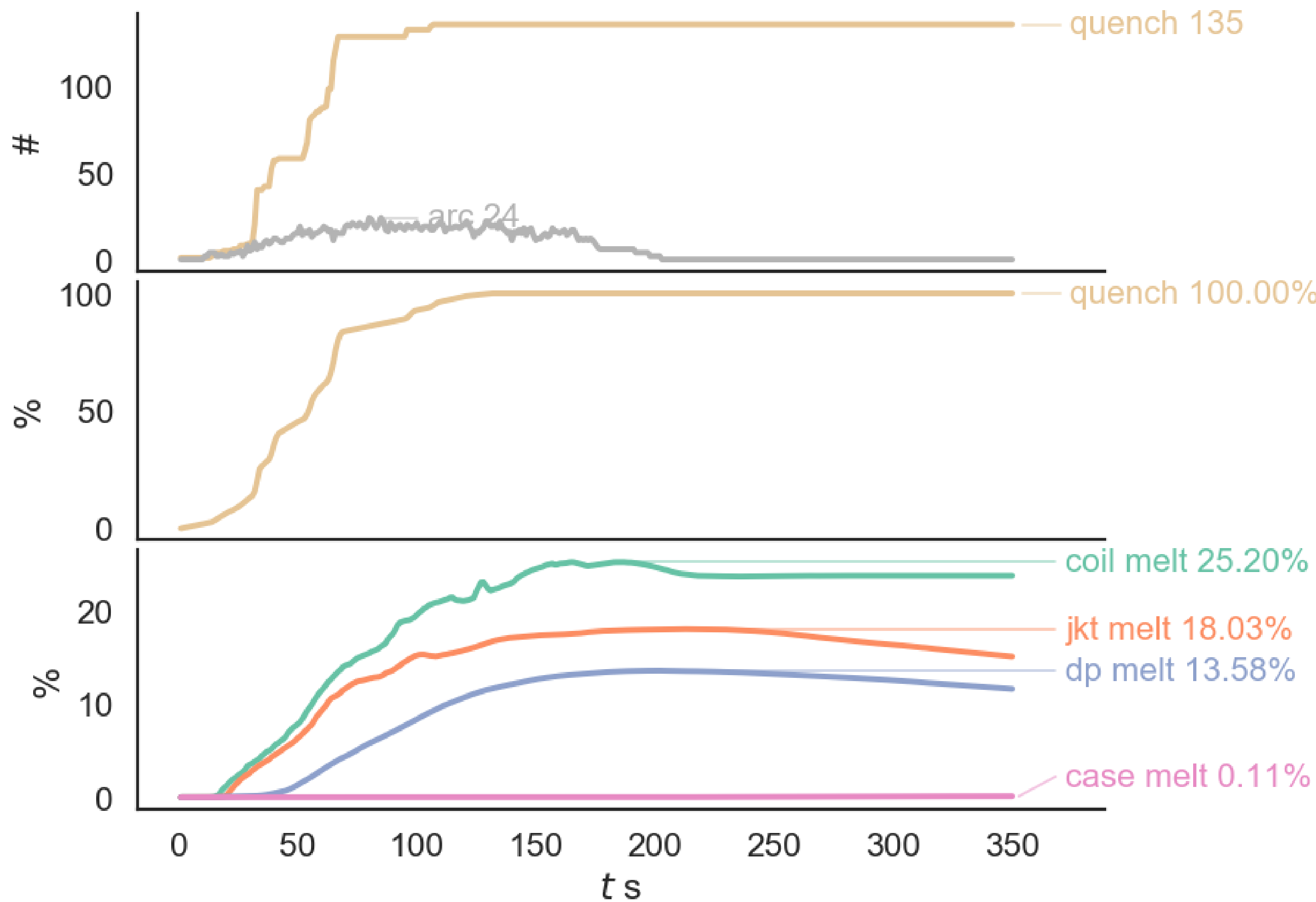
#	Coil	Initiating length	Quench model	Initiating location	Arc model	Driving circuit	Melt short-circuits
1	TF	34cm	$5ms^{-1}$	Outer turn	Kronhardt	Inline	No
2	TF	34cm	$5ms^{-1}$	Outer turn	Kronhardt	Inline	Yes
3	TF	5cm	MIT	Inner turn	Kronhardt	Stranded	Yes
4	TF	5cm	MIT	Inner turn	Holmes	Stranded	Yes
5	TF	5cm	MIT	Outer turn	Kronhardt	Stranded	Yes
6	TF	5cm	MIT	Inner turn	Kronhardt	Inline	Yes
7	PF3	5cm	MIT	Inner turn	Kronhardt	No FDU 3	Yes
8	PF3	5cm	MIT	Inner turn	Kronhardt	No FDU 3,6	Yes
9	PF2	5cm	MIT	Inner turn	Kronhardt	No FDU 2	Yes
10	CSU2	5cm	MIT	Inner turn	Kronhardt	No FDU 5	Yes

- Matrix allows comparisons to be made between:
- **Benchmark against MagArc** code (1 and 2)
- Influence of **arc model,** Kronhardt vs Holmes (3 and 4)
- Influence of **initiating quench location,** inboard vs outboard (3 and 5)
- Influence of **TF driving circuit,** inline vs stranded (3 and 6)
- Additional **failure of FDU6** (7 and 8)

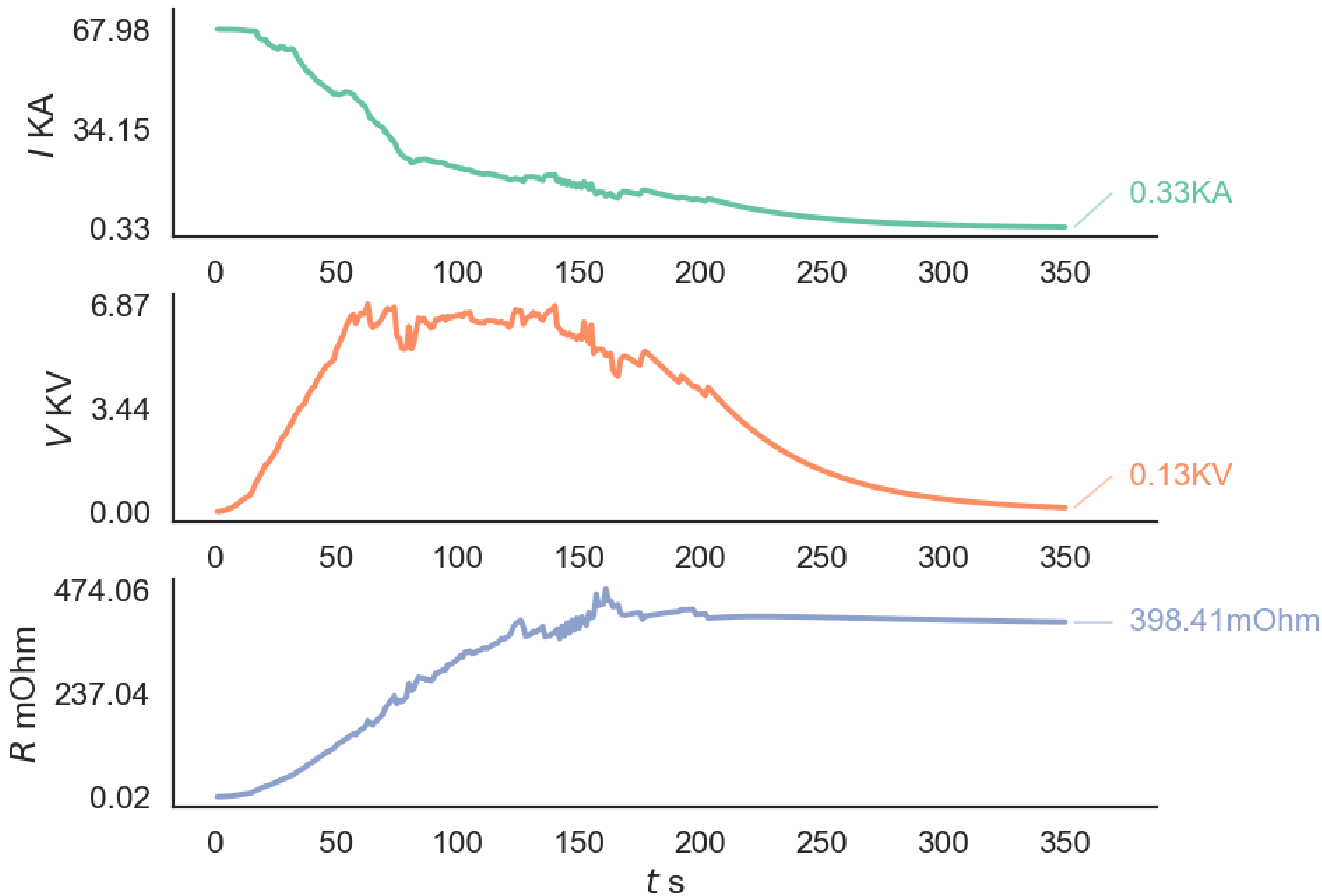
Simulation 1 - MagArc reference (melt short-circuits disabled)



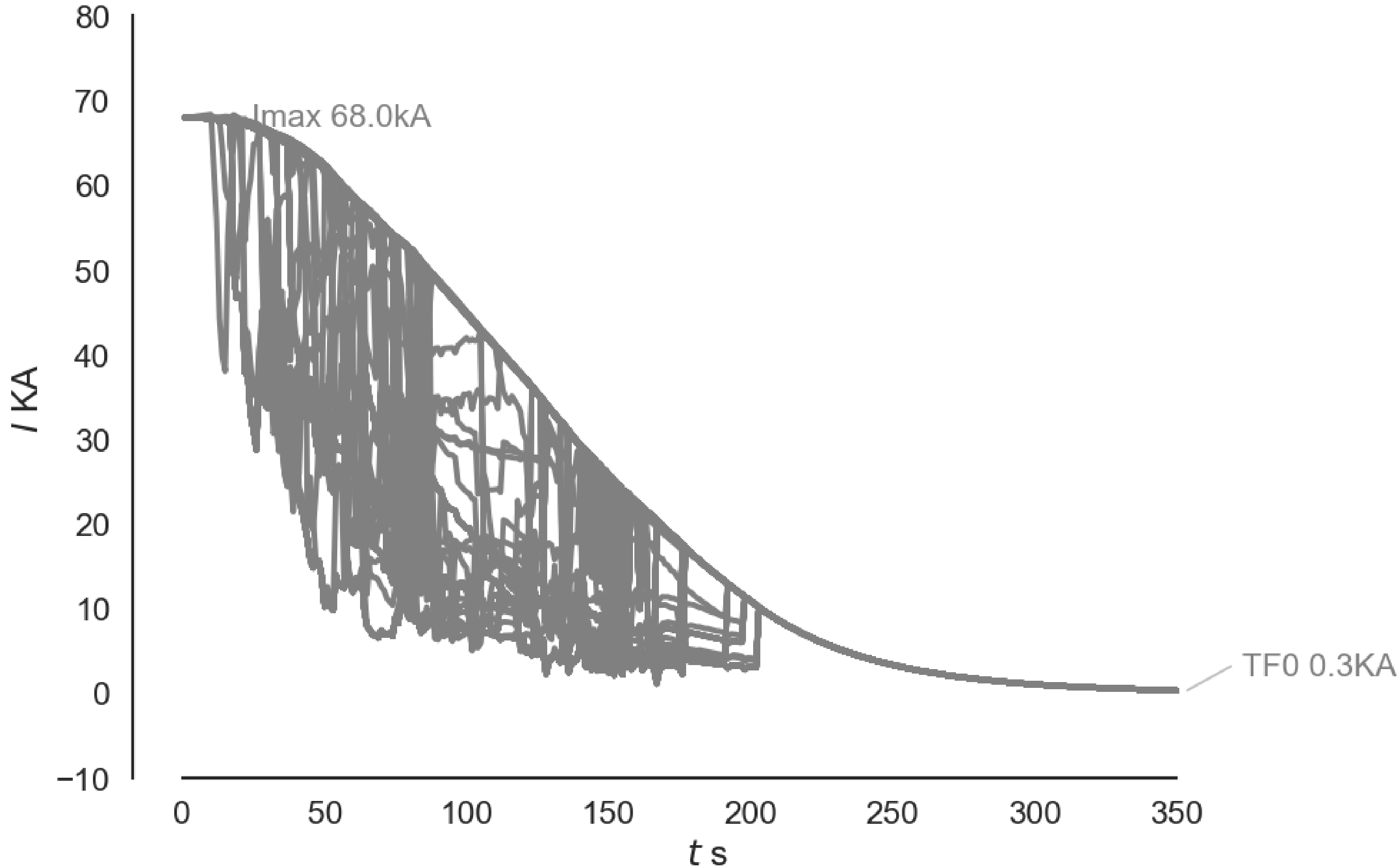
Simulation 1 - MagArc reference (melt short-circuits disabled)



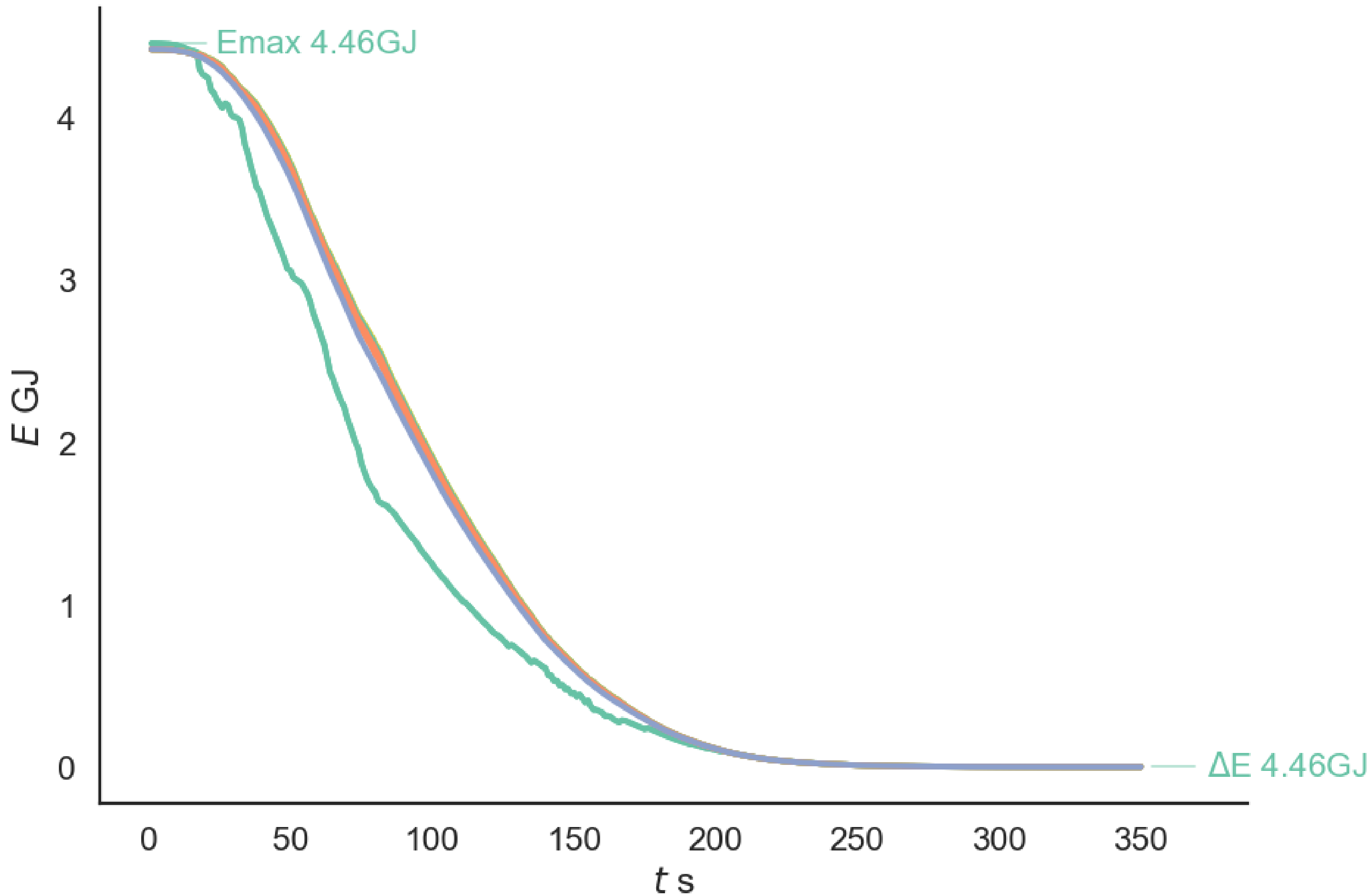
Simulation 1 - MagArc reference (melt short-circuits disabled)



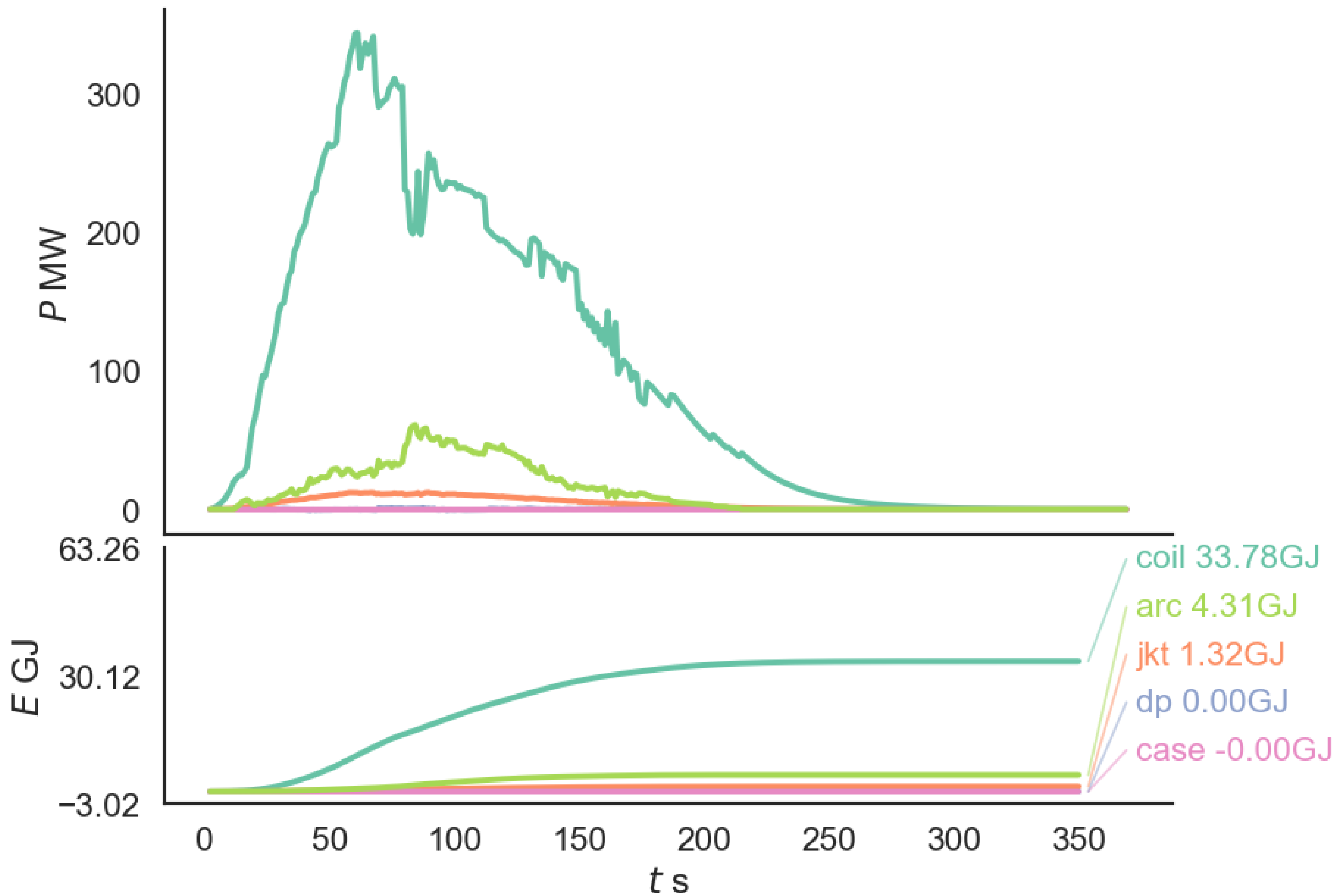
Simulation 1 - MagArc reference (melt short-circuits disabled)



Simulation 1 - MagArc reference (melt short-circuits disabled)



Simulation 1 - MagArc reference (melt short-circuits disabled)



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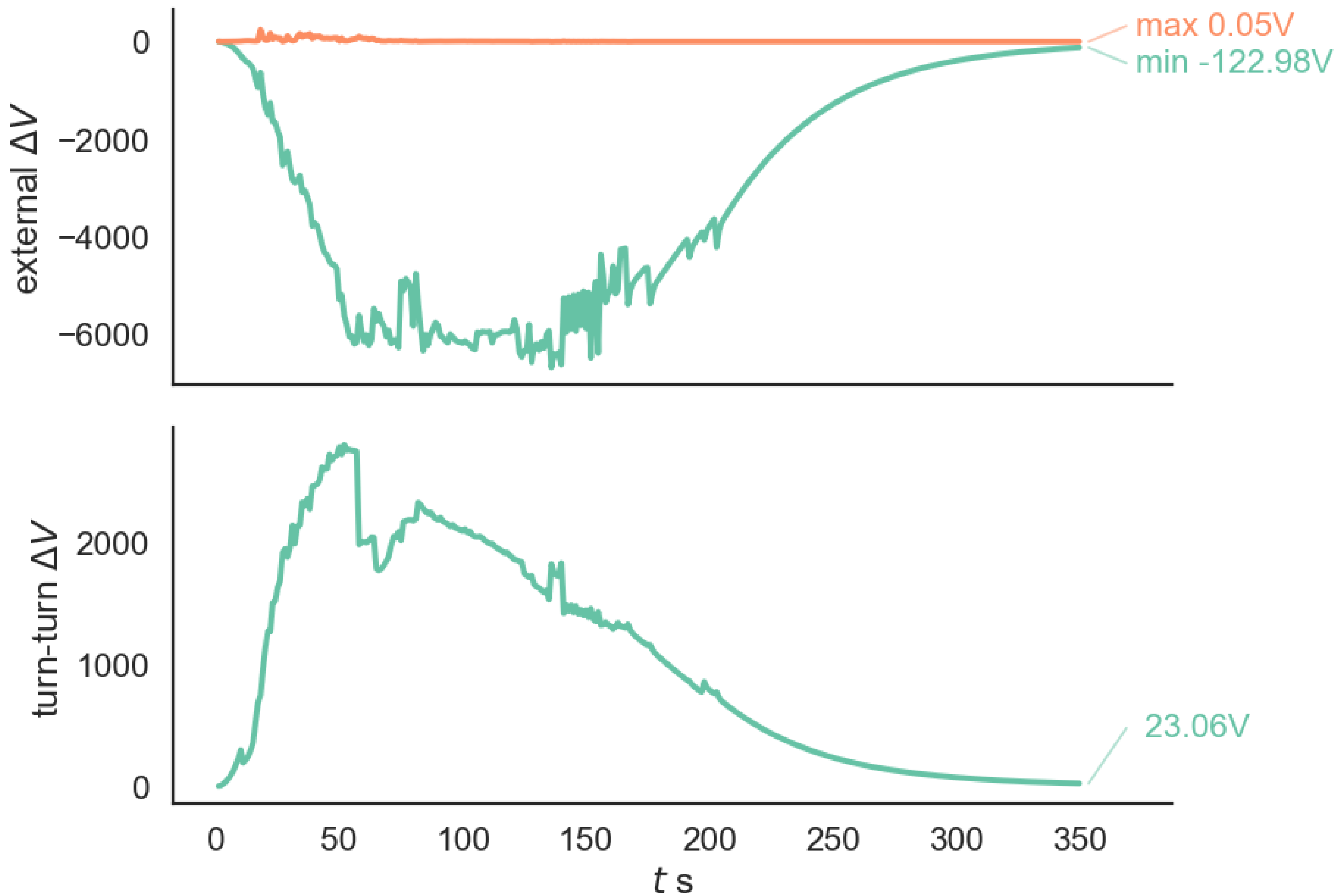
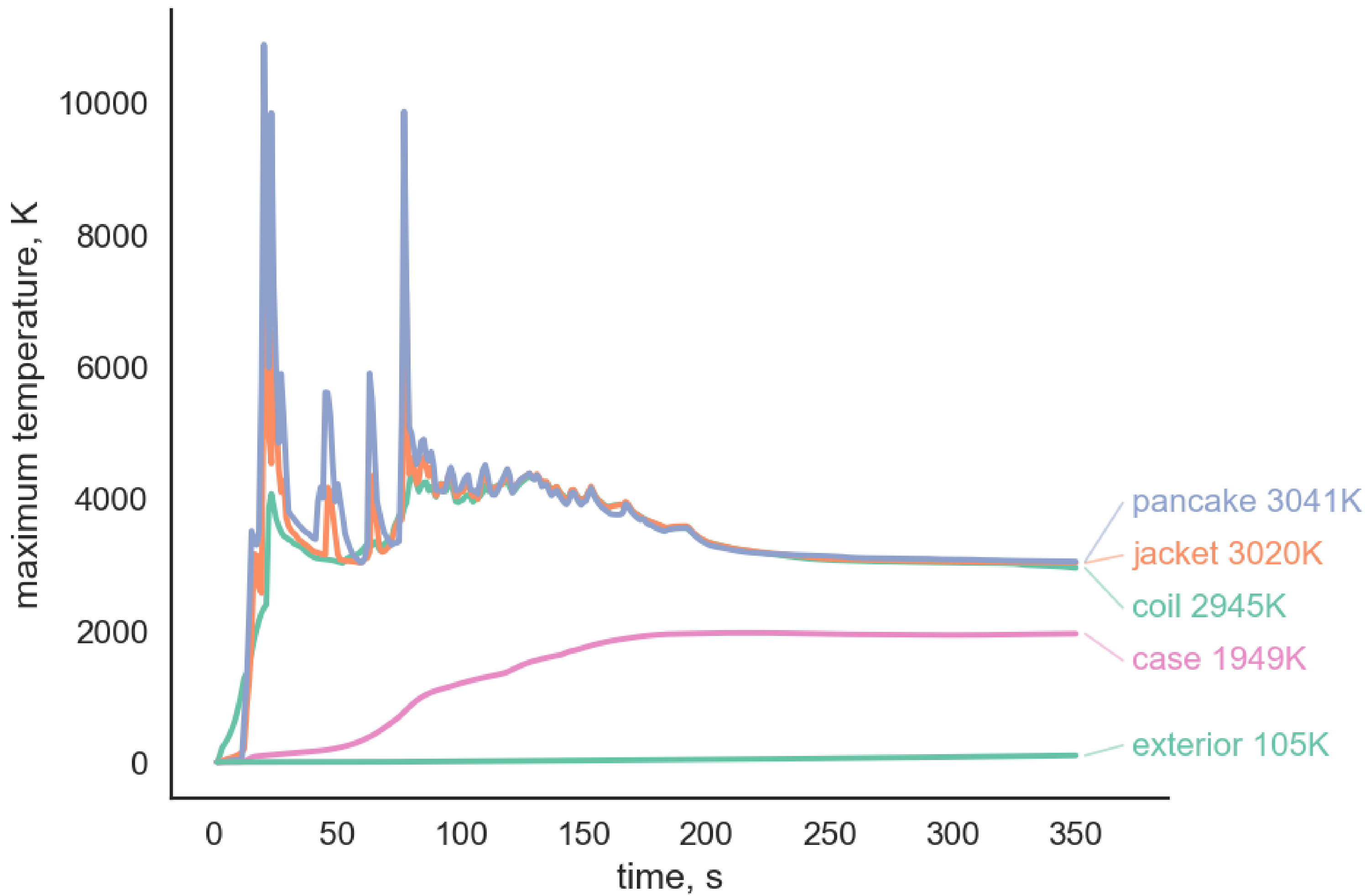
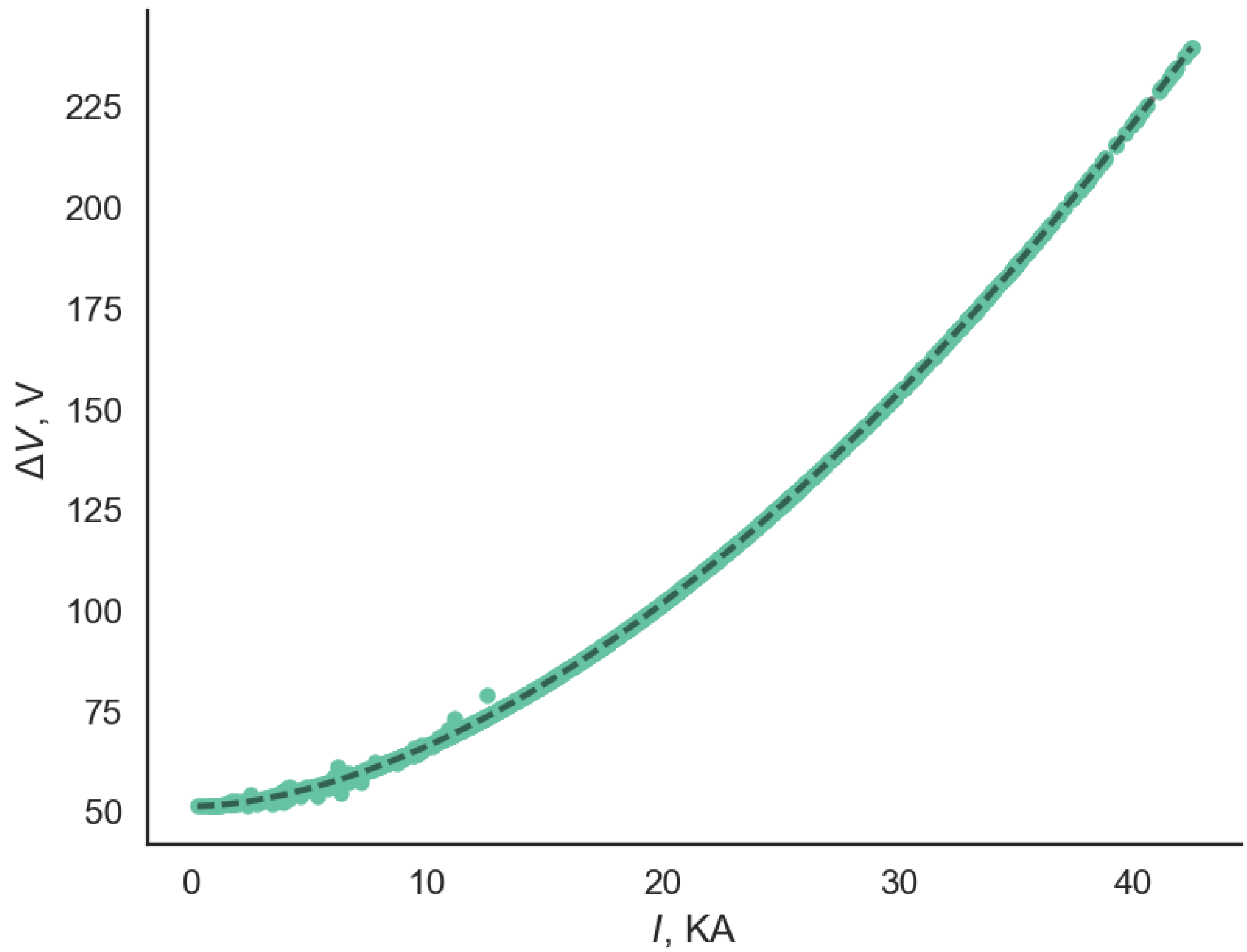


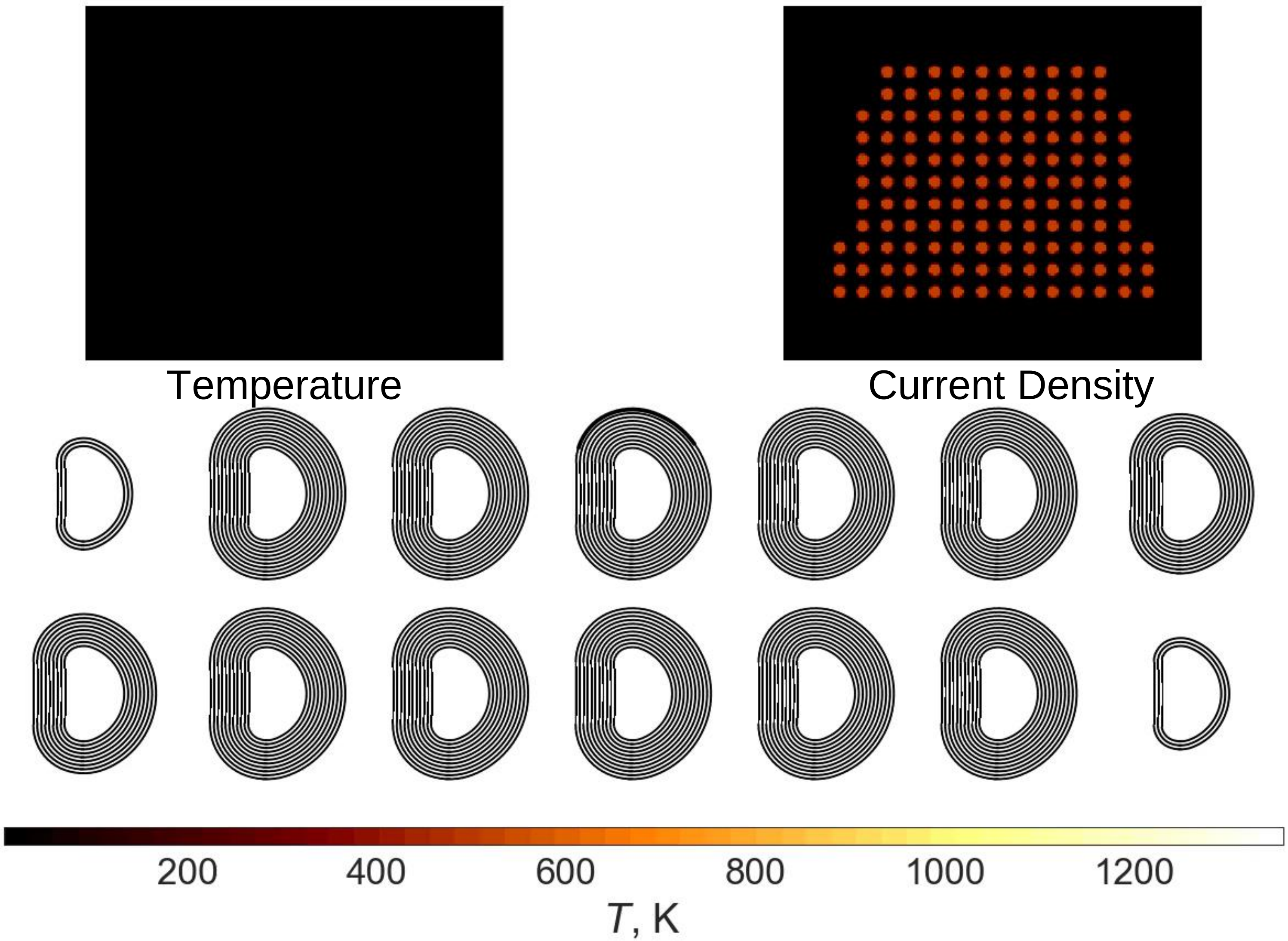
Simulation 1 - MagArc reference (melt short-circuits disabled)



Simulation 1 - MagArc reference (melt short-circuits disabled)



Simulation 2 - MagArc reference (melt short-circuits enabled)



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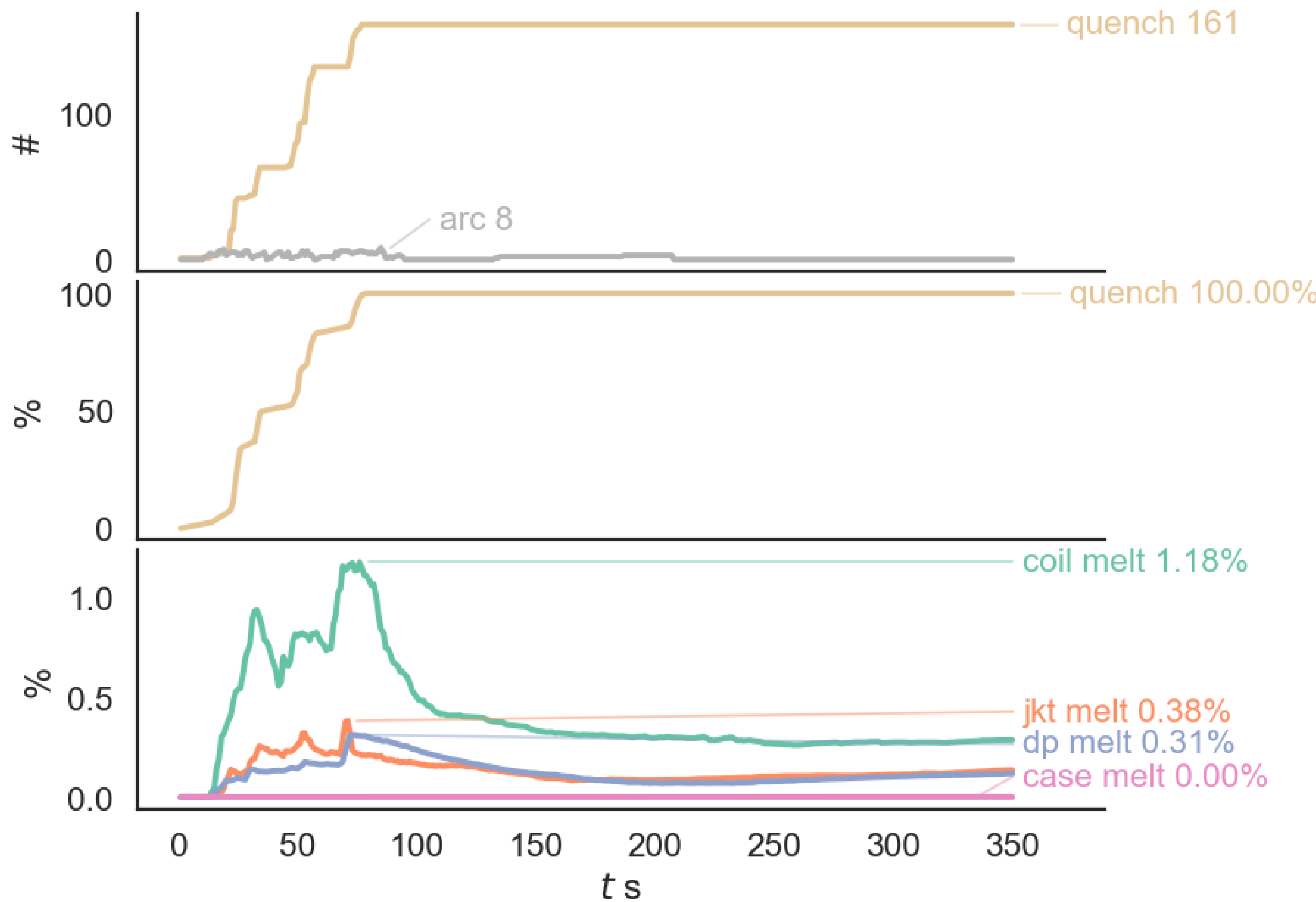

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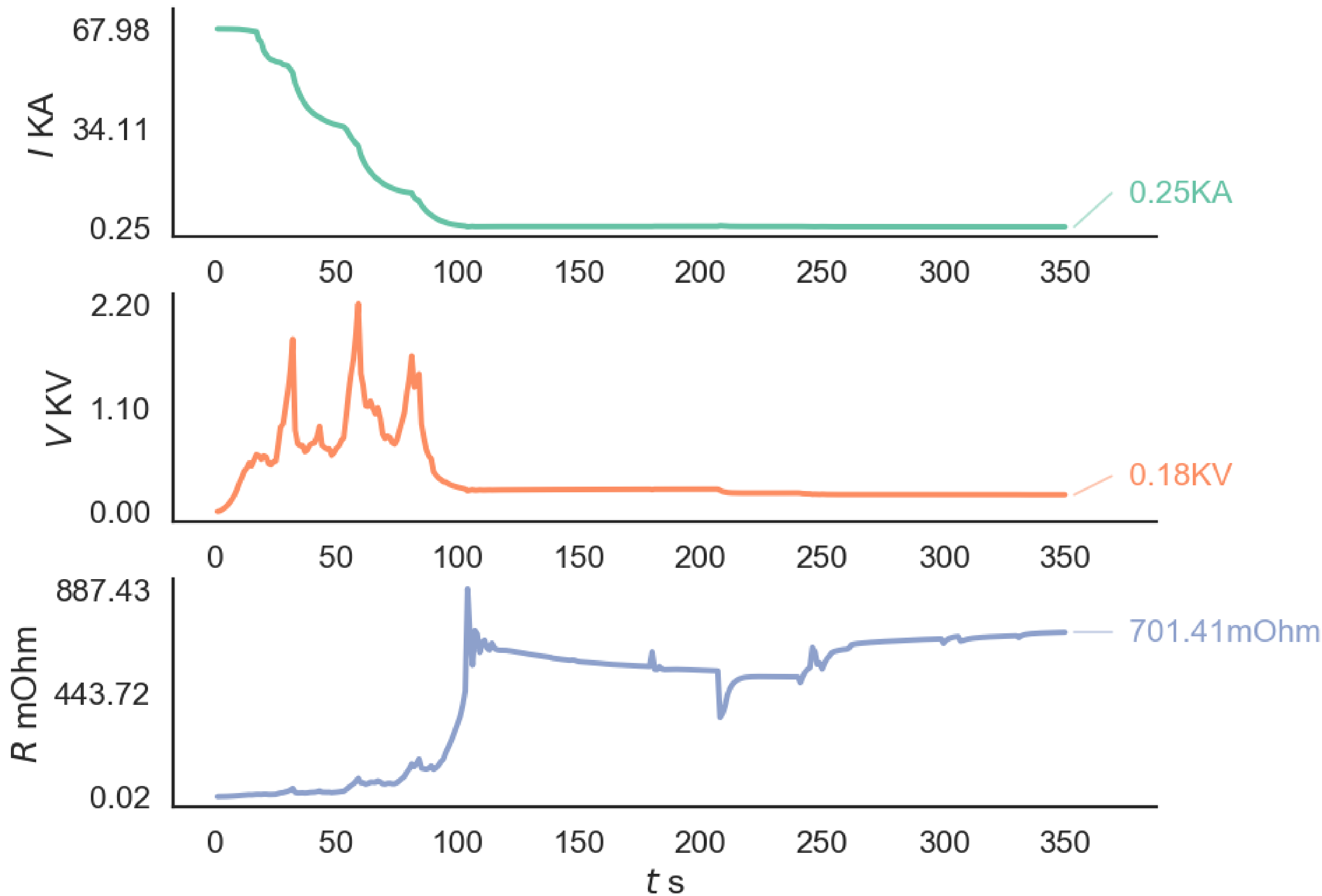

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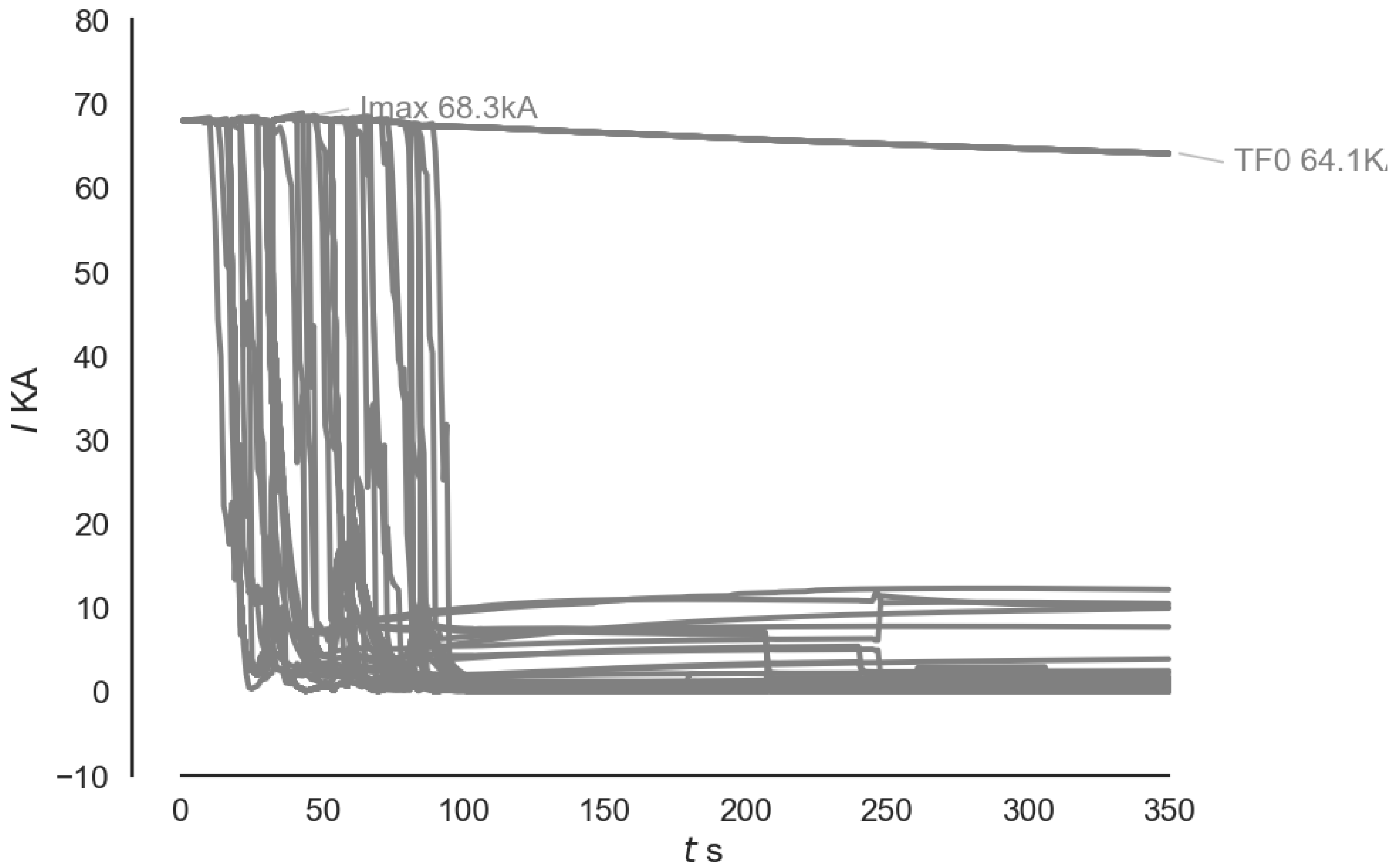

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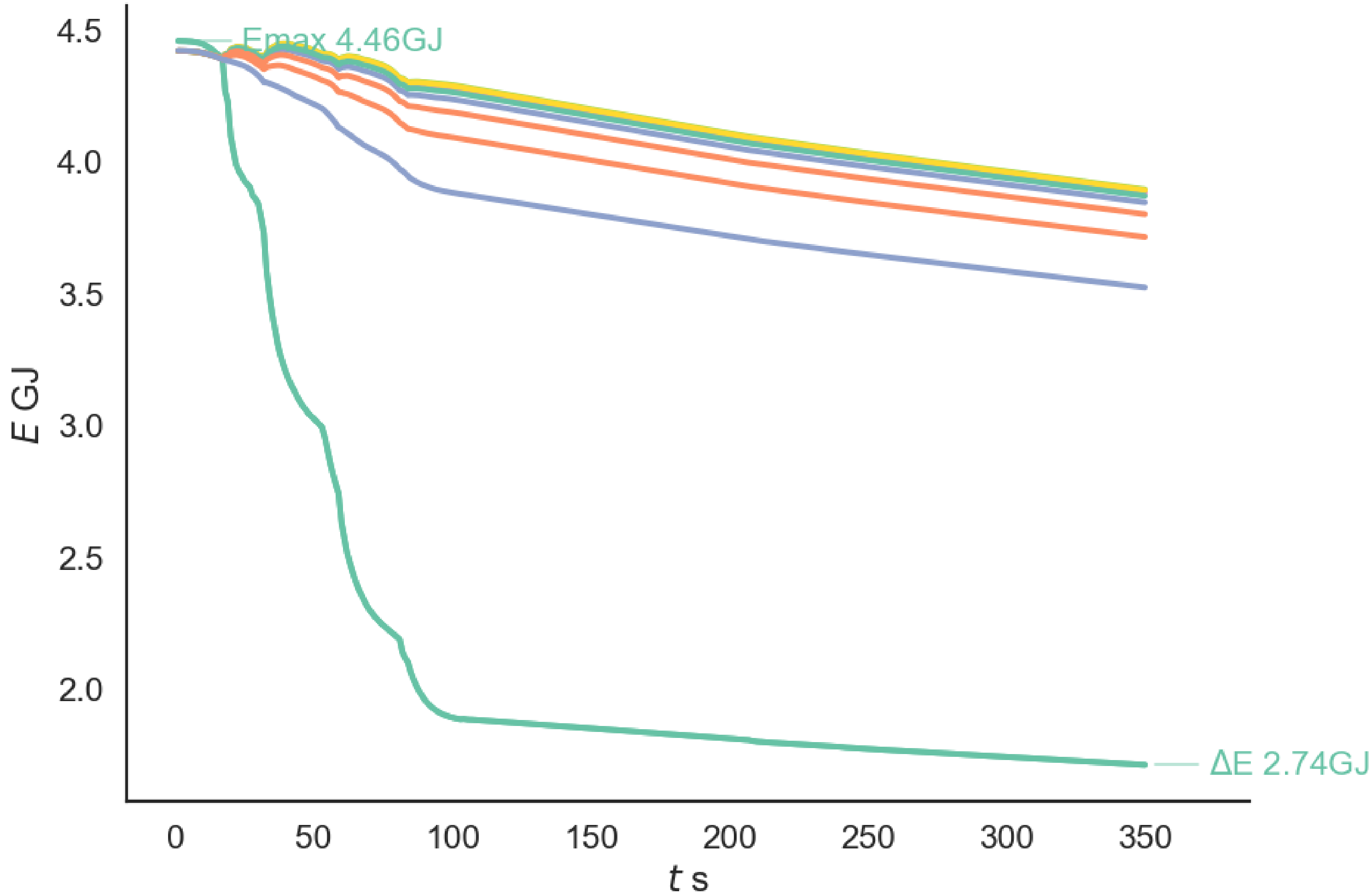

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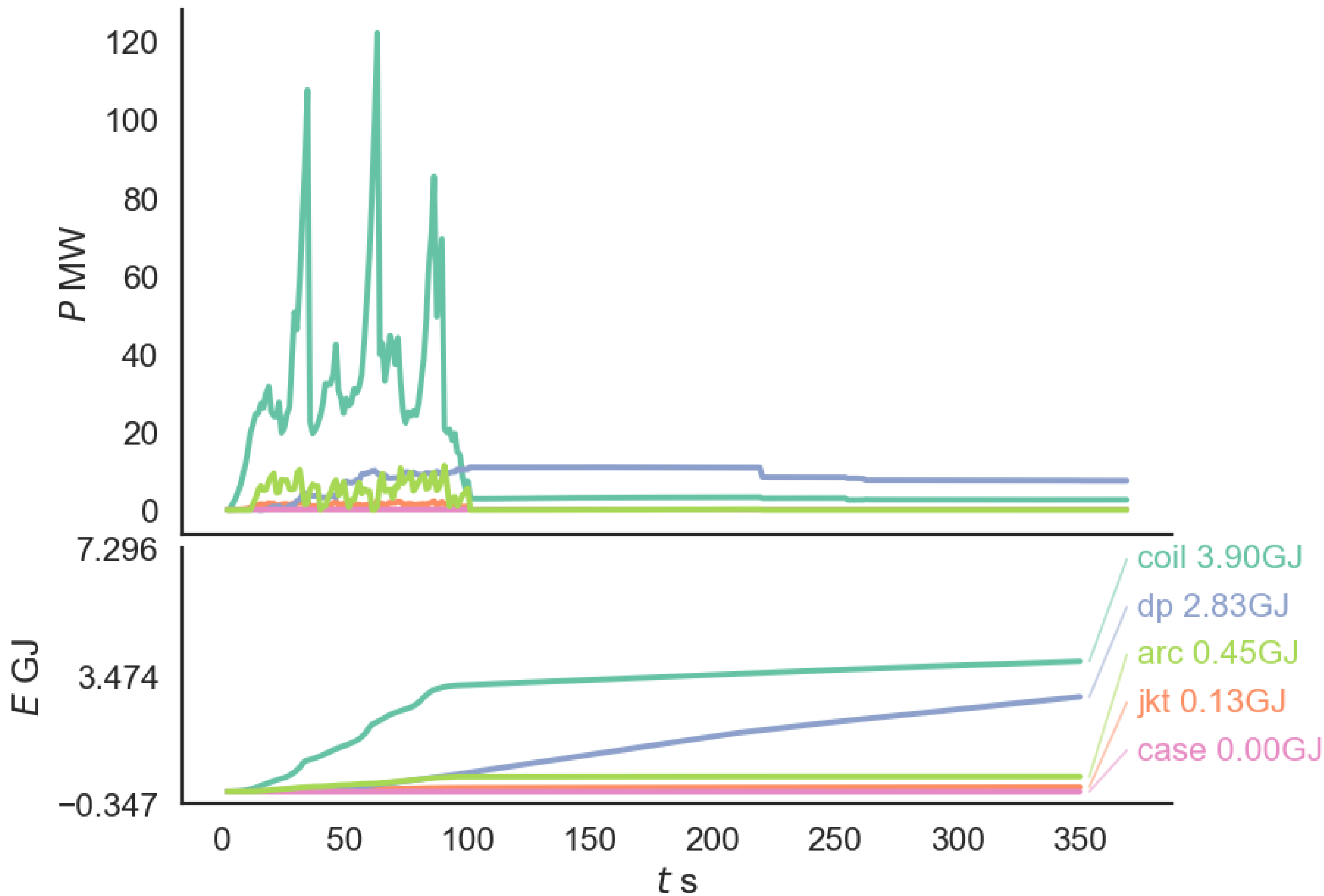

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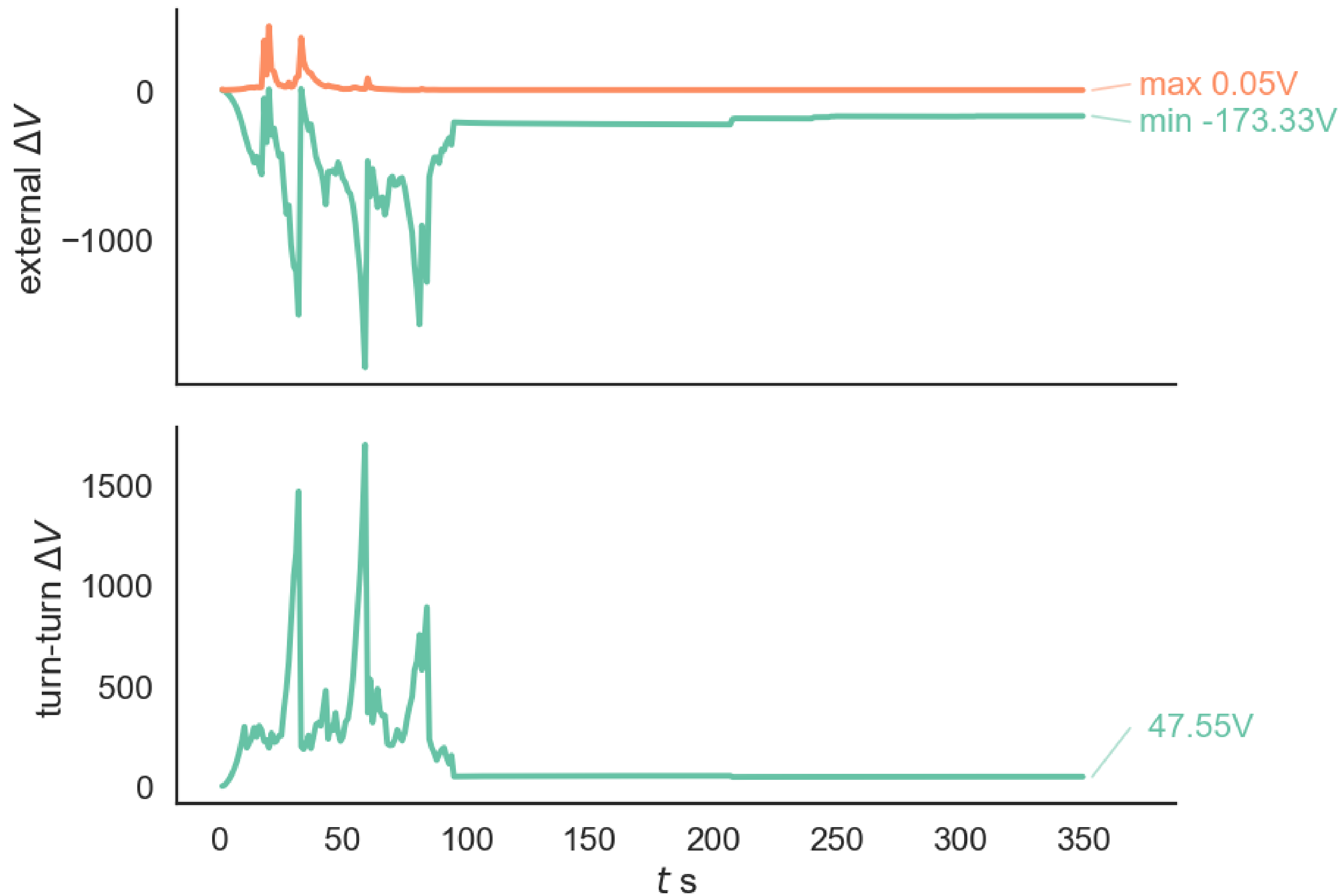

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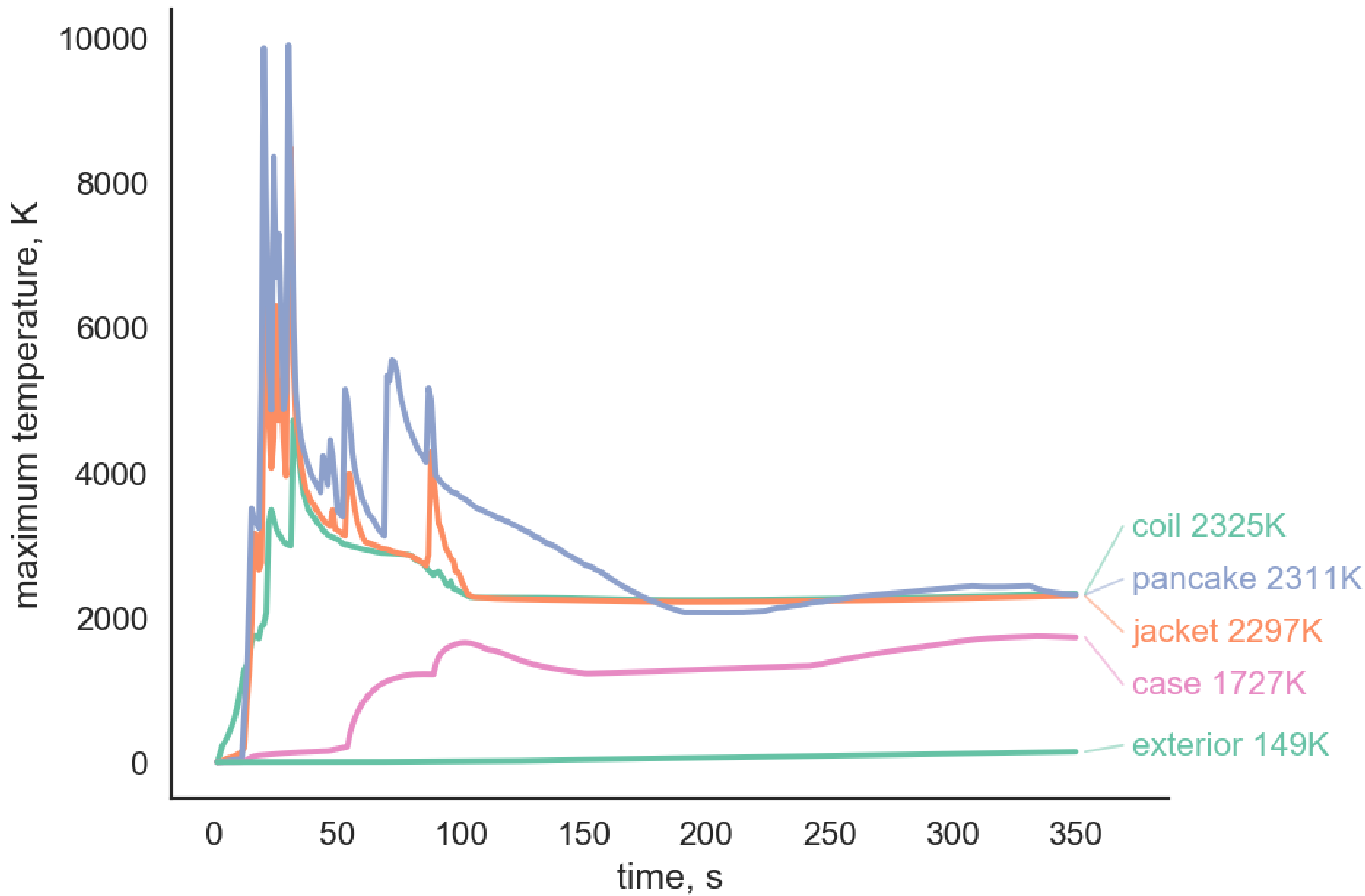
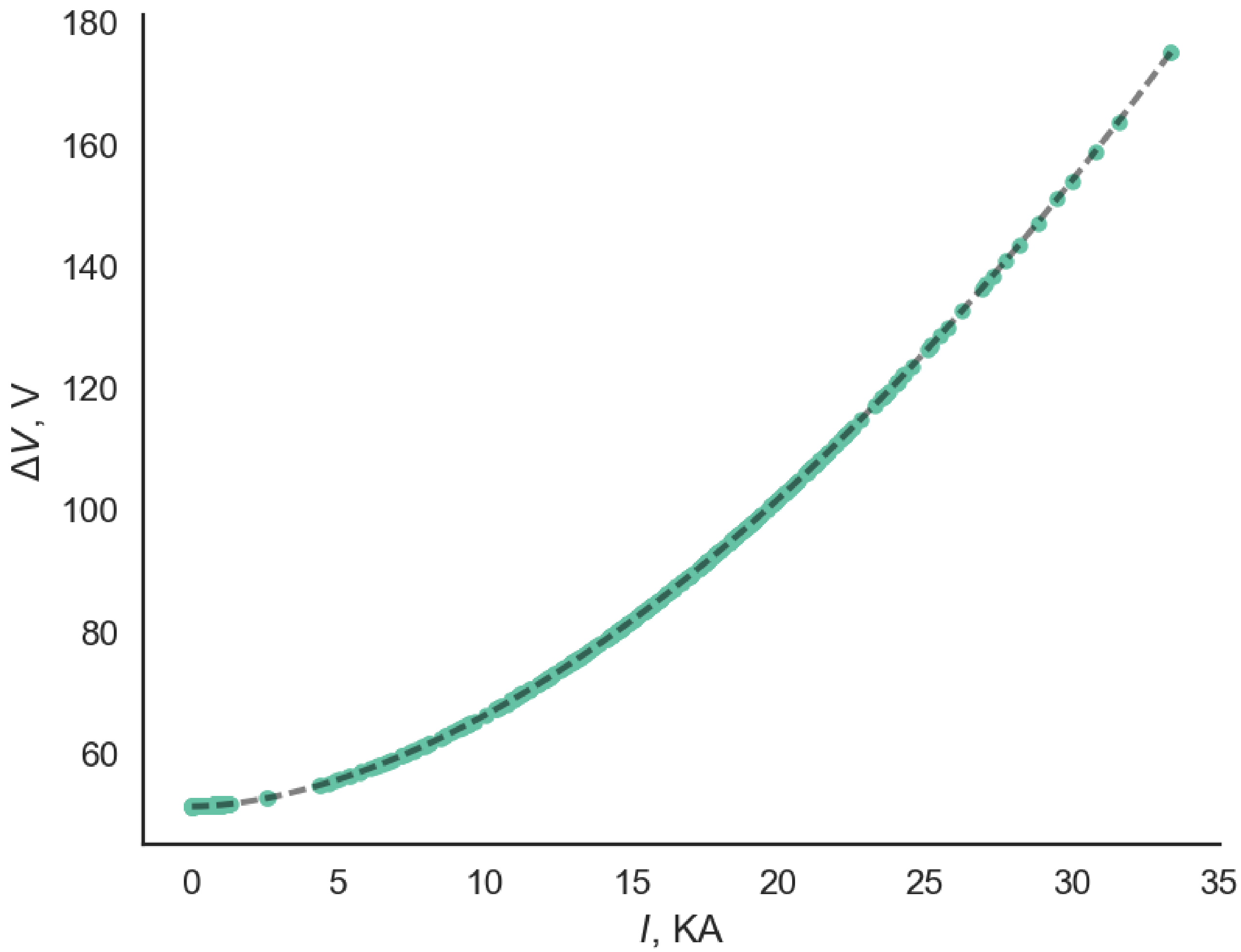
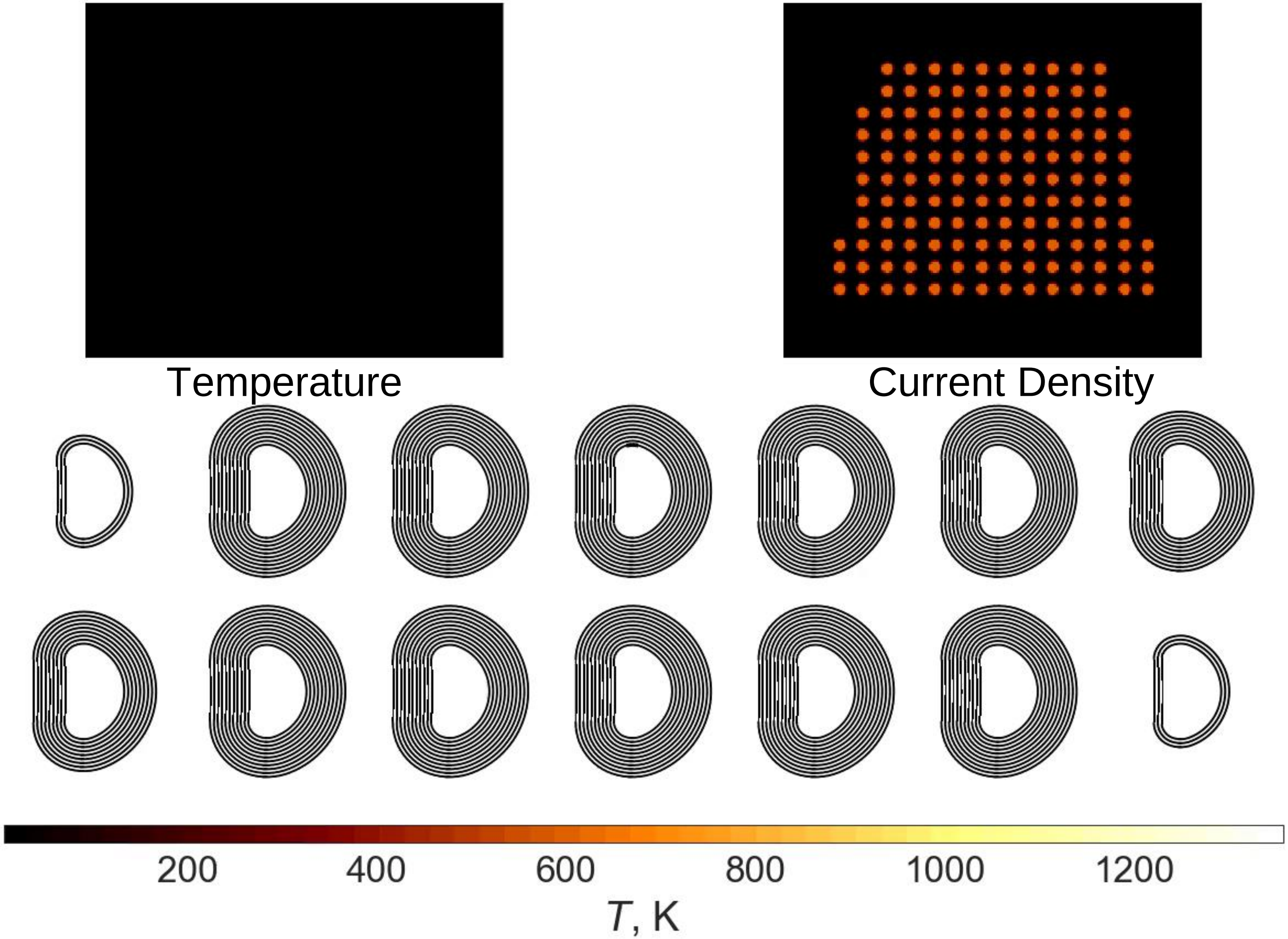


Simulation 2 - MagArc reference (melt short-circuits enabled)



Simulation 3 - TF reference



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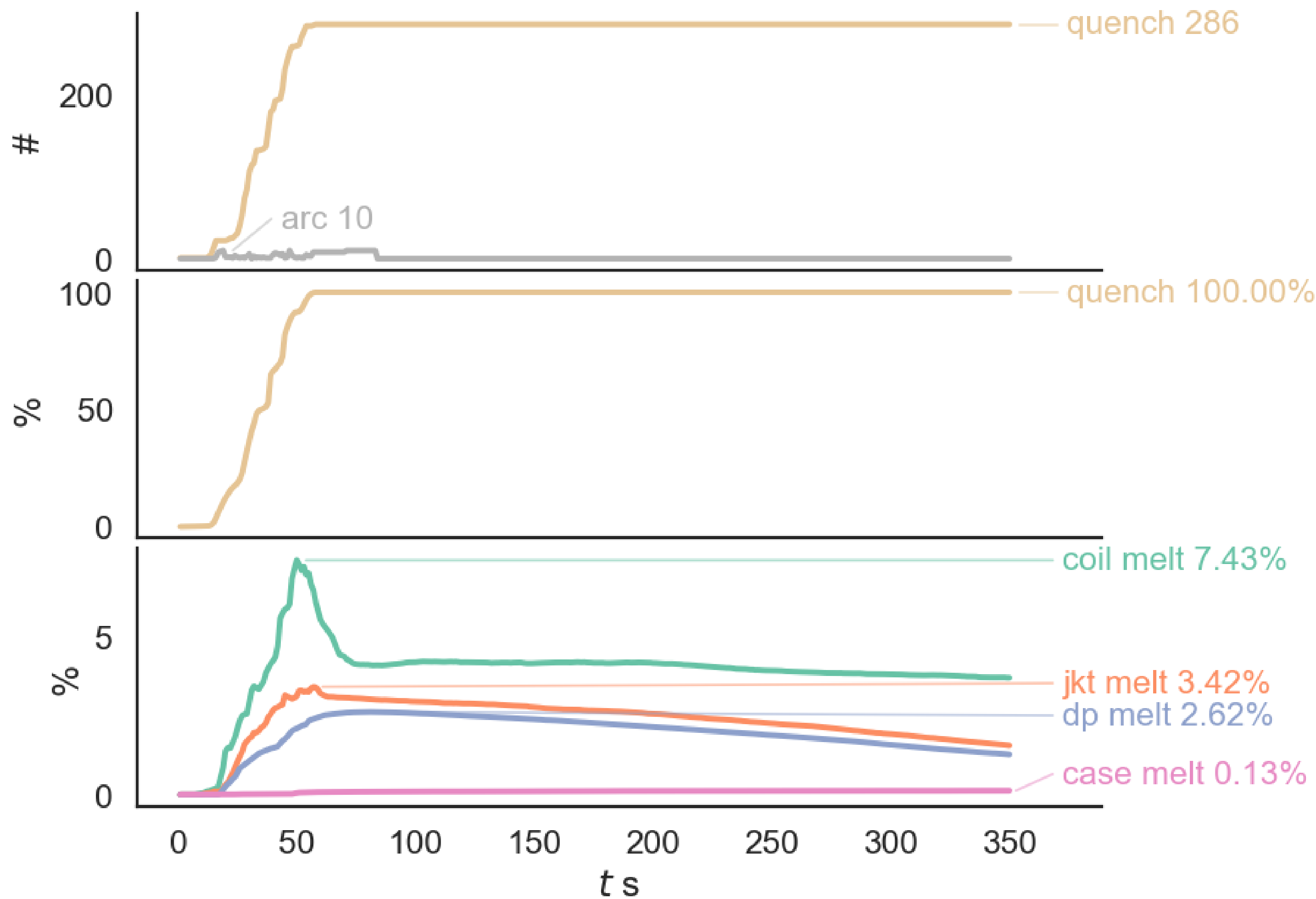

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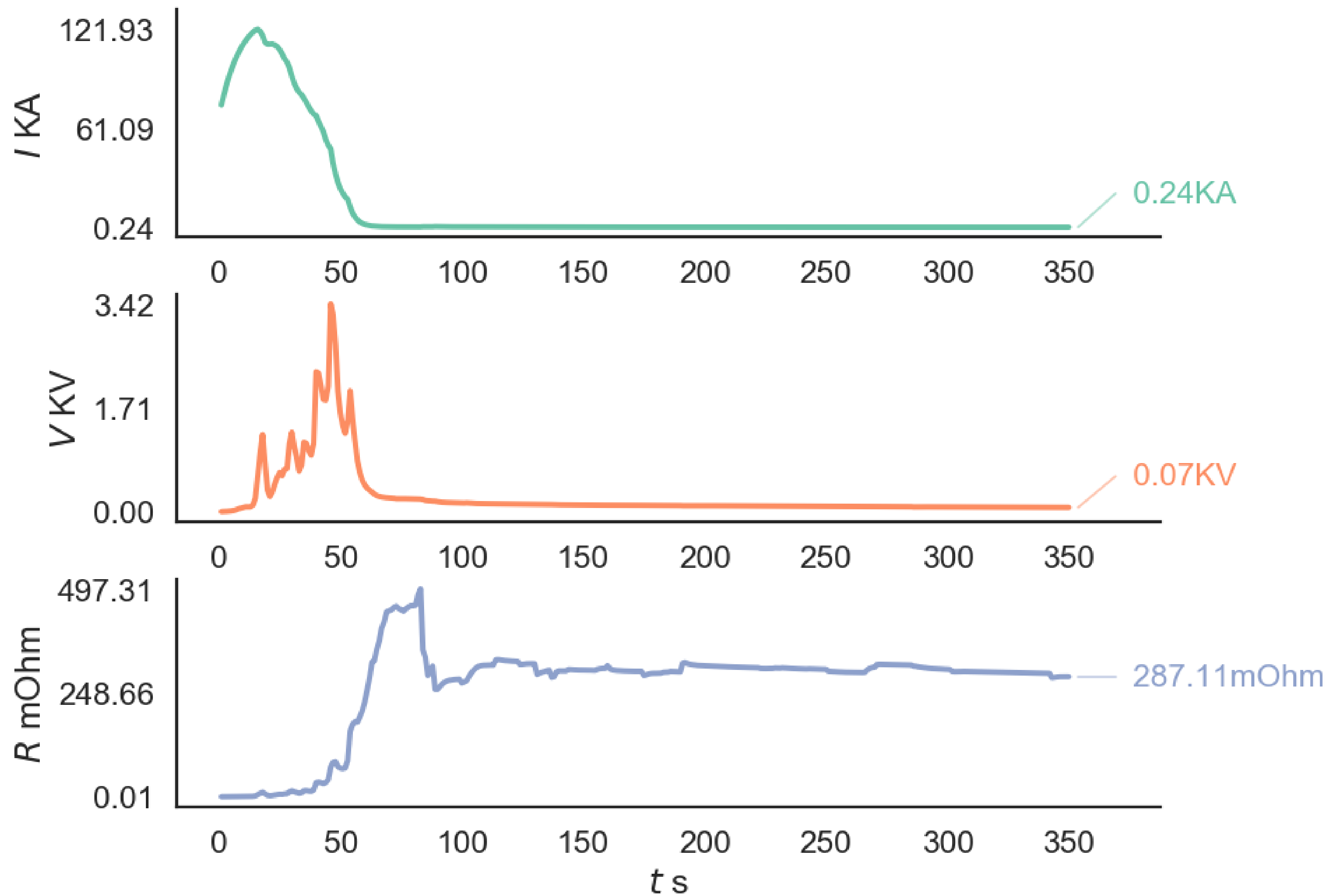

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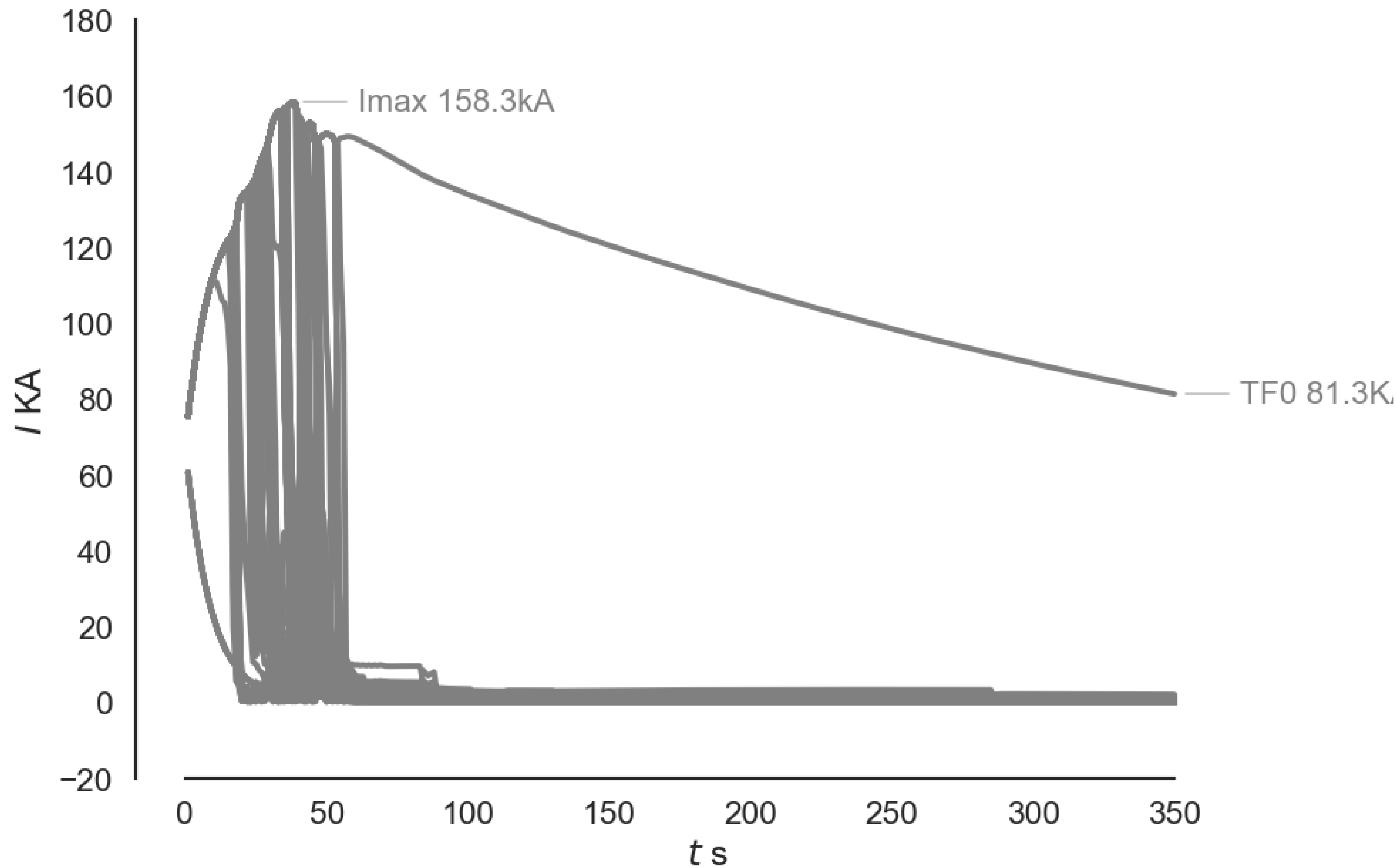
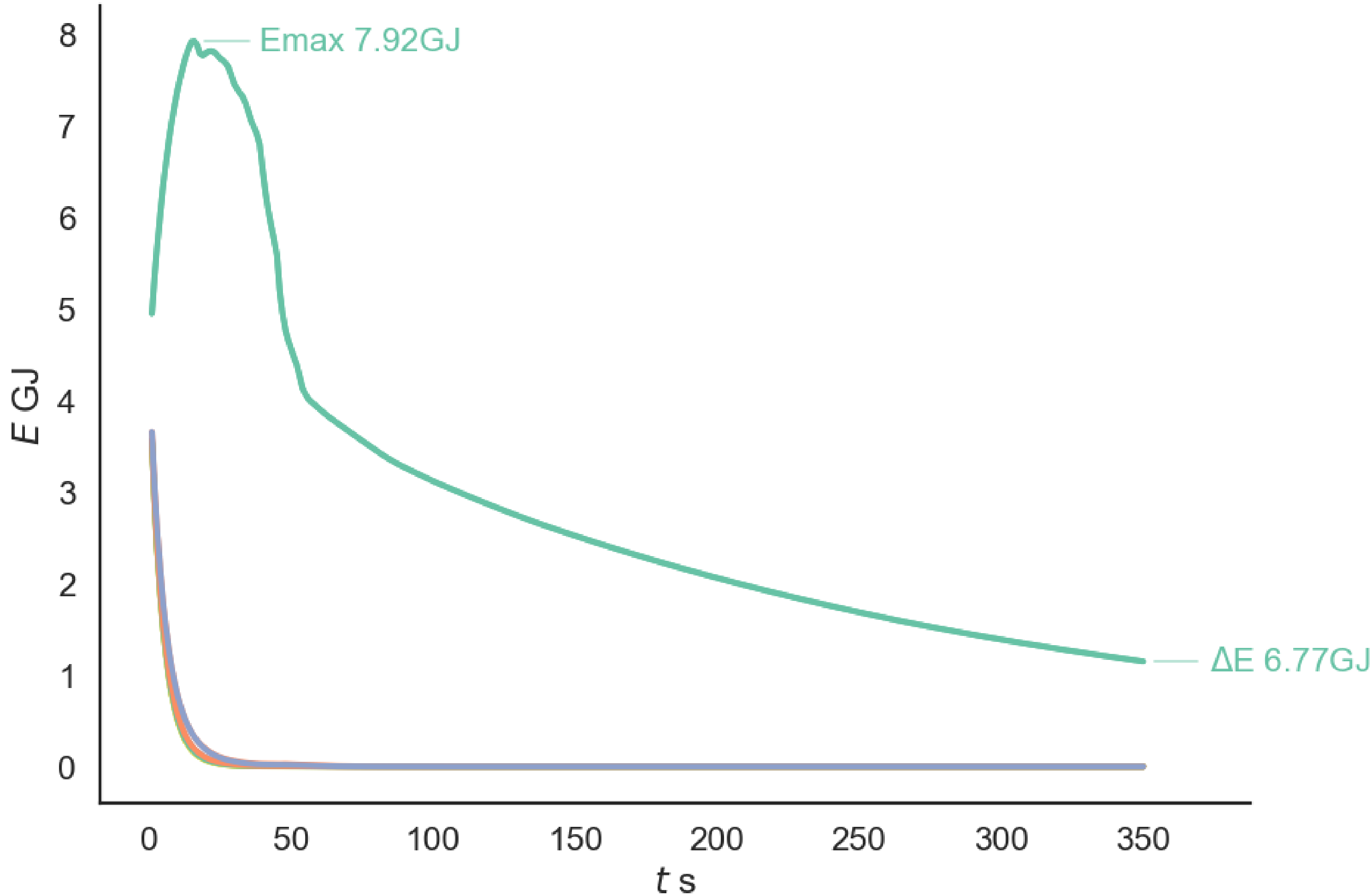
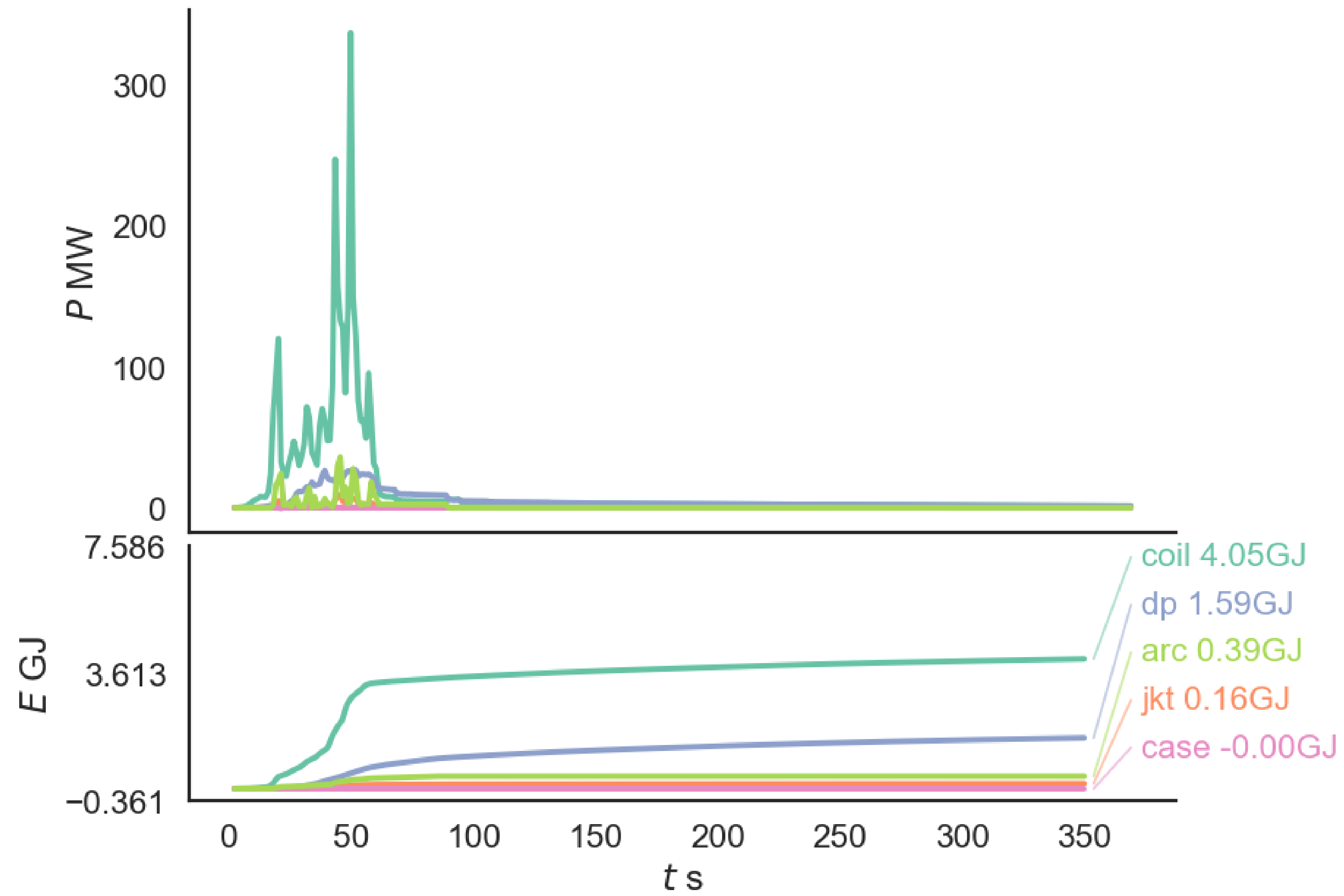


Simulation 3 - TF reference



Simulation 3 - TF reference



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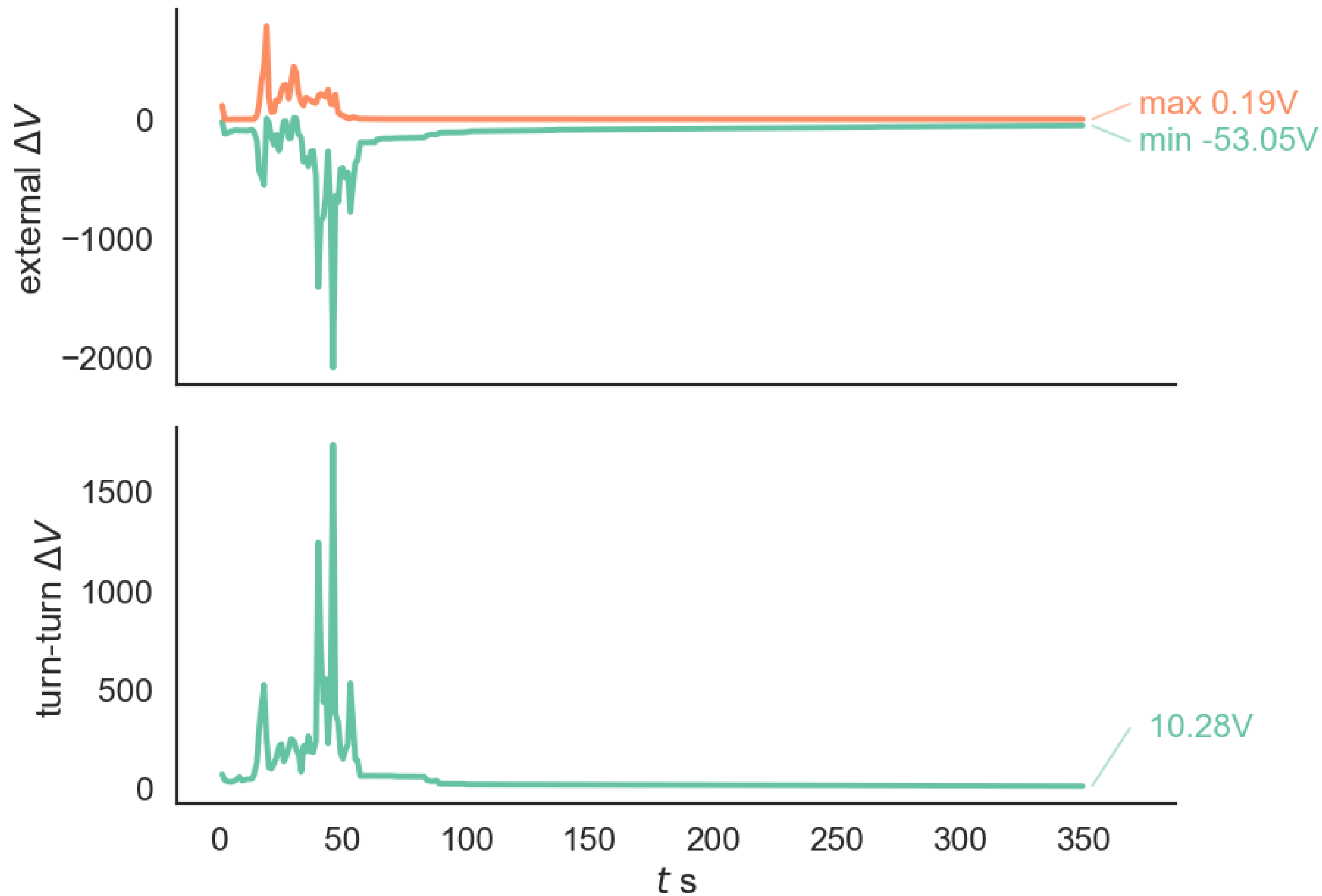

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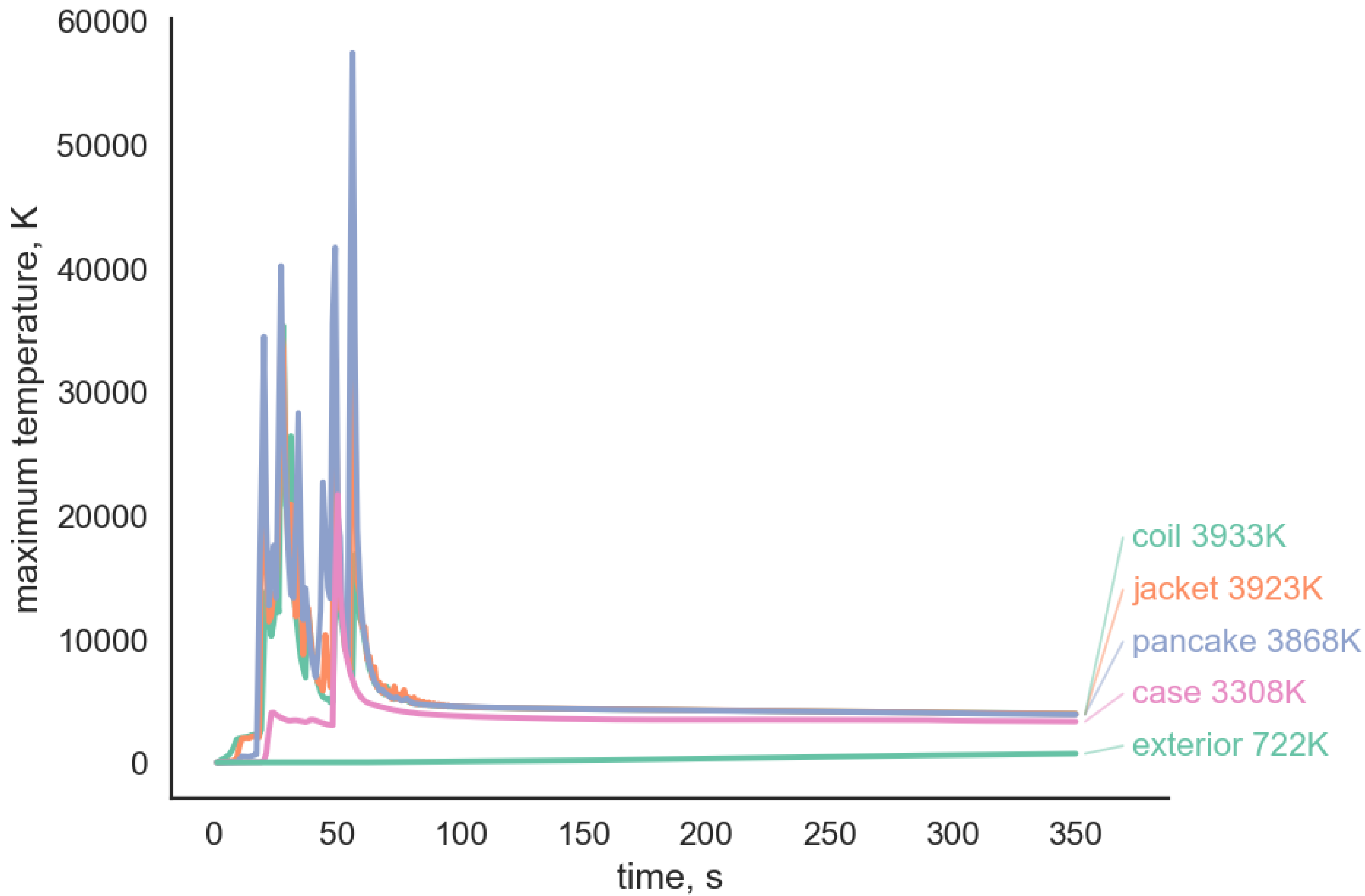
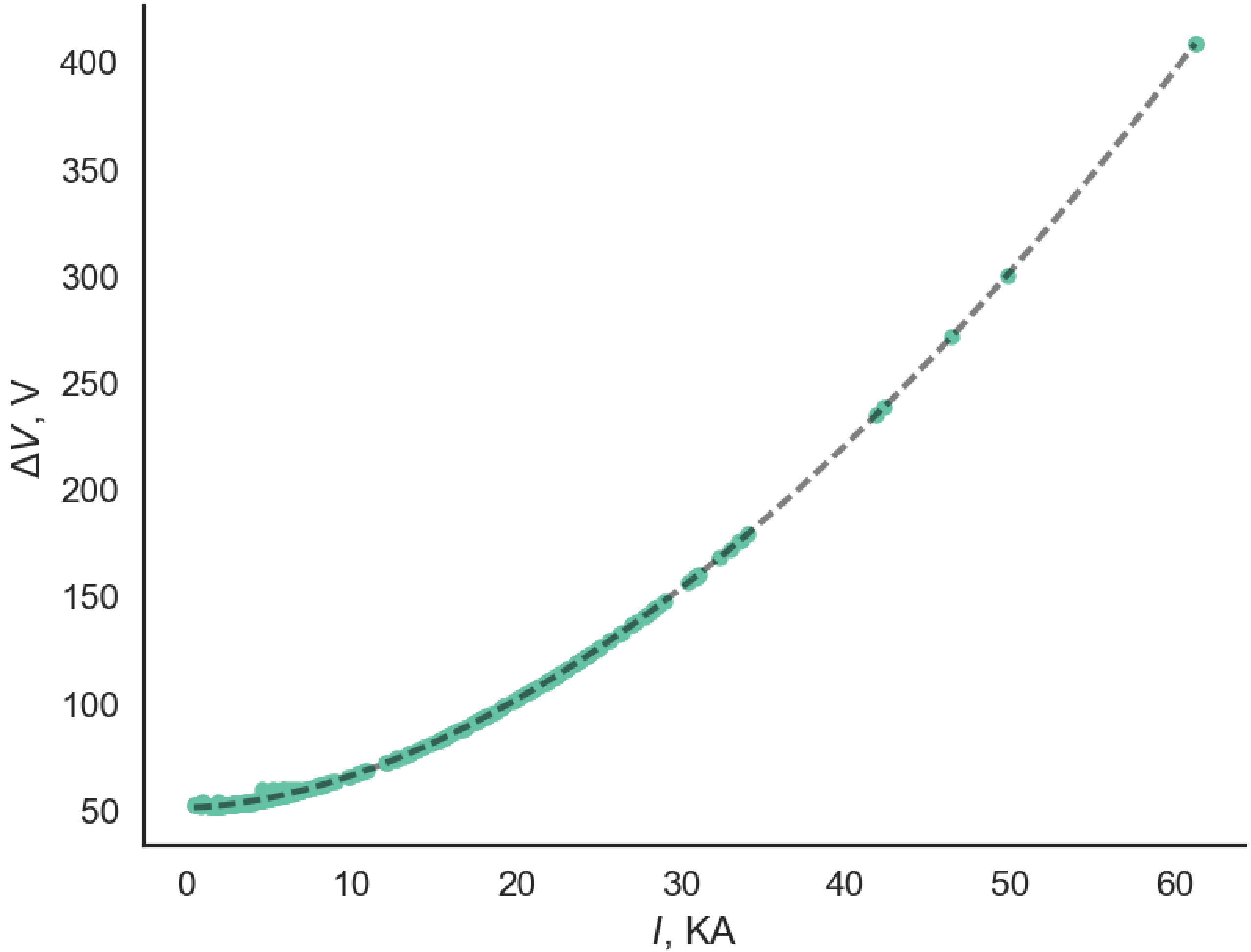
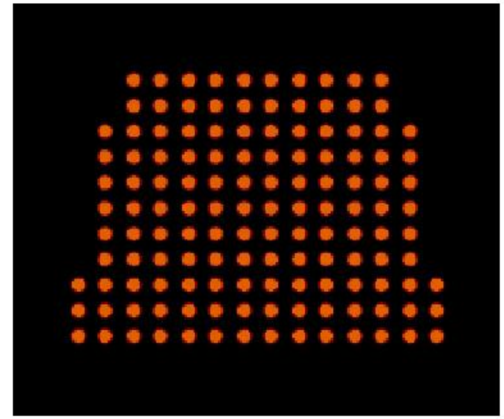


Simulation 3 - TF reference

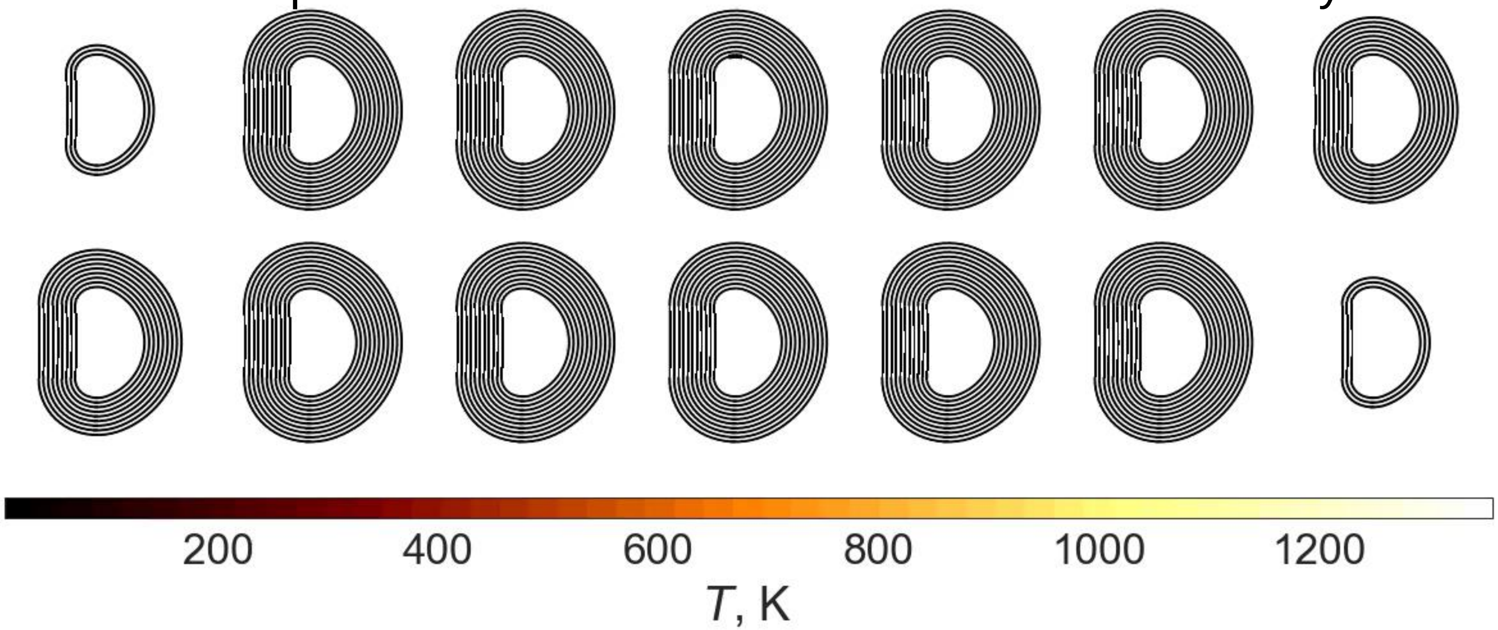


Simulation 4 - TF reference (+ Holmes arc model)

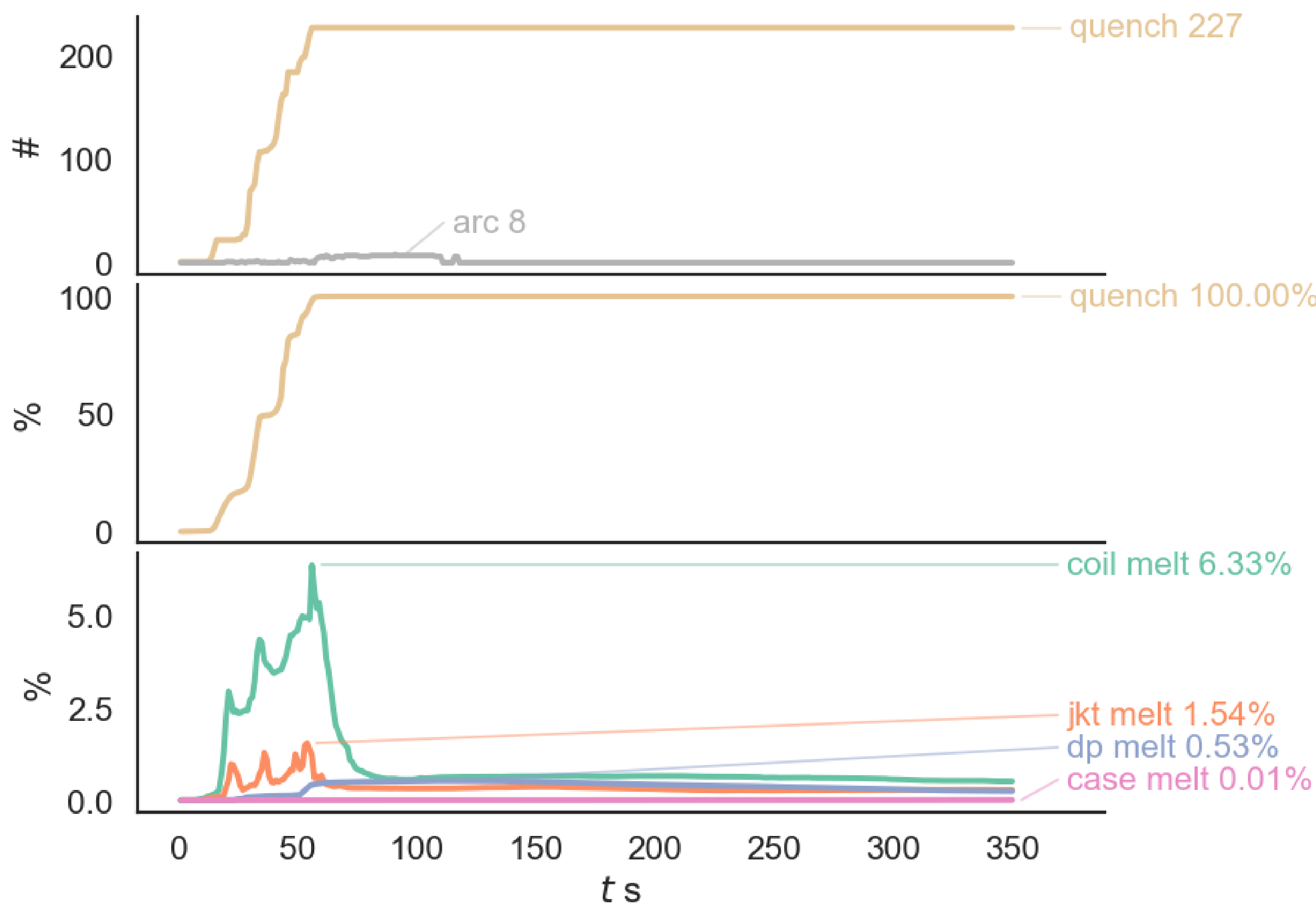
Temperature



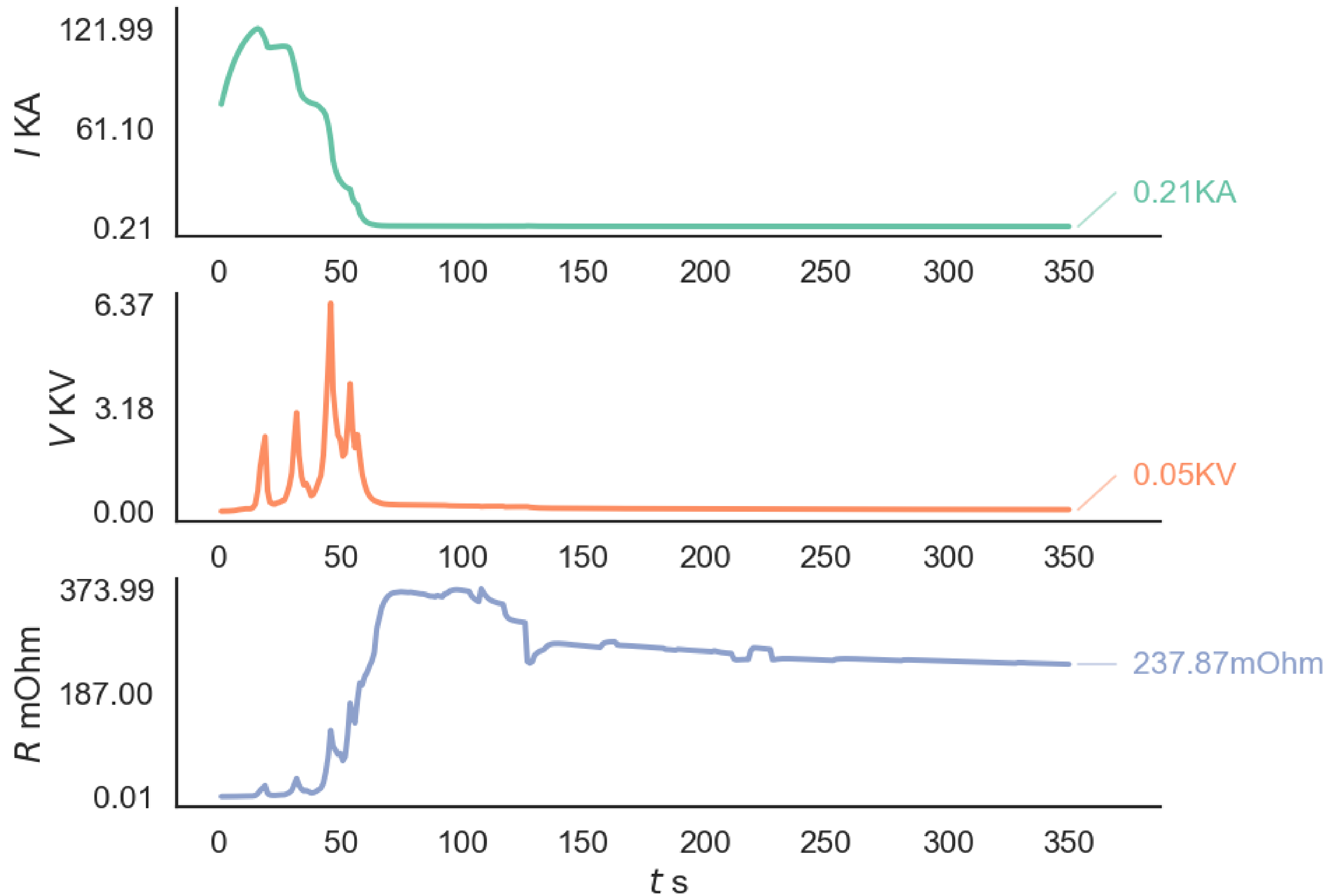
Current Density



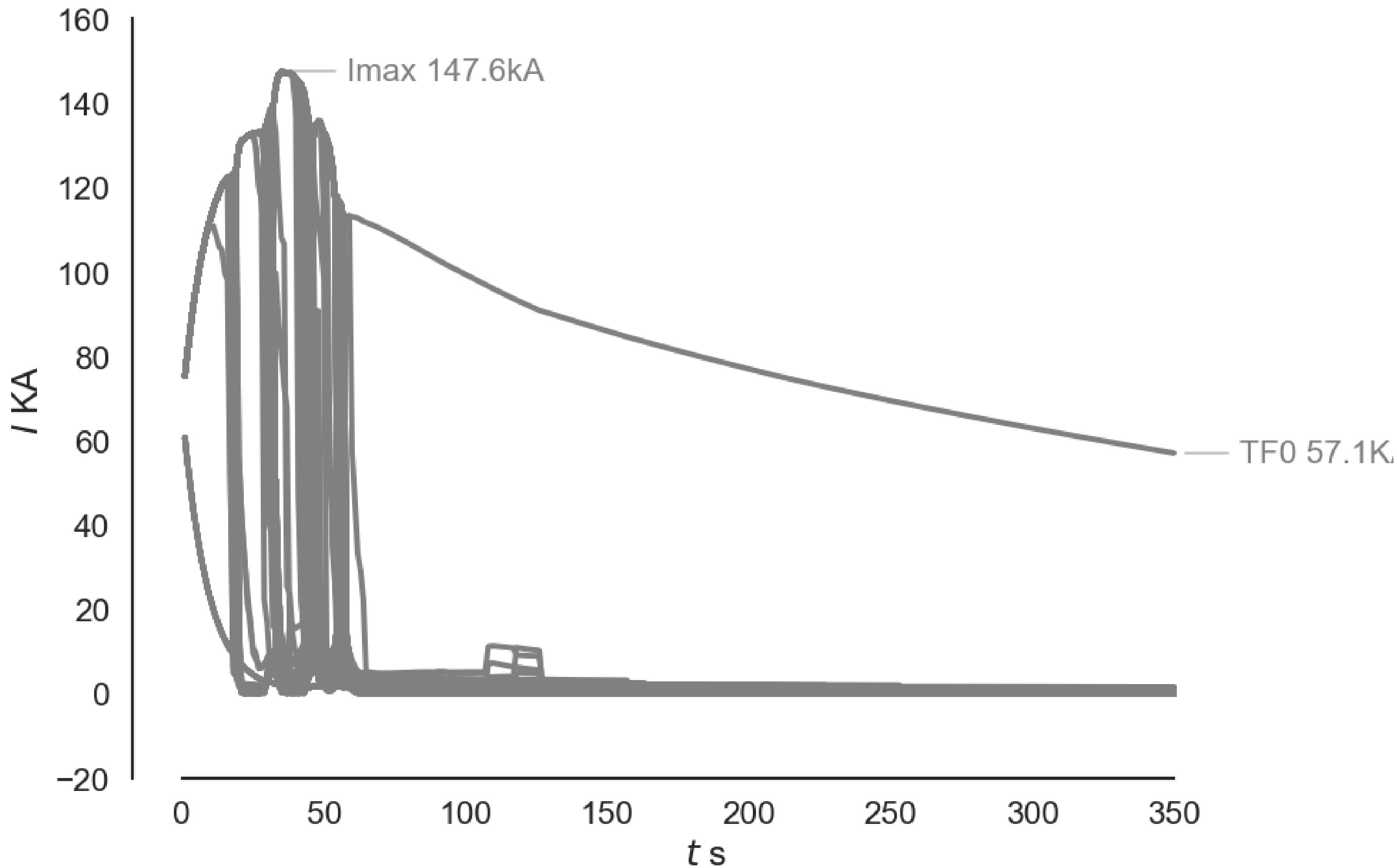
Simulation 4 - TF reference (+ Holmes arc model)



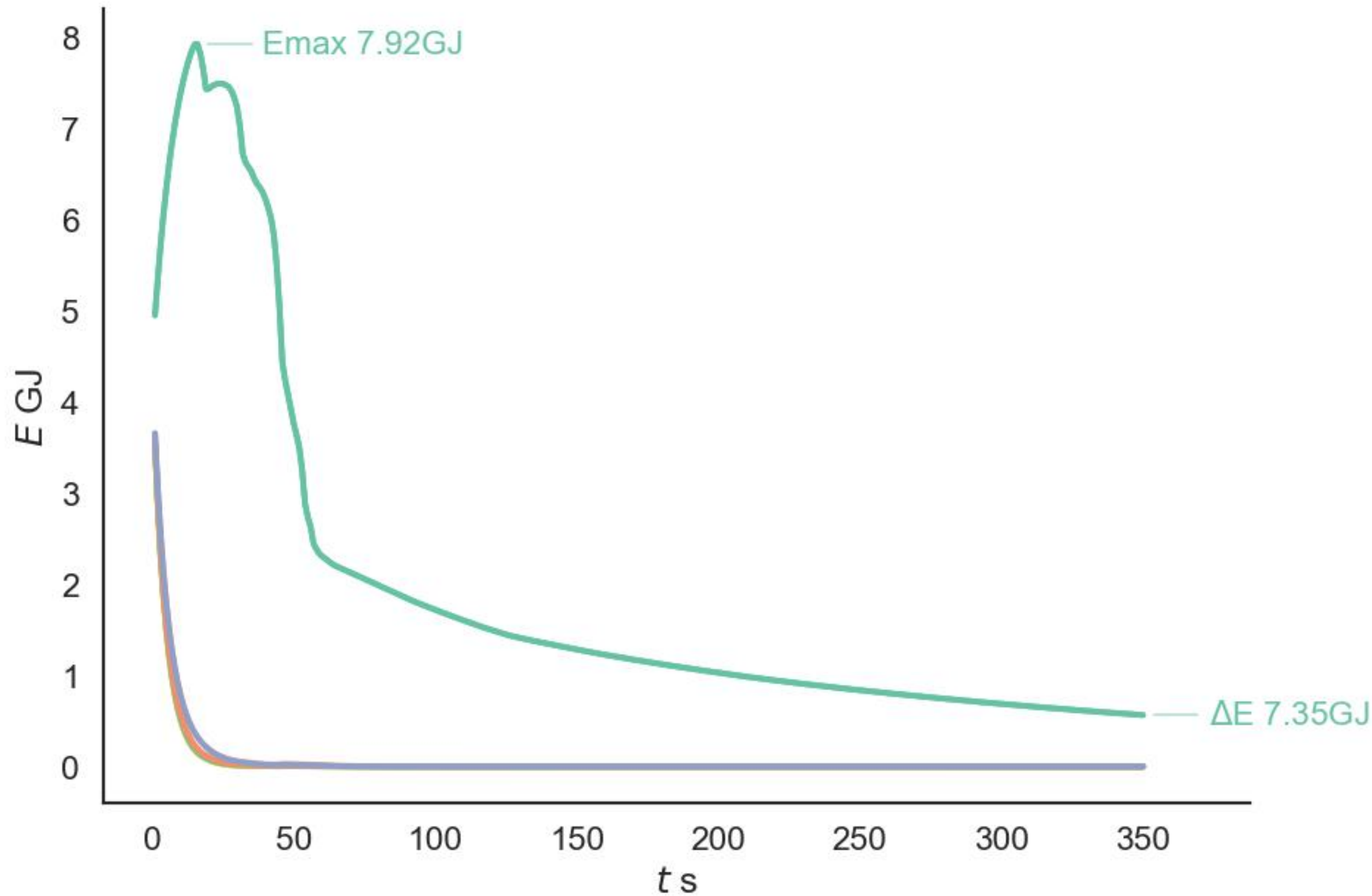
Simulation 4 - TF reference (+ Holmes arc model)



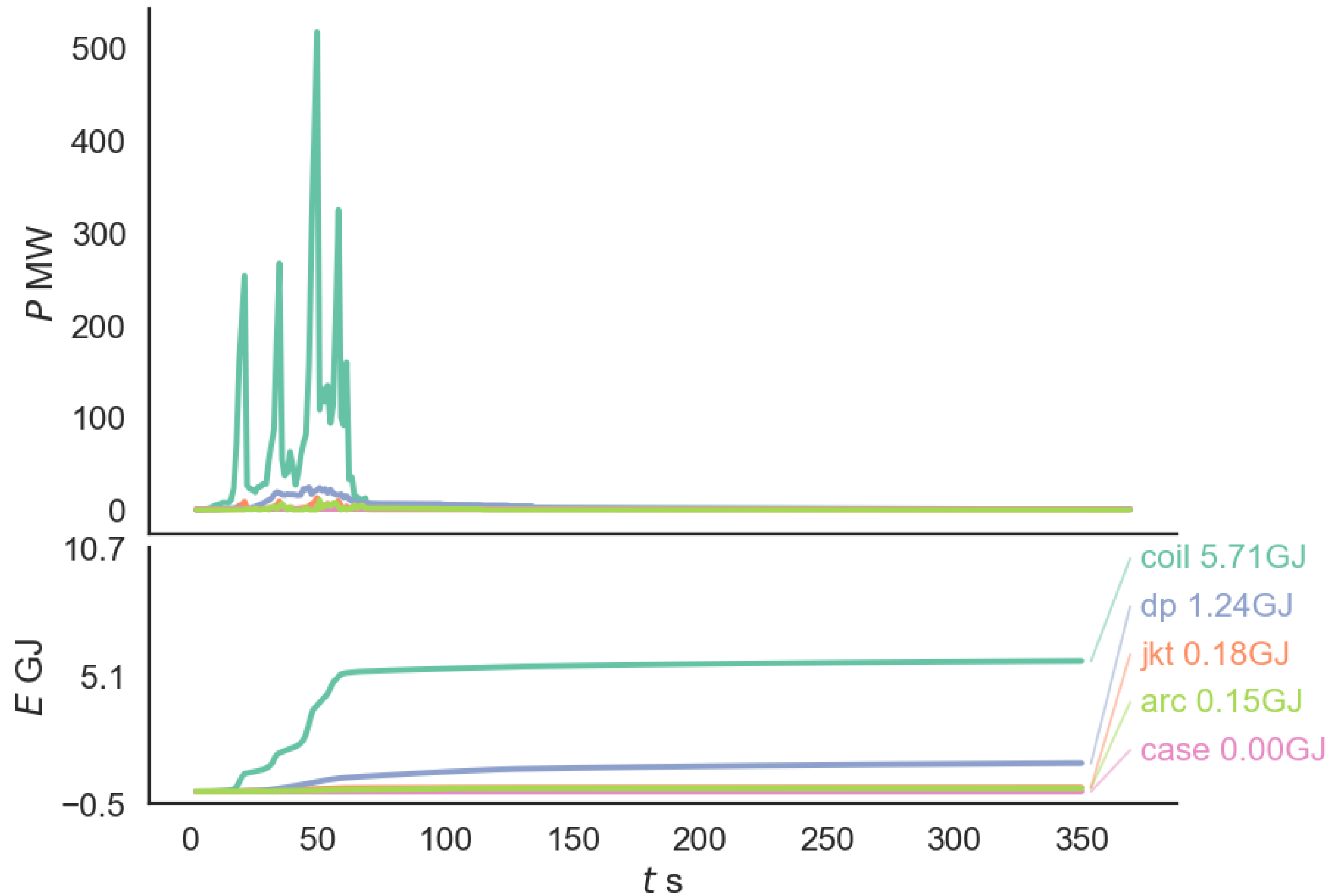
Simulation 4 - TF reference (+ Holmes arc model)



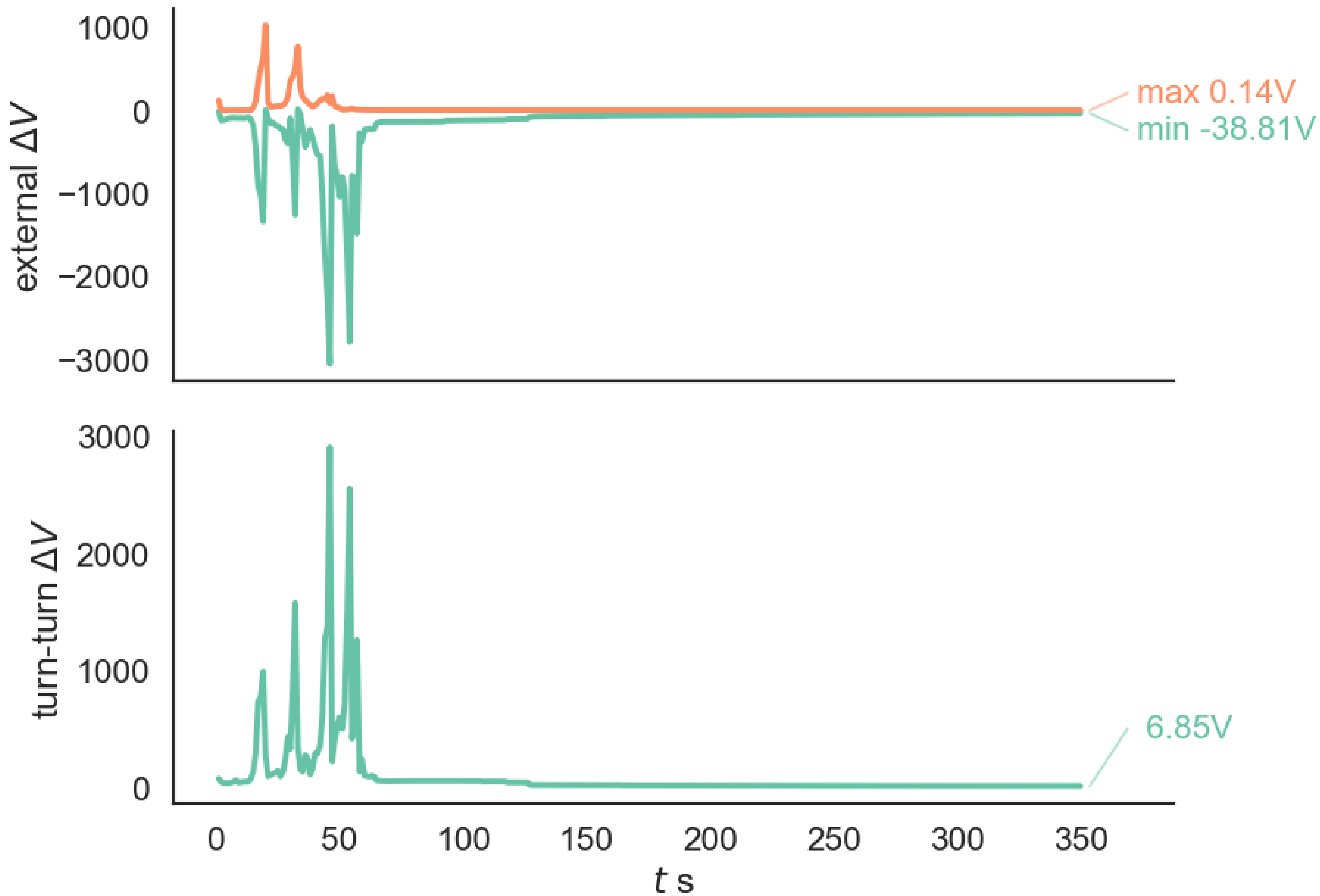
Simulation 4 - TF reference (+ Holmes arc model)



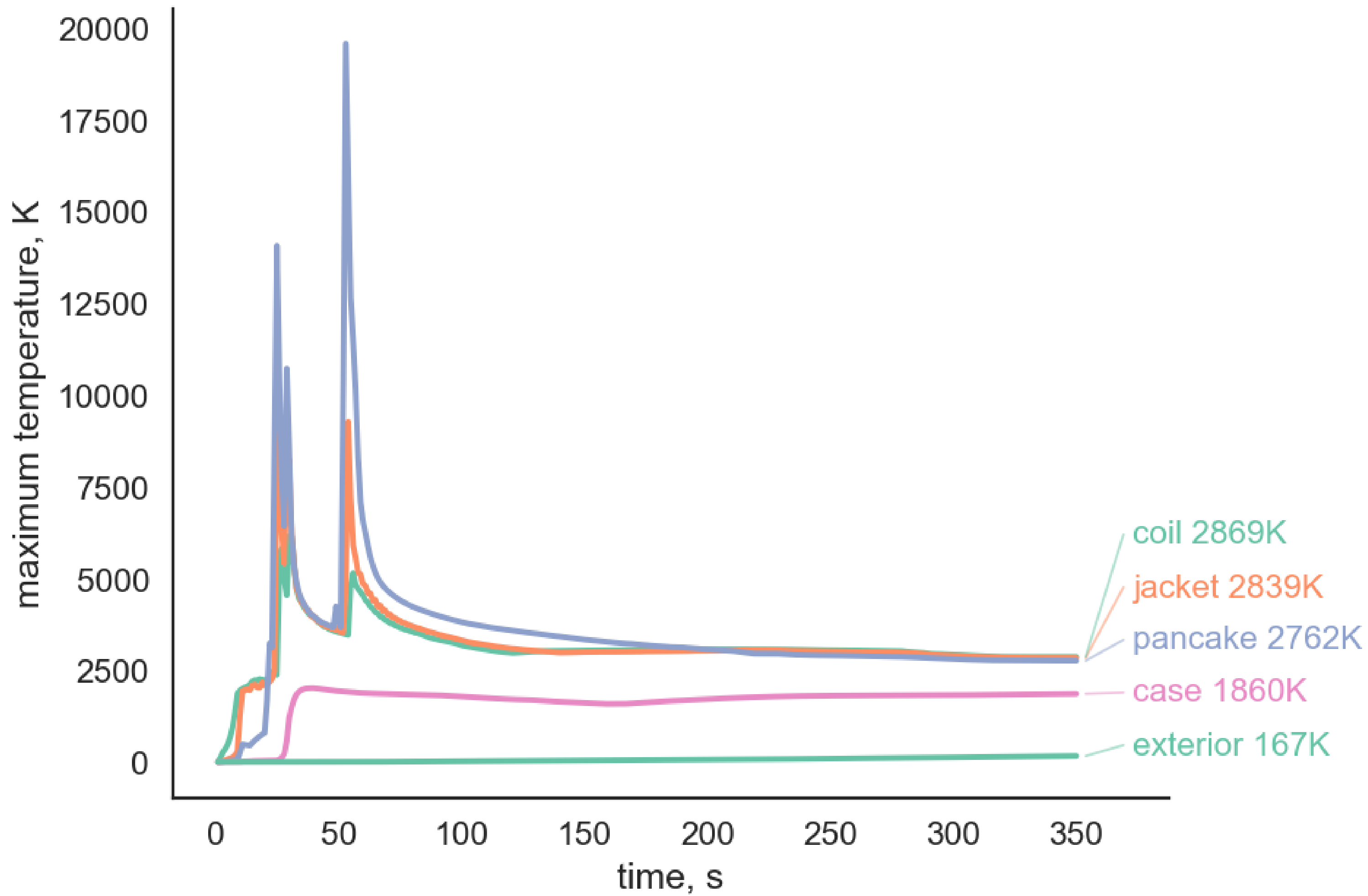
Simulation 4 - TF reference (+ Holmes arc model)



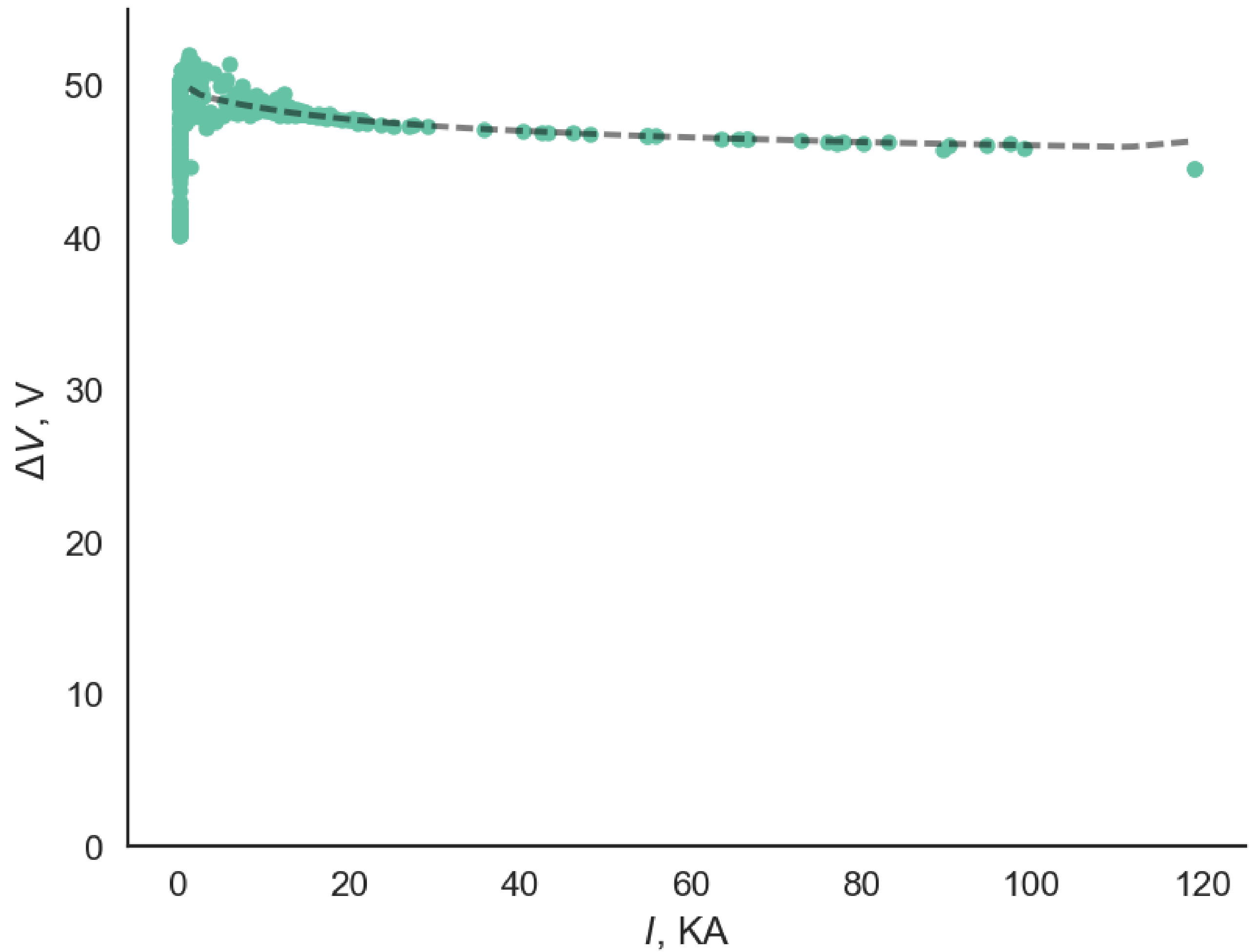
Simulation 4 - TF reference (+ Holmes arc model)



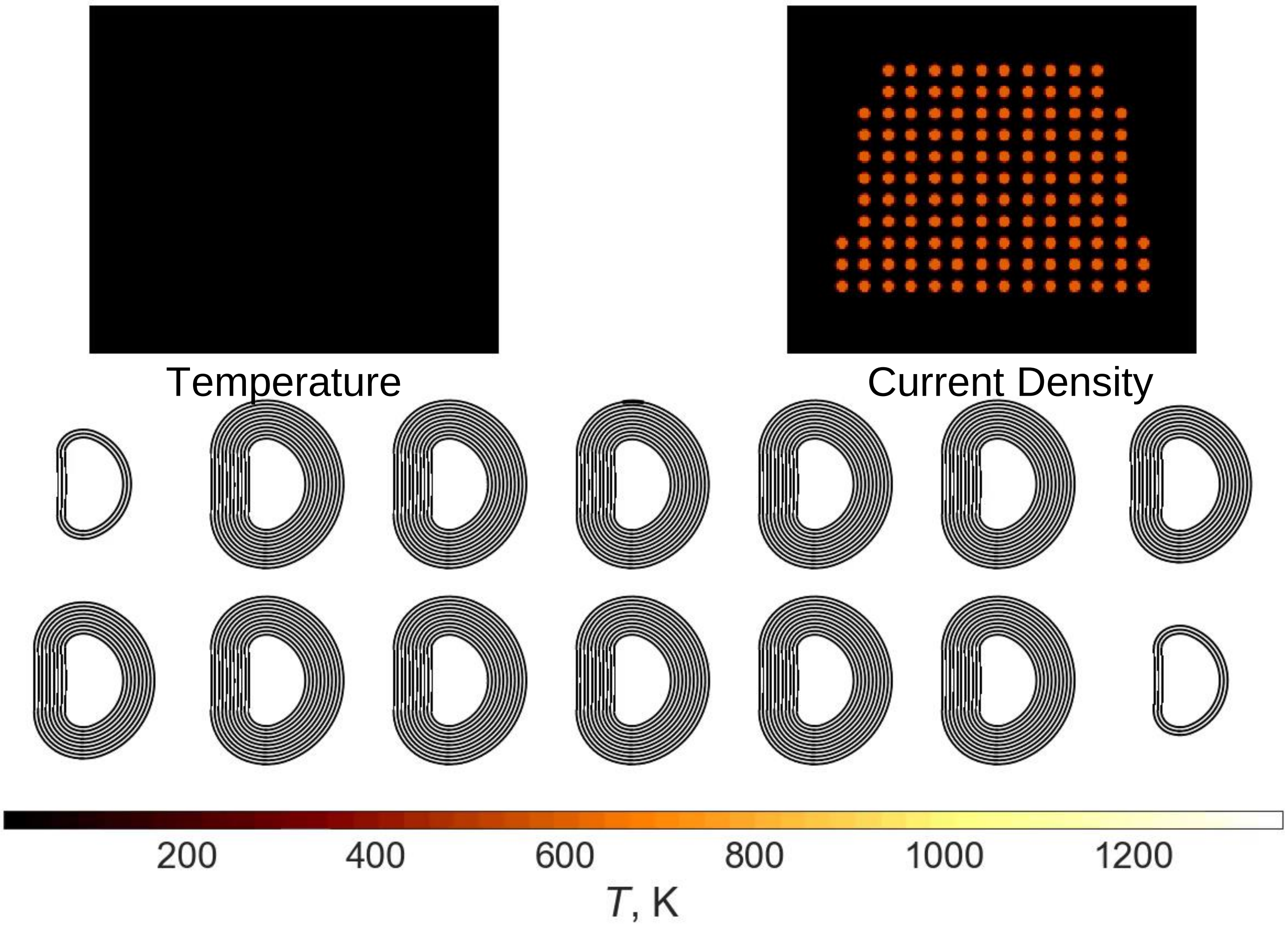
Simulation 4 - TF reference (+ Holmes arc model)



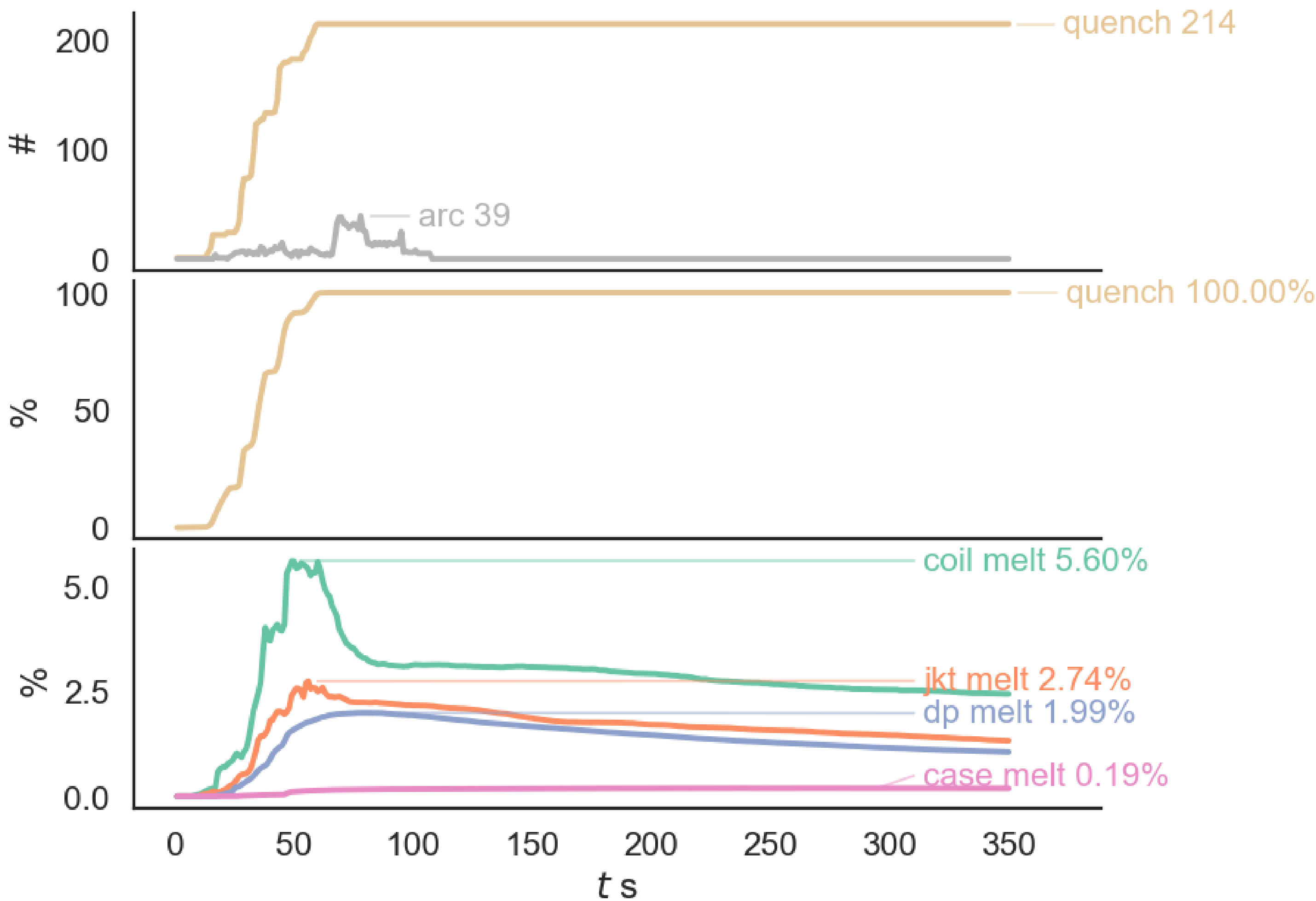
Simulation 4 - TF reference (+ Holmes arc model)



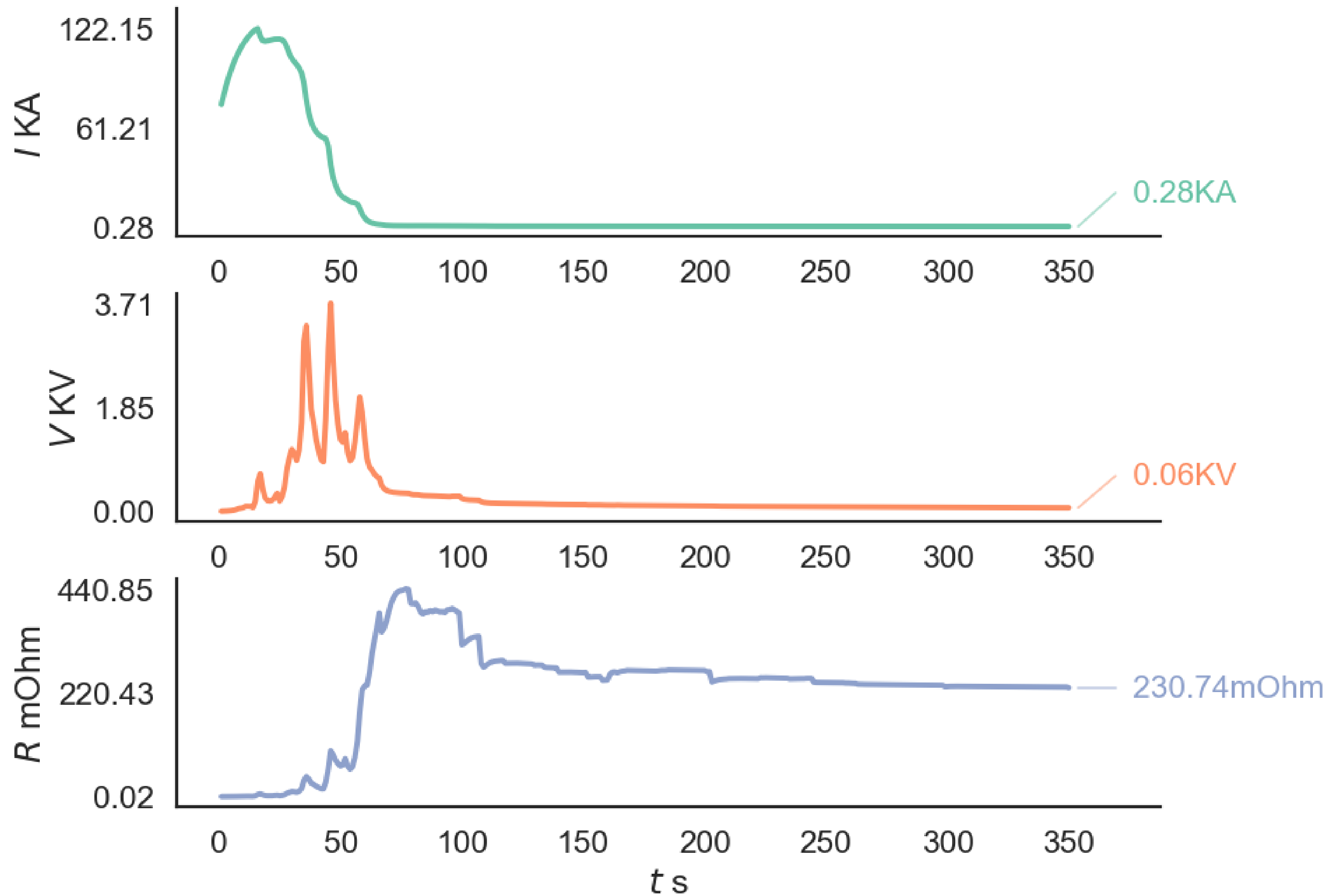
Simulation 5 - TF reference (+ outer turn initiation)



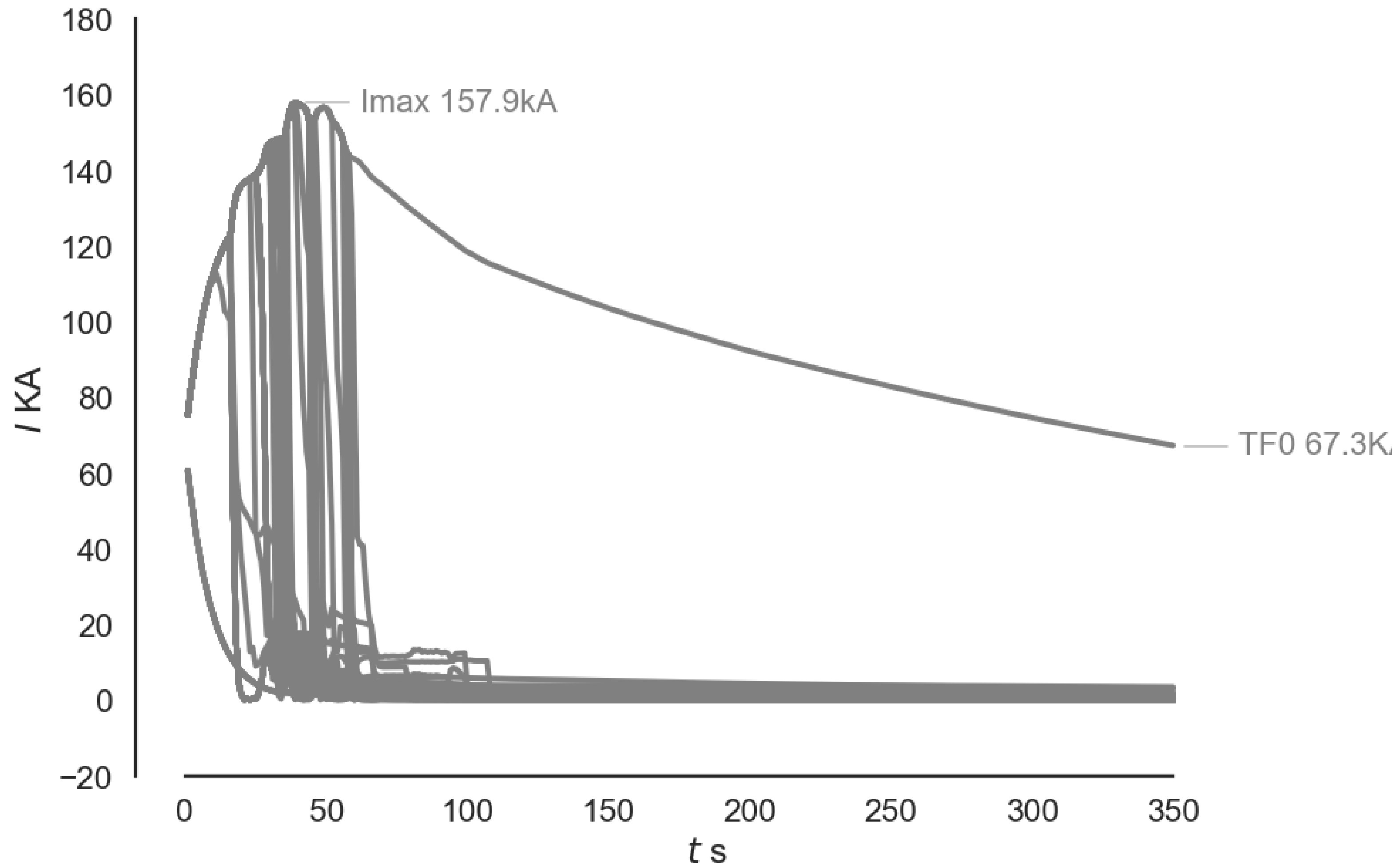
Simulation 5 - TF reference (+ outer turn initiation)



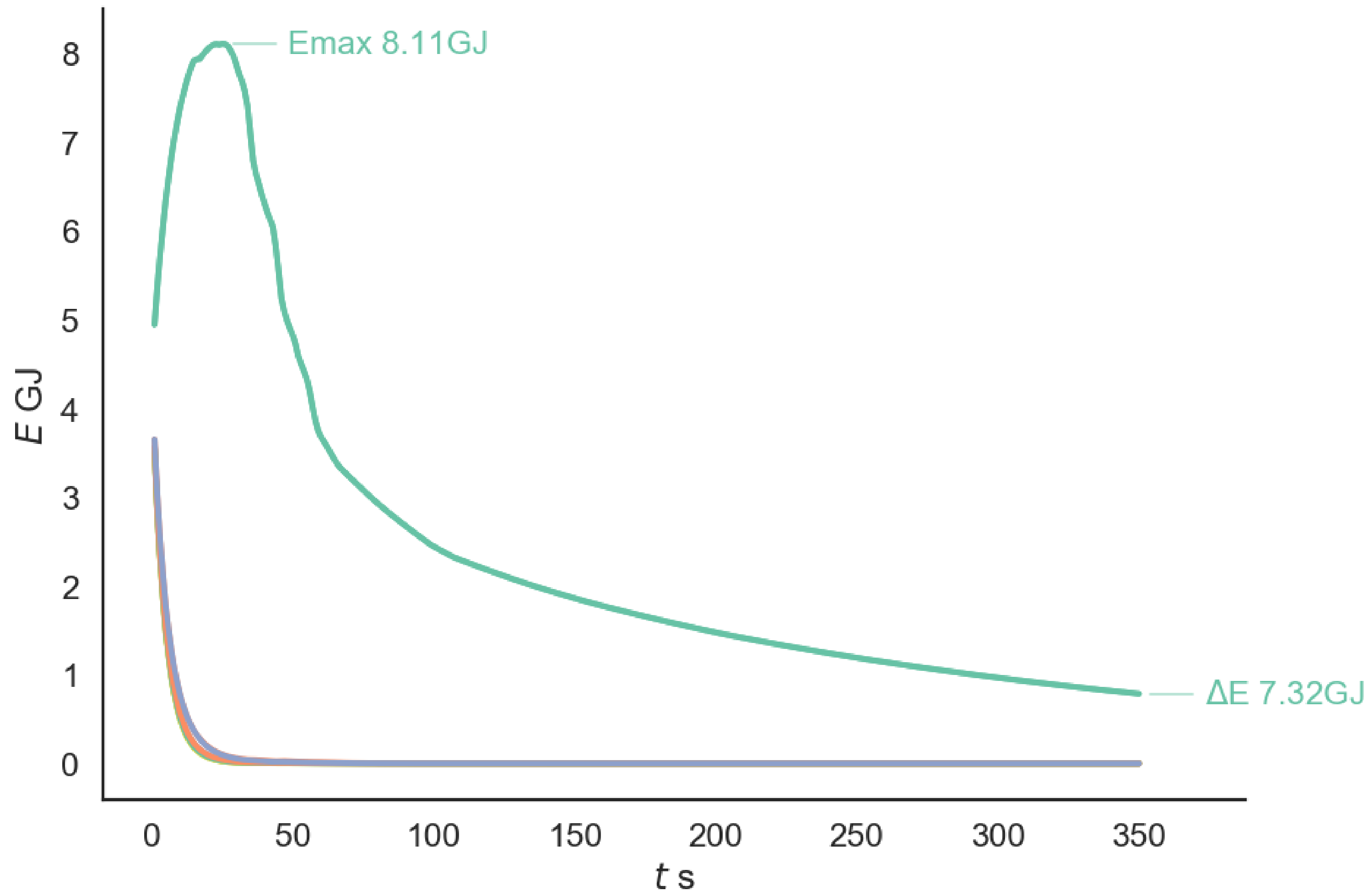
Simulation 5 - TF reference (+ outer turn initiation)



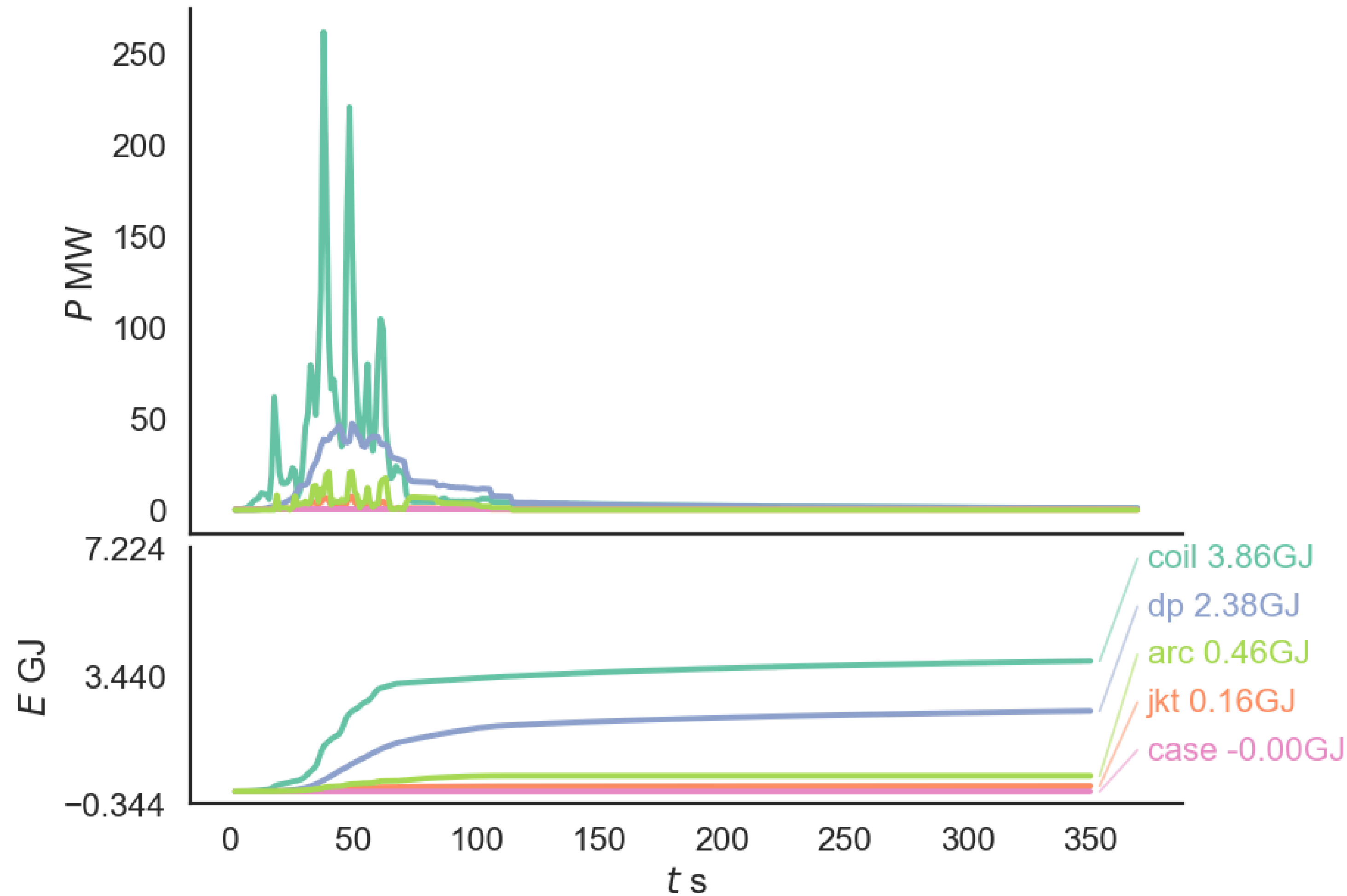
Simulation 5 - TF reference (+ outer turn initiation)



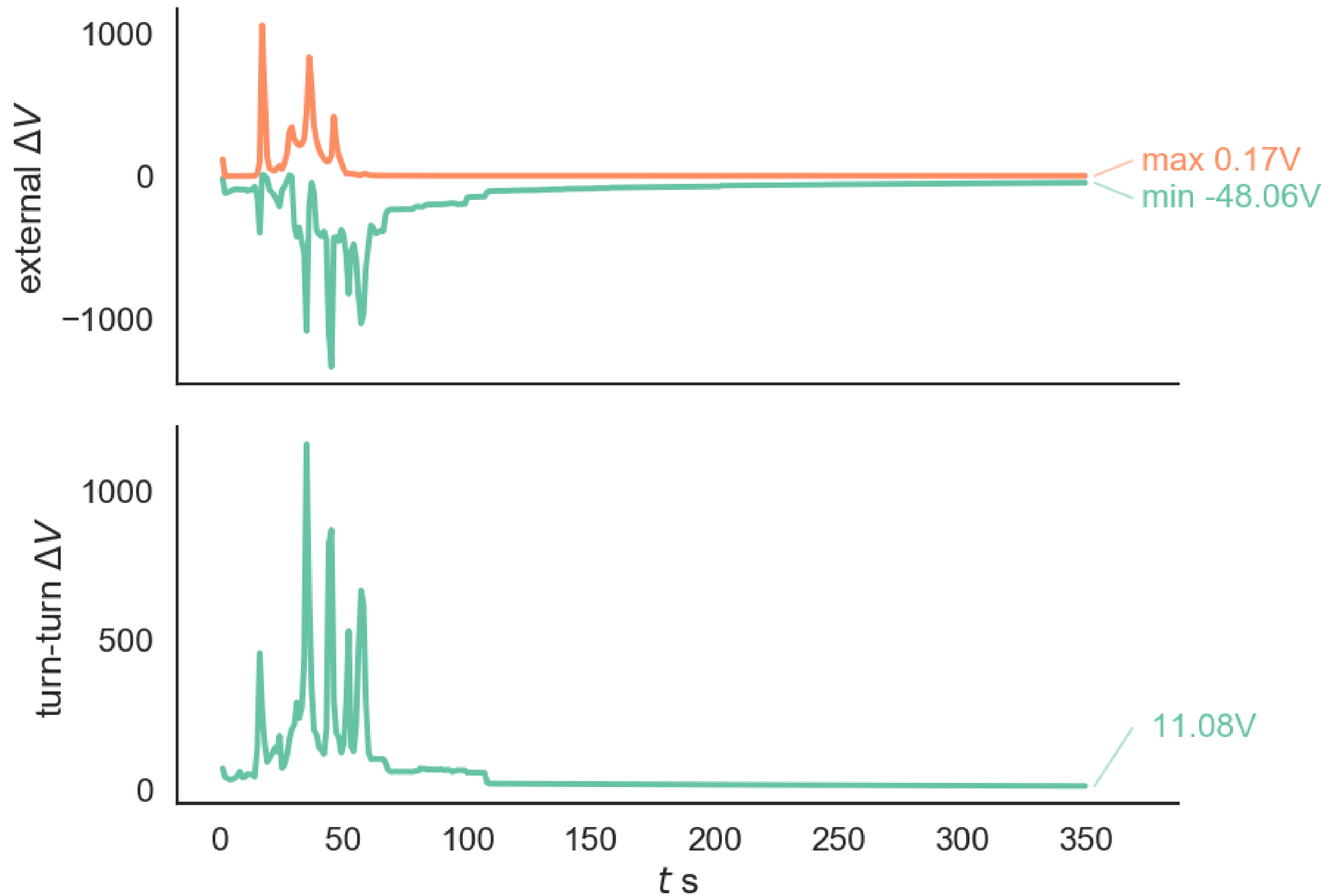
Simulation 5 - TF reference (+ outer turn initiation)



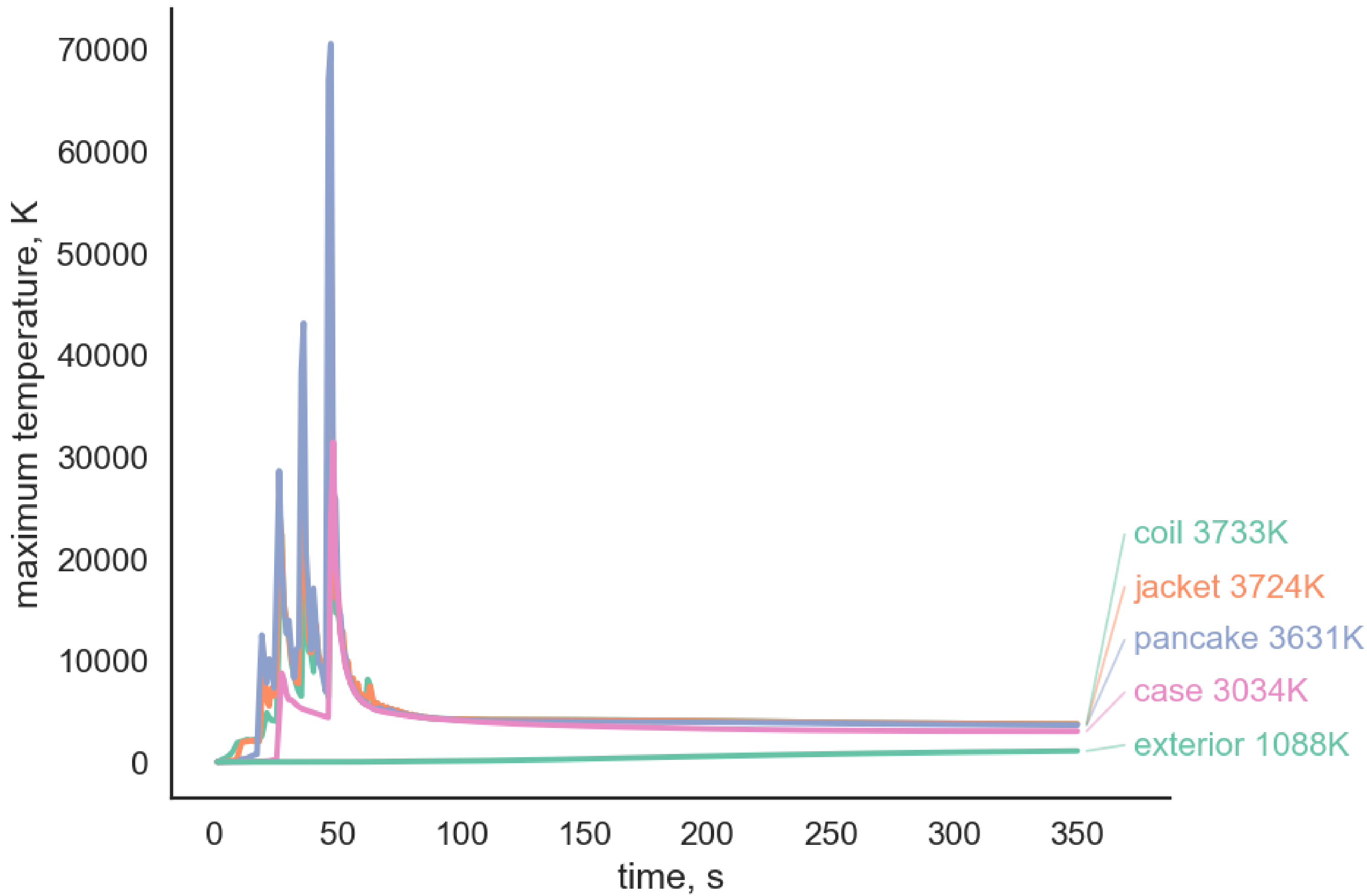
Simulation 5 - TF reference (+ outer turn initiation)



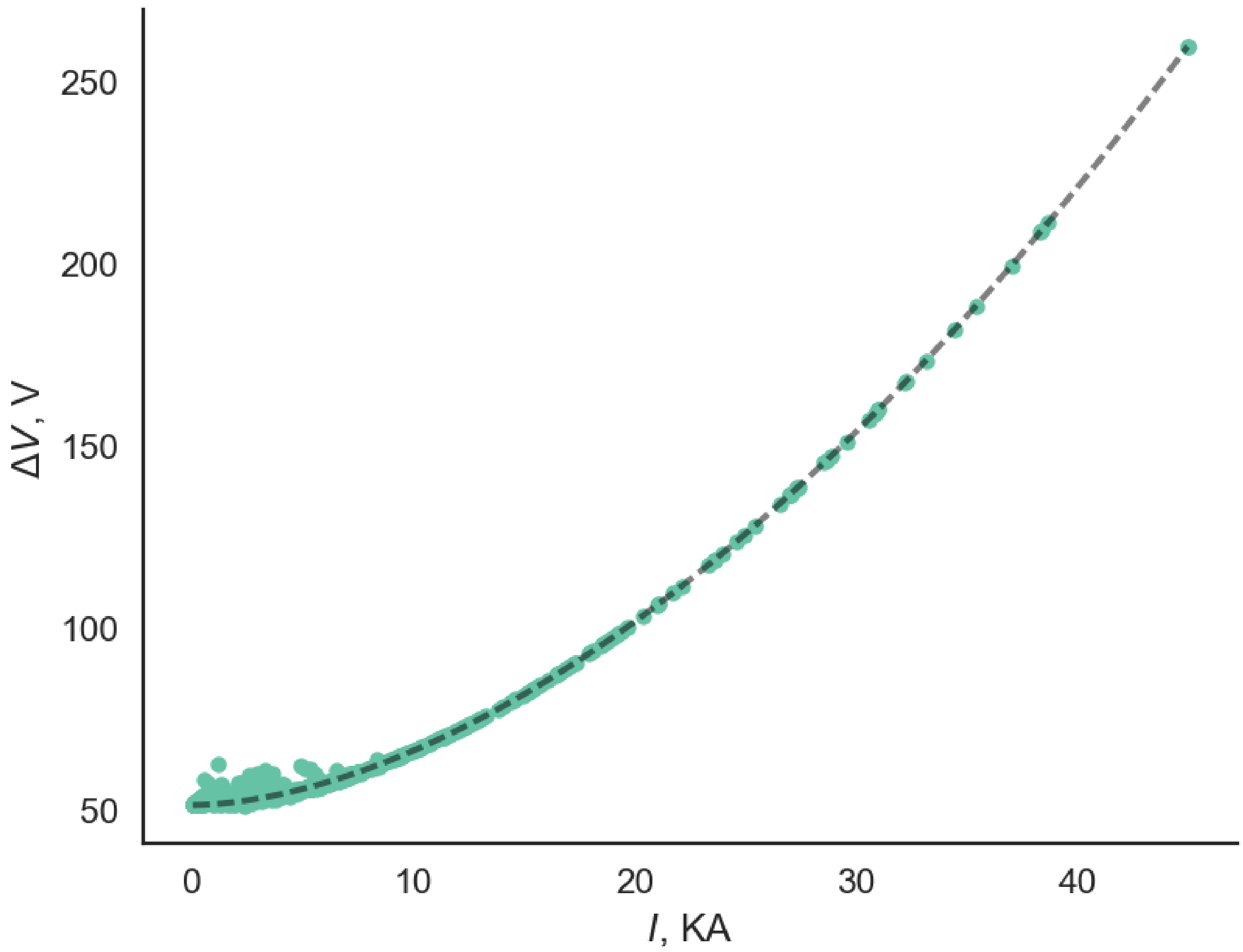
Simulation 5 - TF reference (+ outer turn initiation)



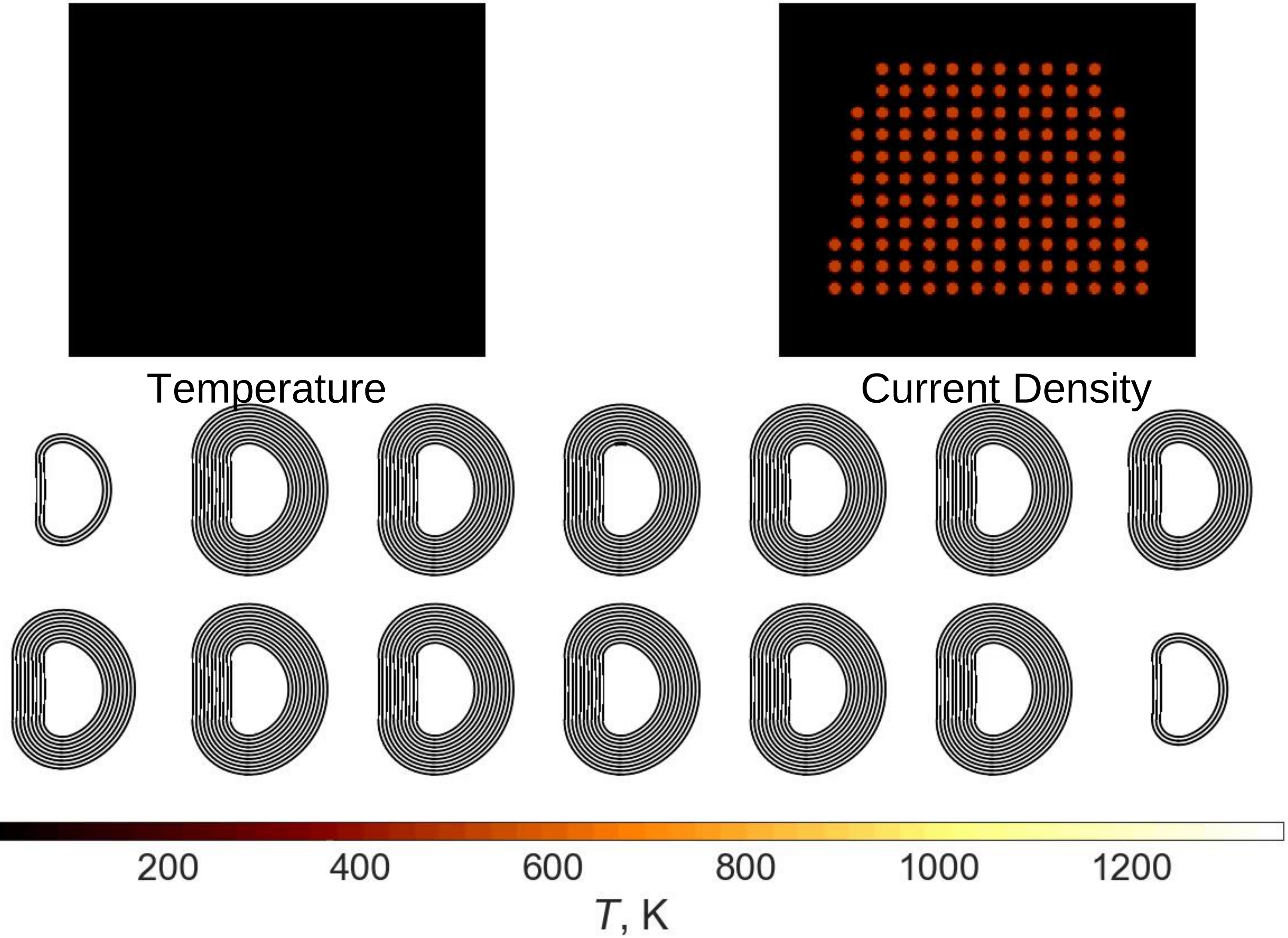
Simulation 5 - TF reference (+ outer turn initiation)



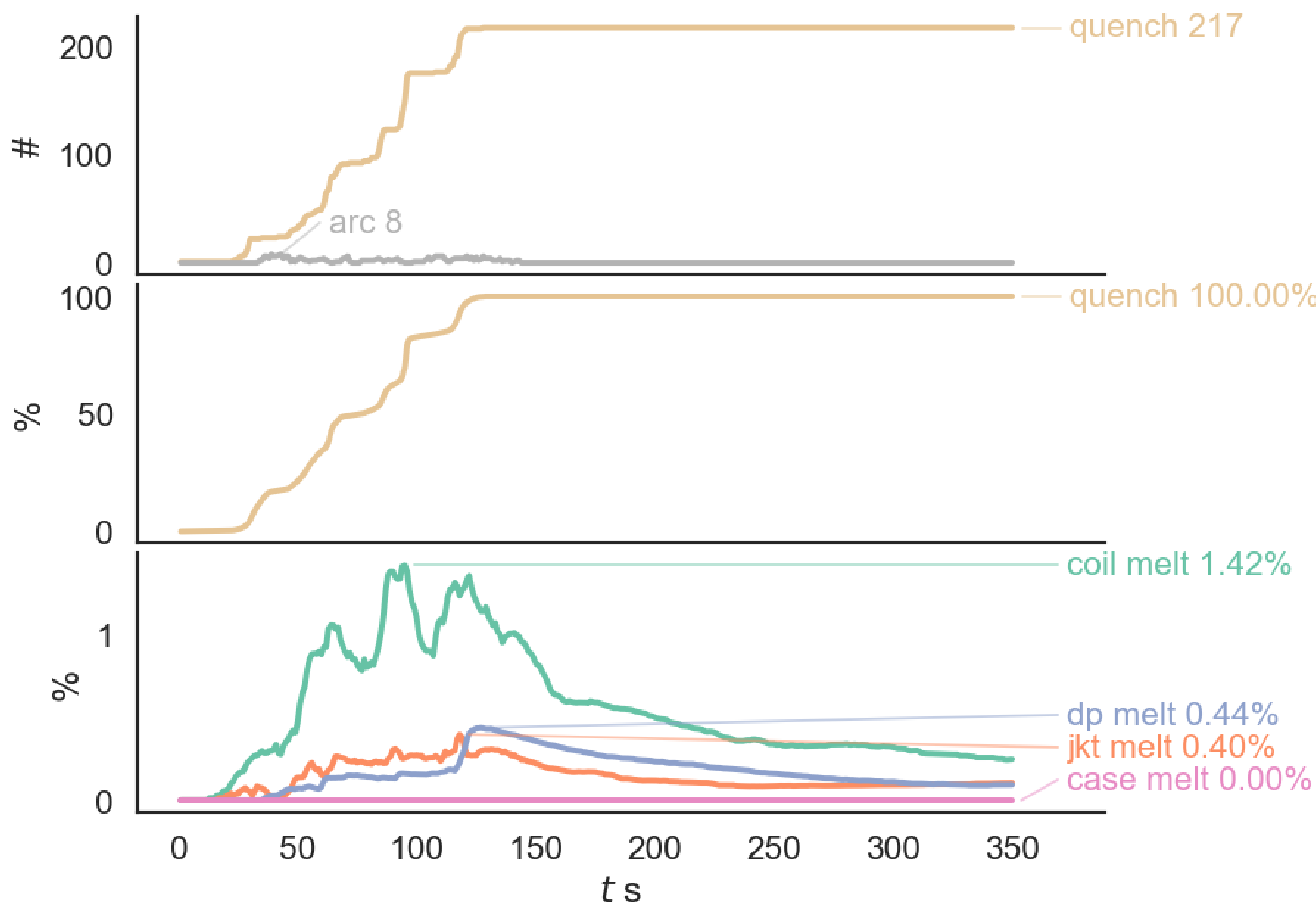
Simulation 5 - TF reference (+ outer turn initiation)



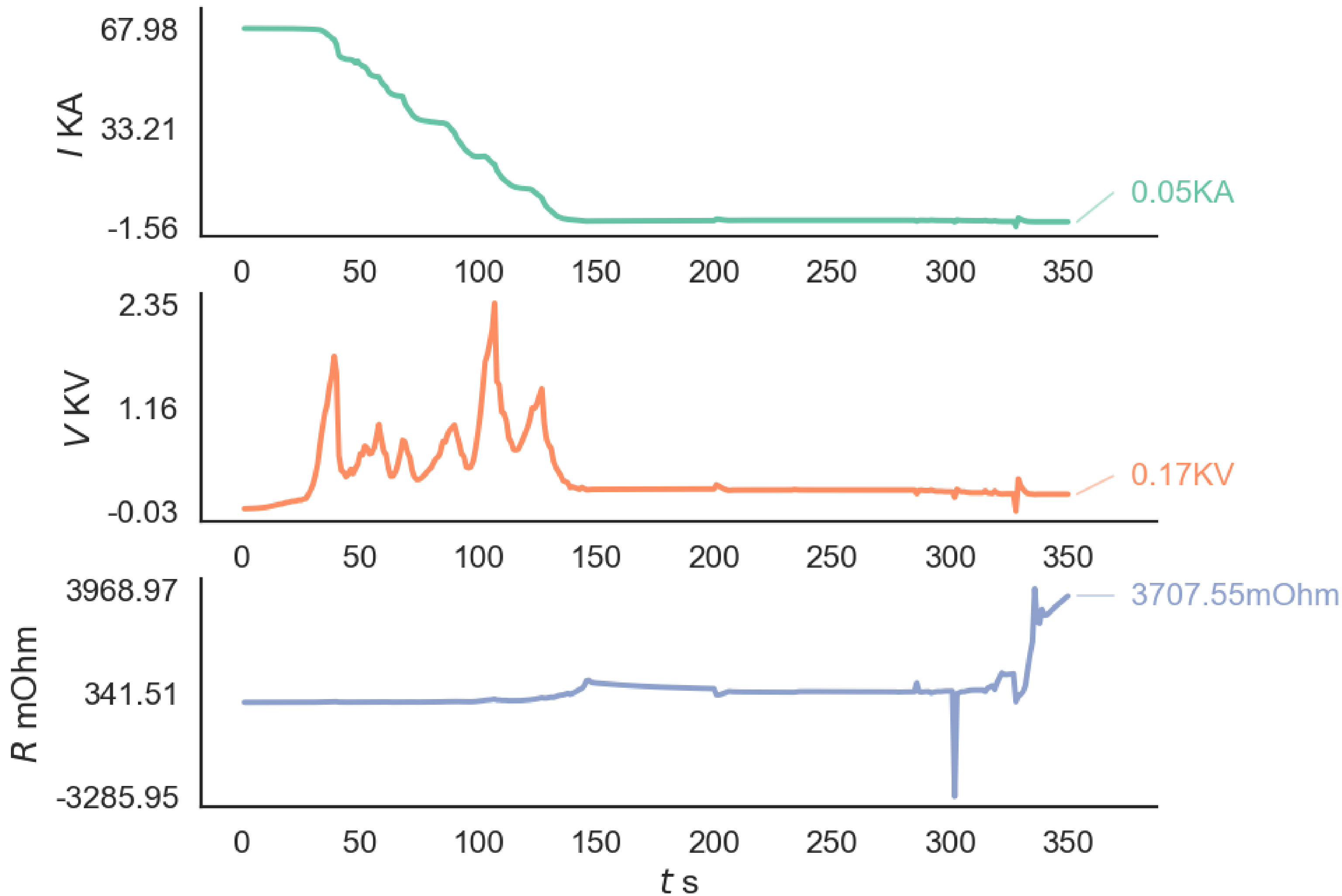
Simulation 6 - TF reference (+ inline discharge)



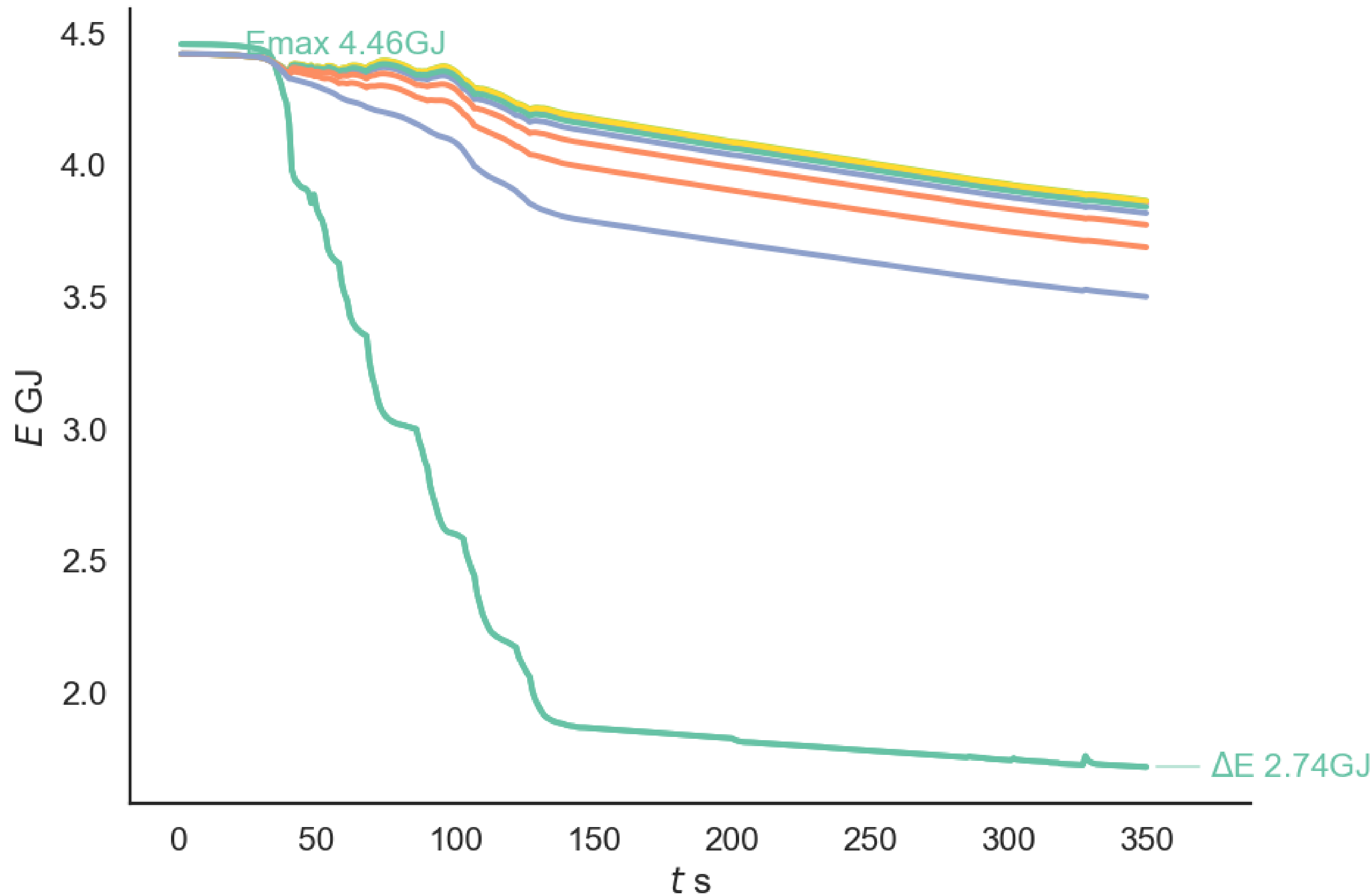
Simulation 6 - TF reference (+ inline discharge)



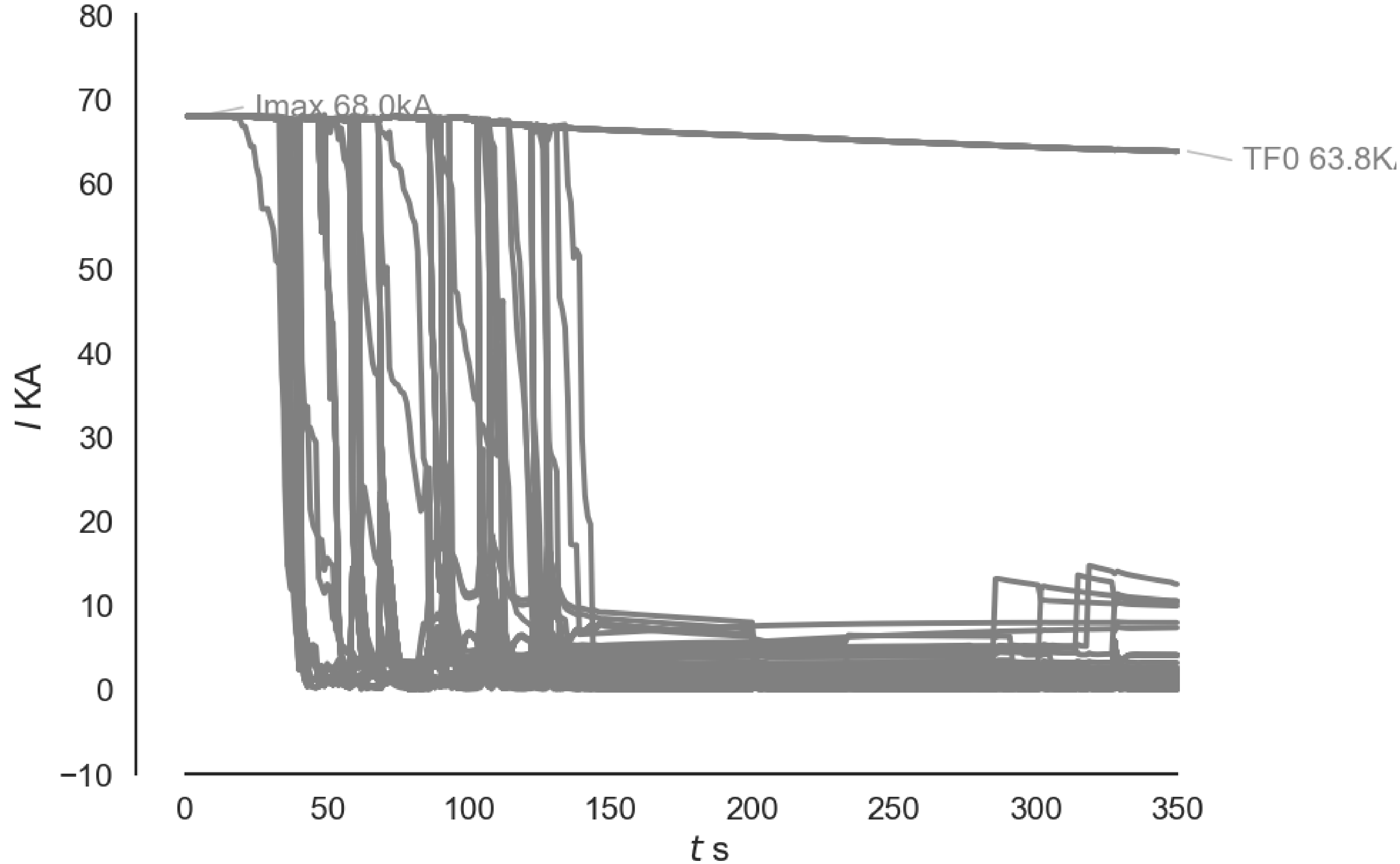
Simulation 6 - TF reference (+ inline discharge)



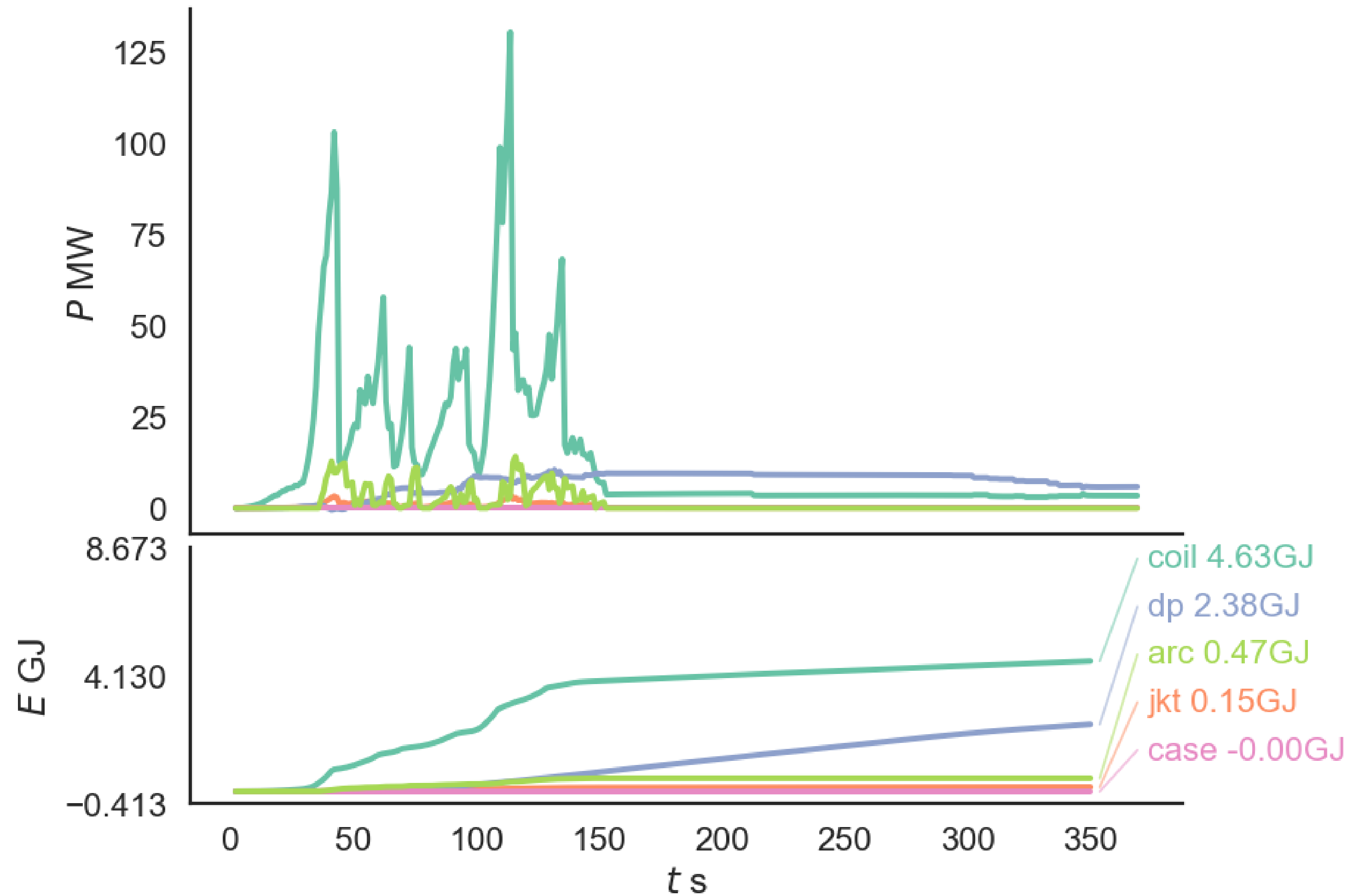
Simulation 6 - TF reference (+ inline discharge)



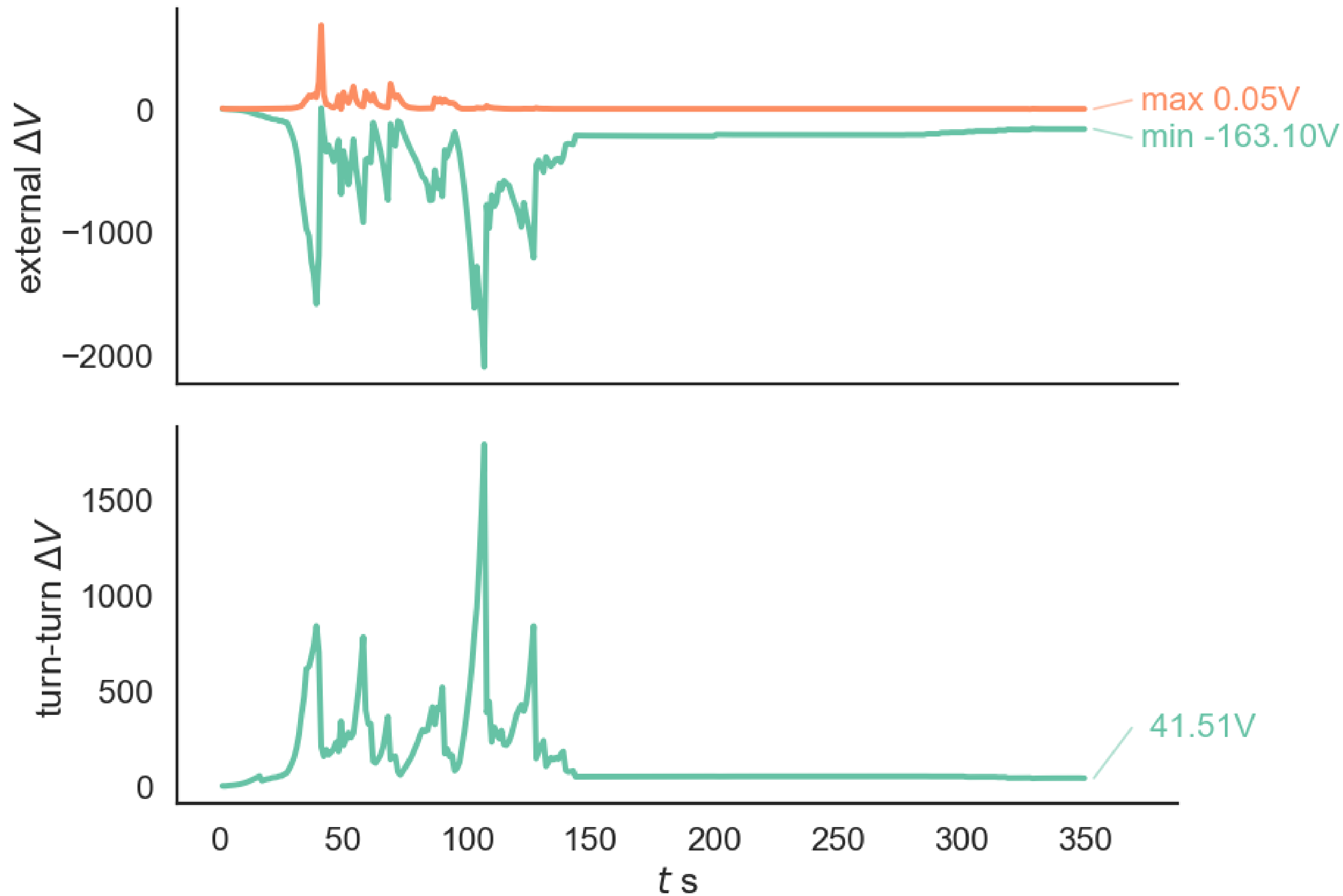
Simulation 6 - TF reference (+ inline discharge)



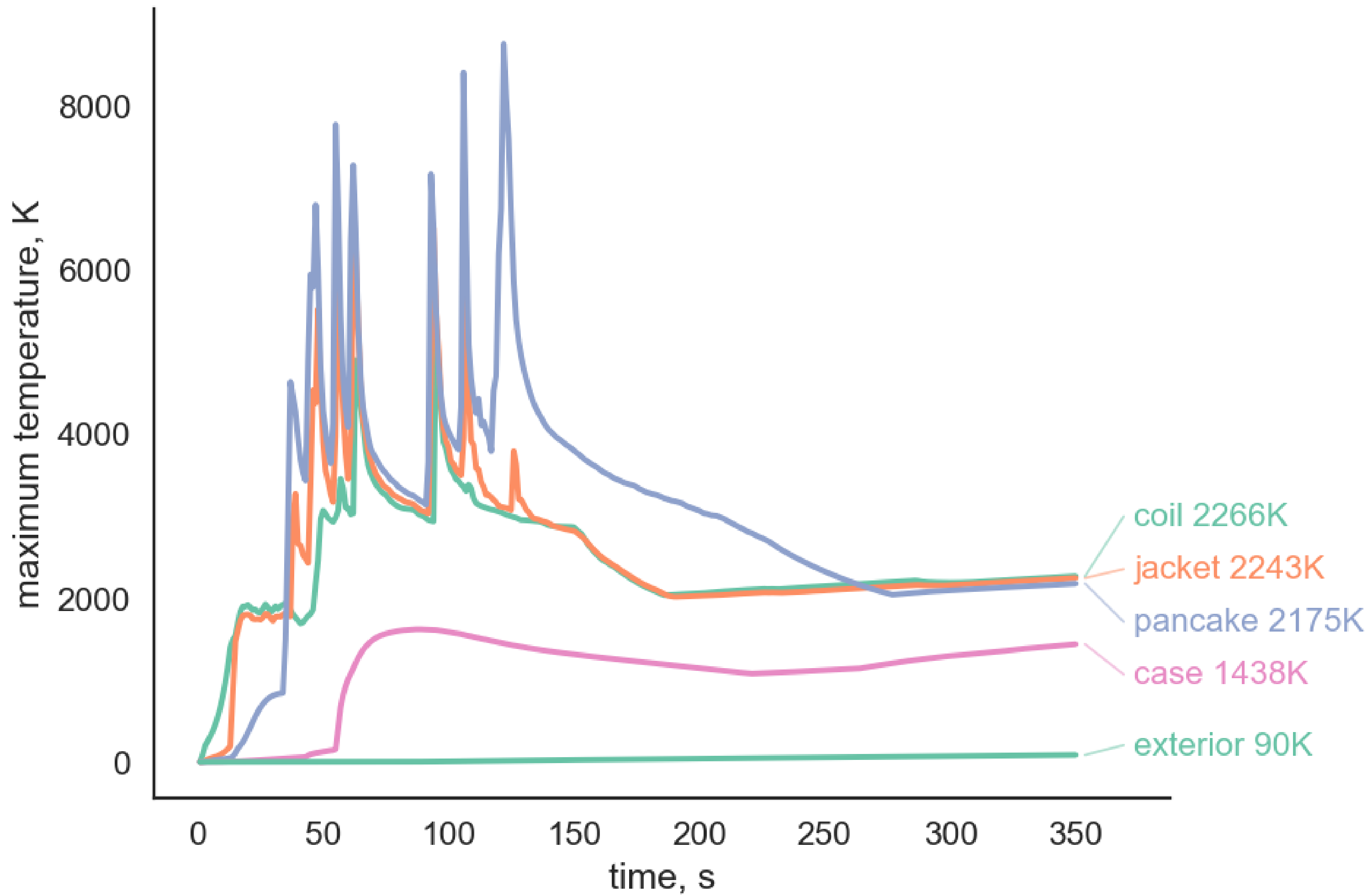
Simulation 6 - TF reference (+ inline discharge)



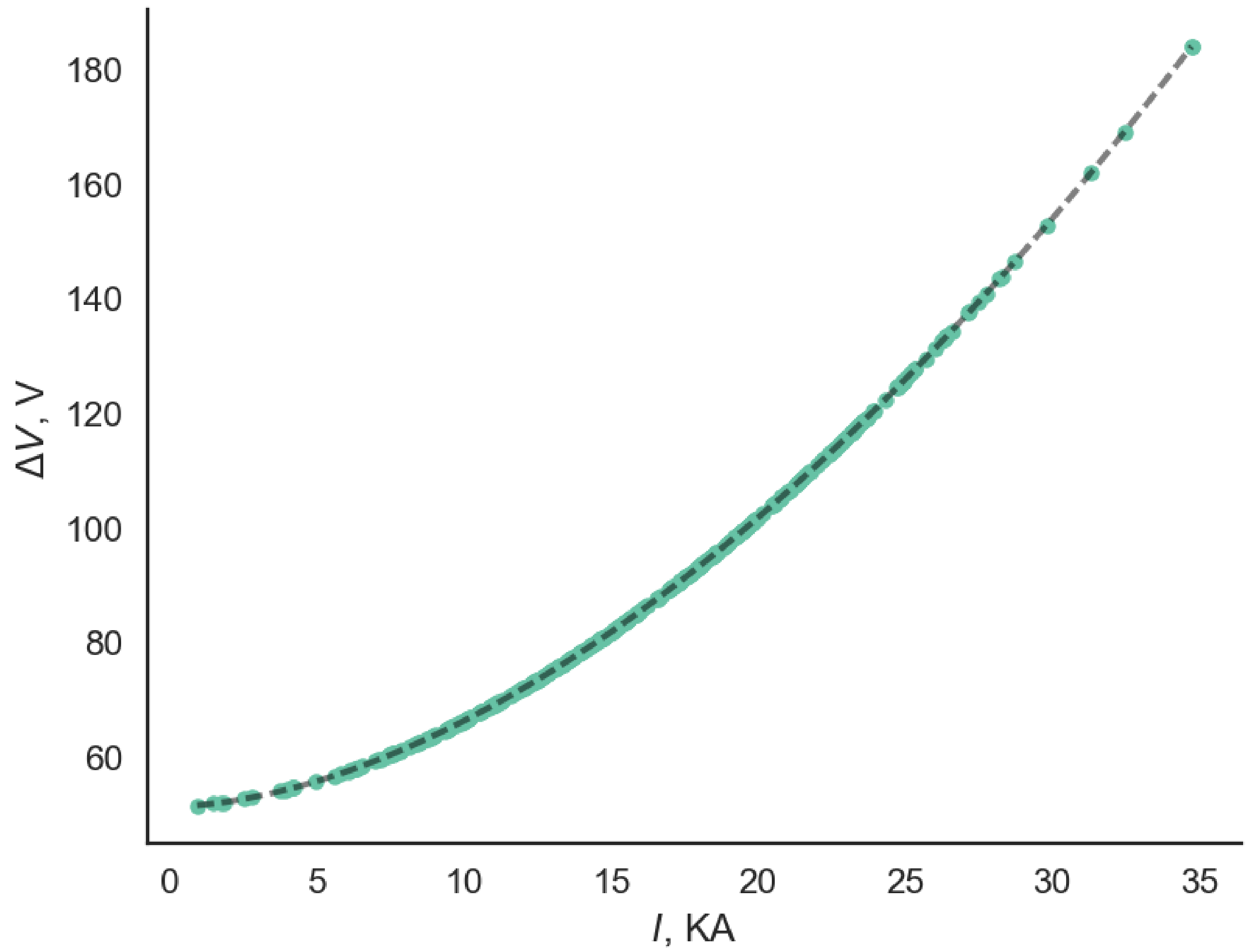
Simulation 6 - TF reference (+ inline discharge)



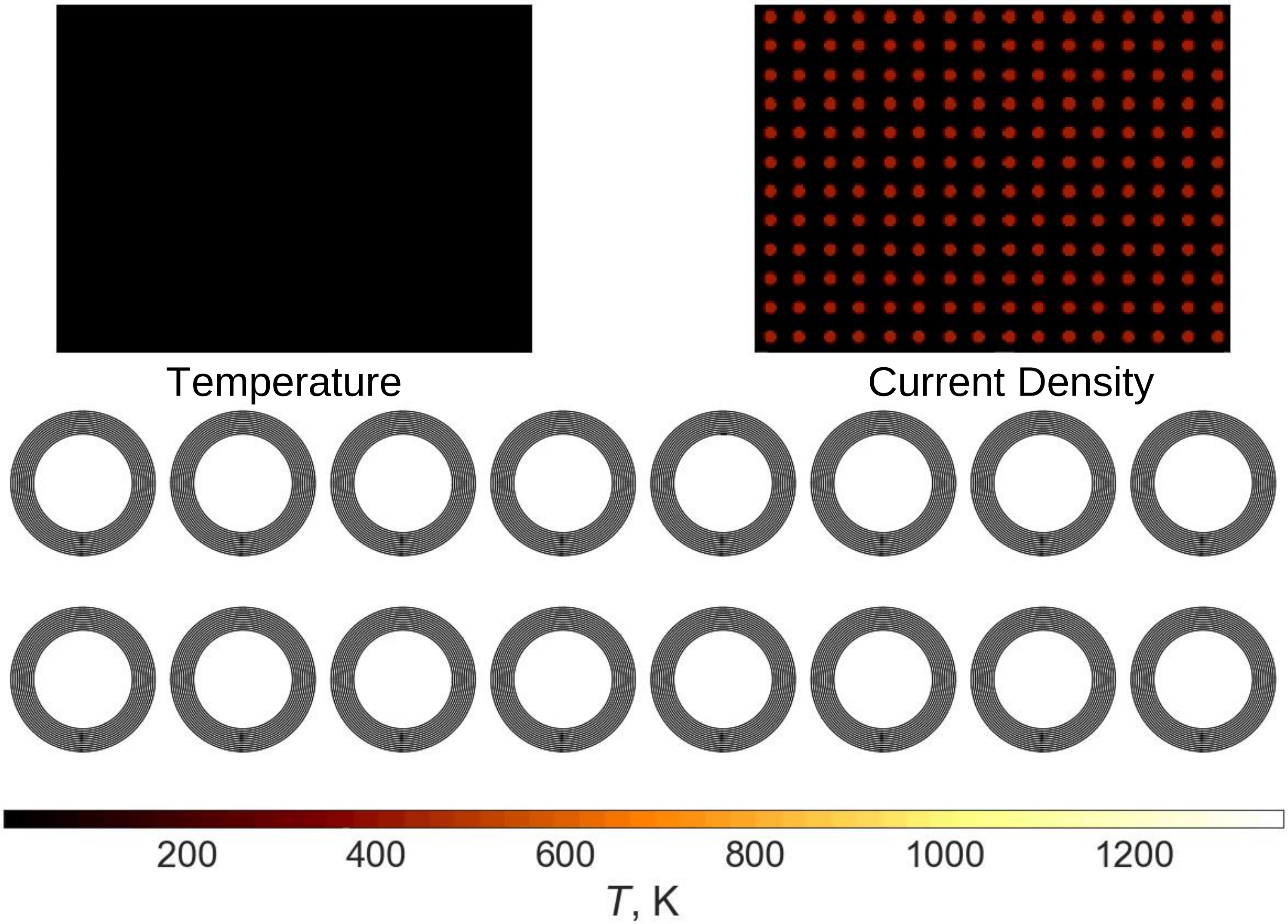
Simulation 6 - TF reference (+ inline discharge)



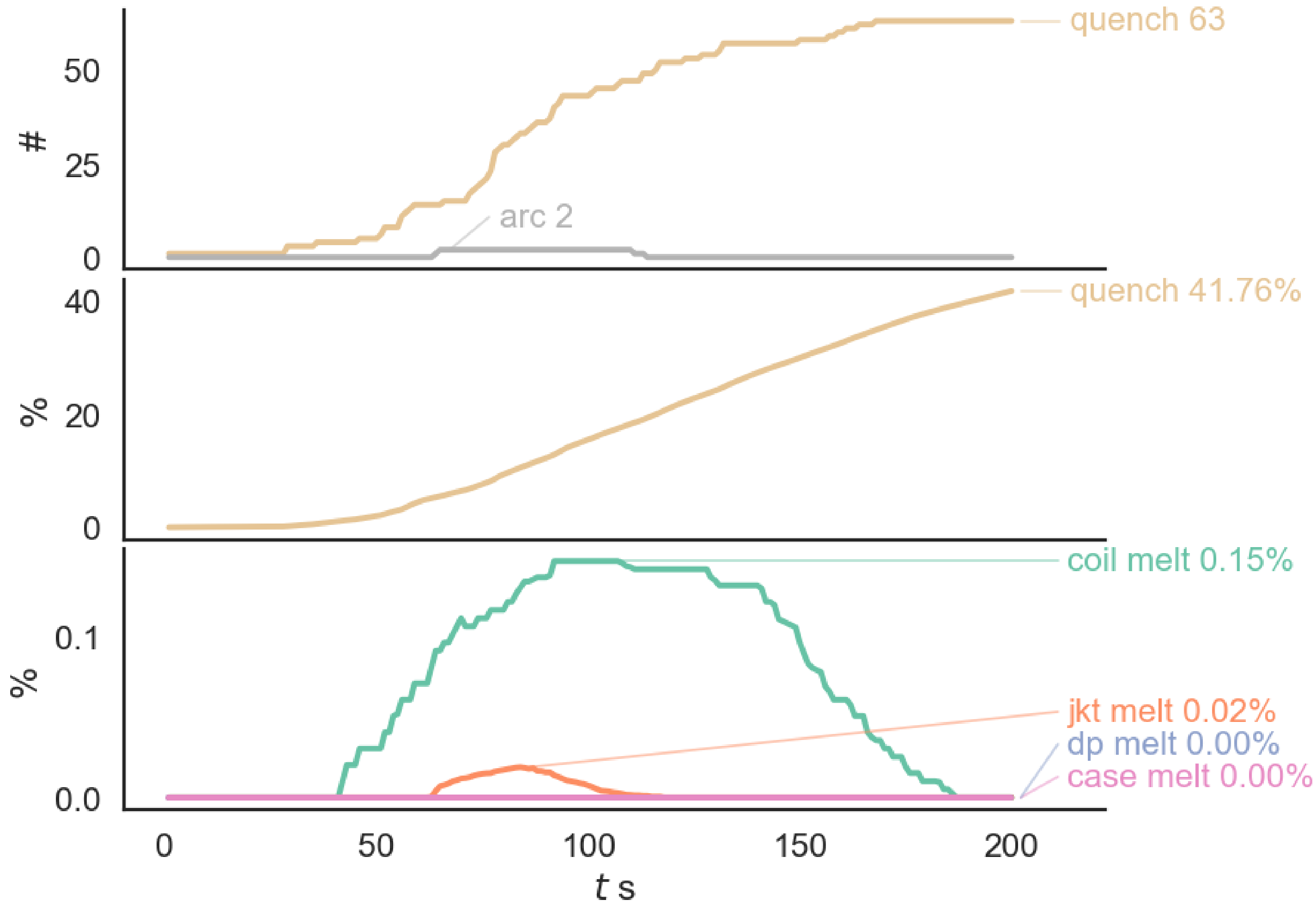
Simulation 6 - TF reference (+ inline discharge)



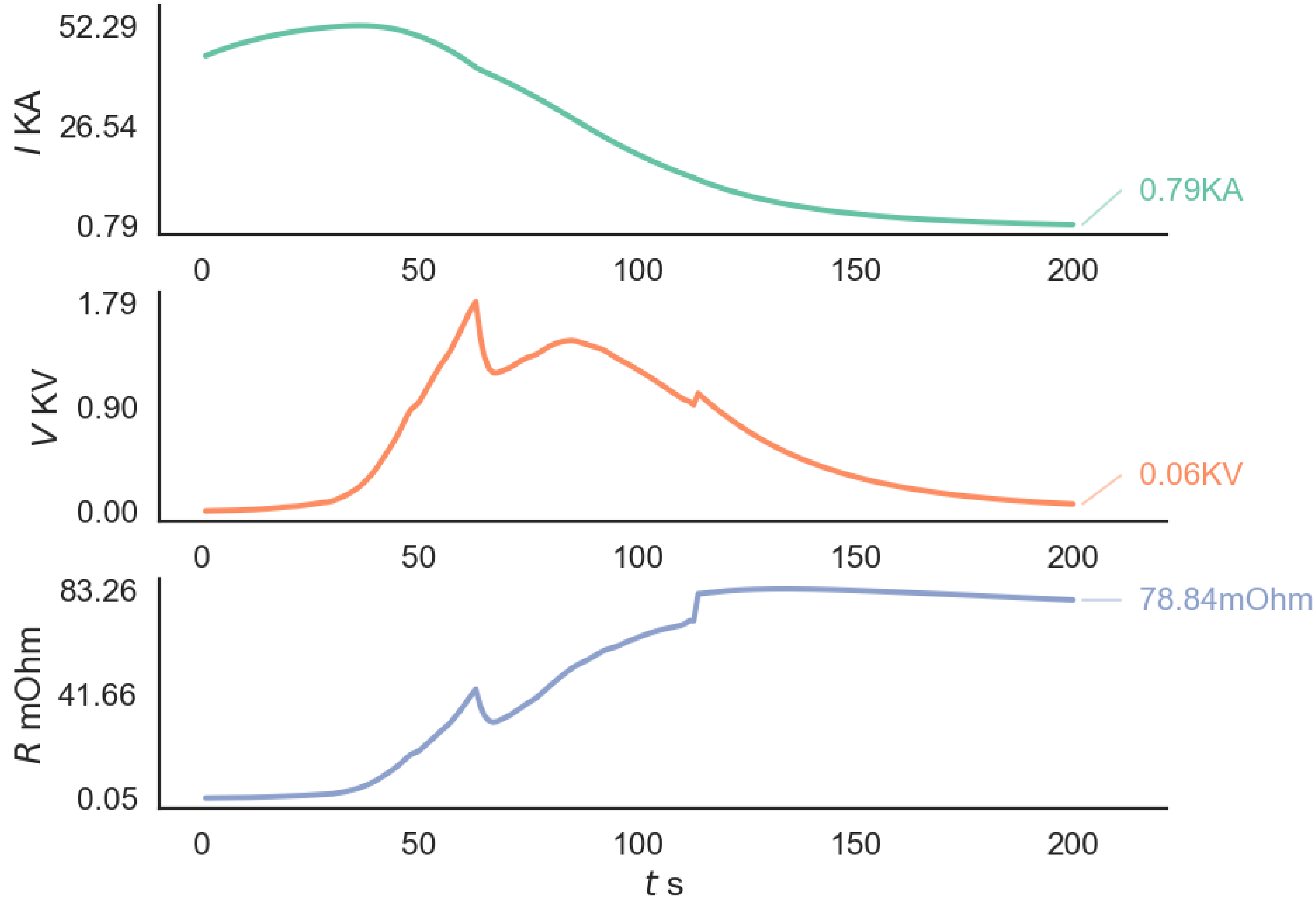
Simulation 7 - PF reference



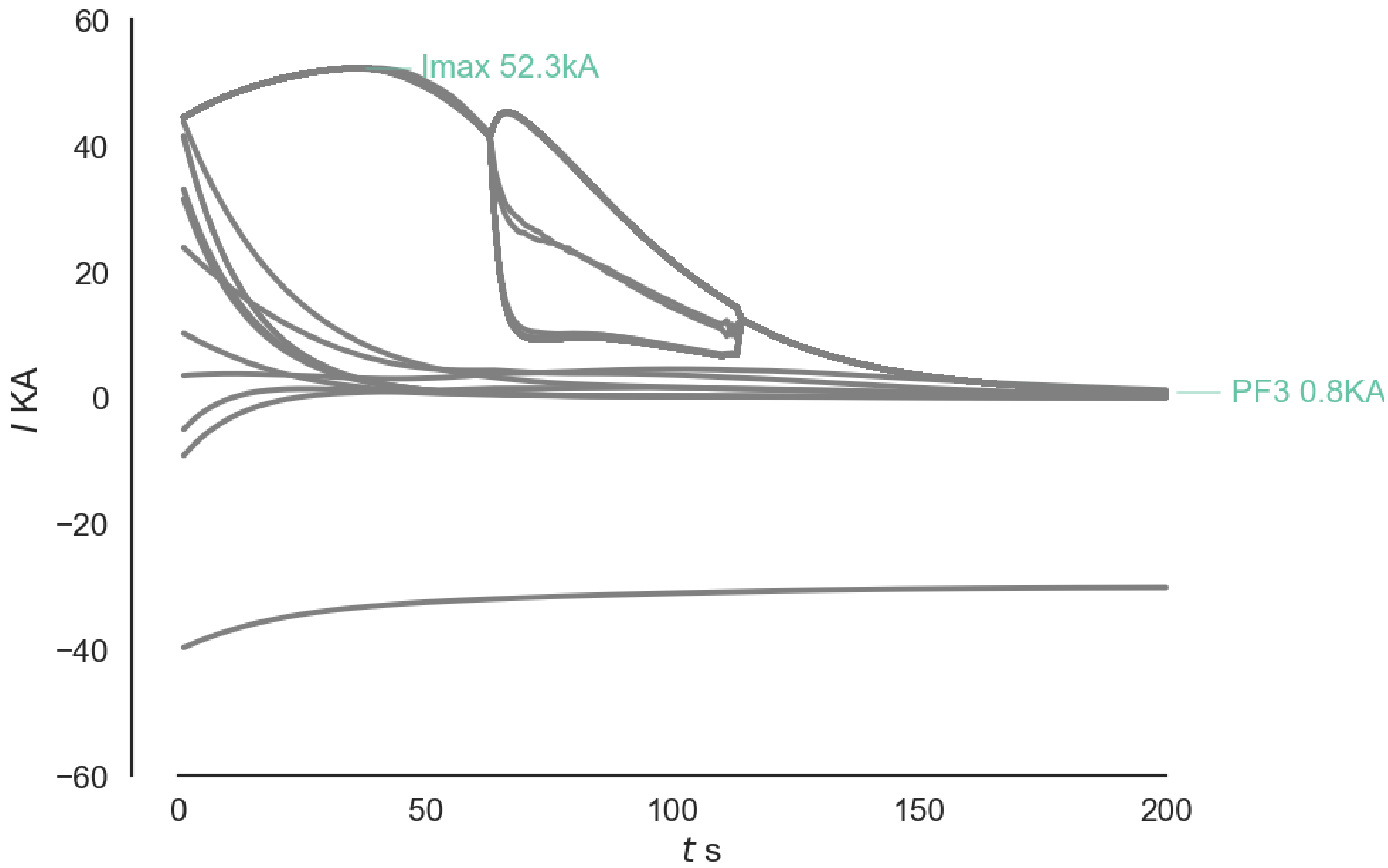
Simulation 7 - PF reference



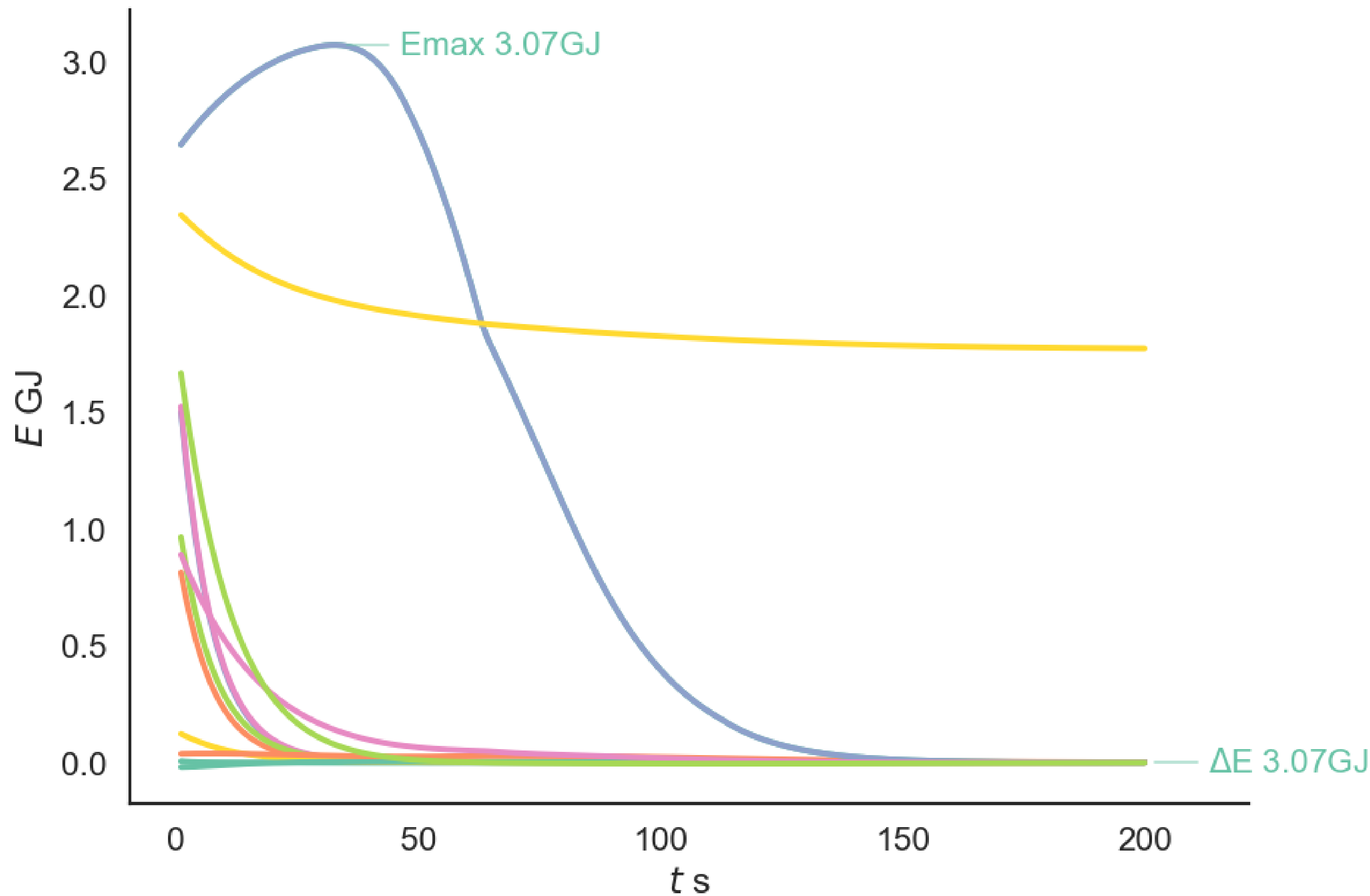
Simulation 7 - PF reference



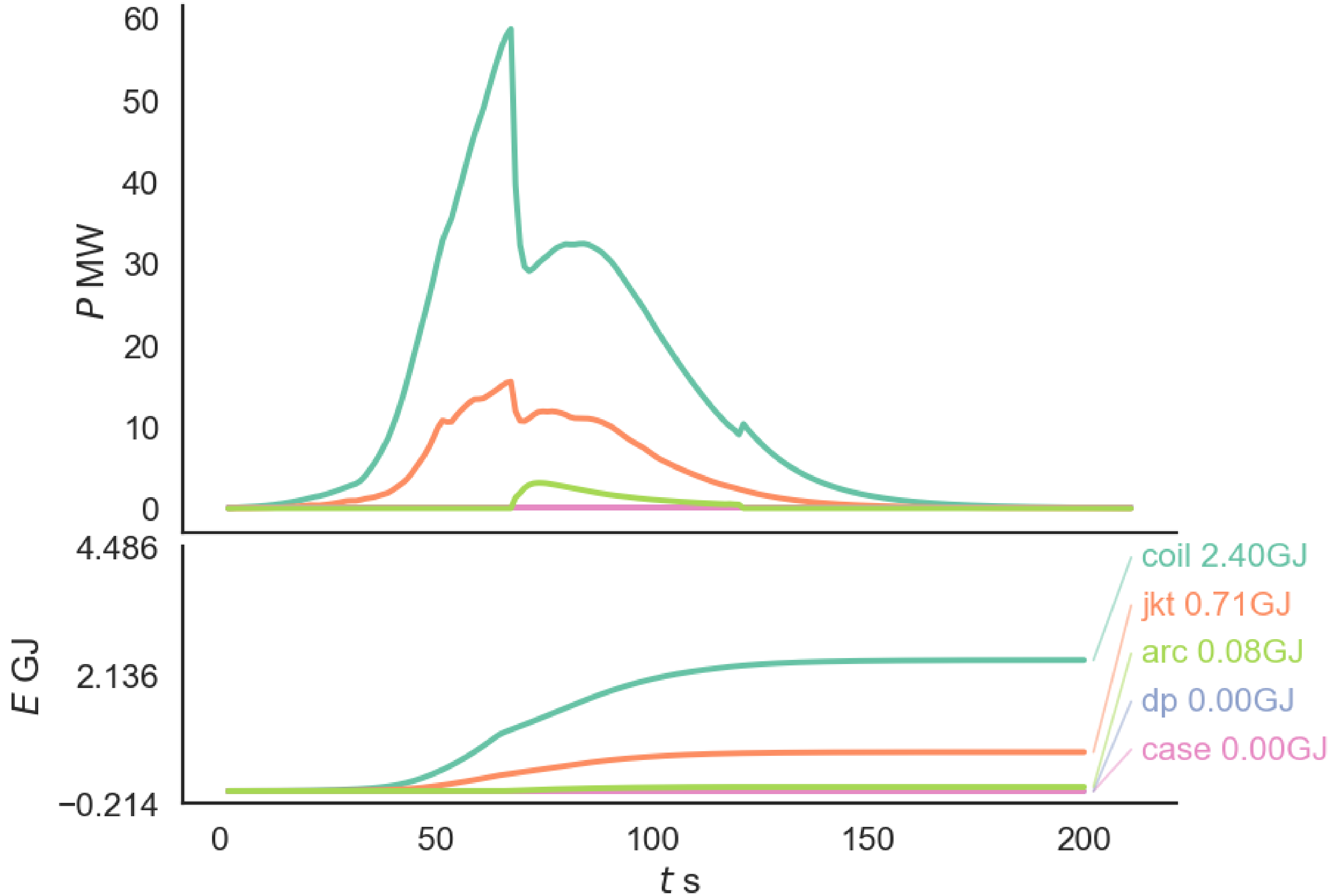
Simulation 7 - PF reference



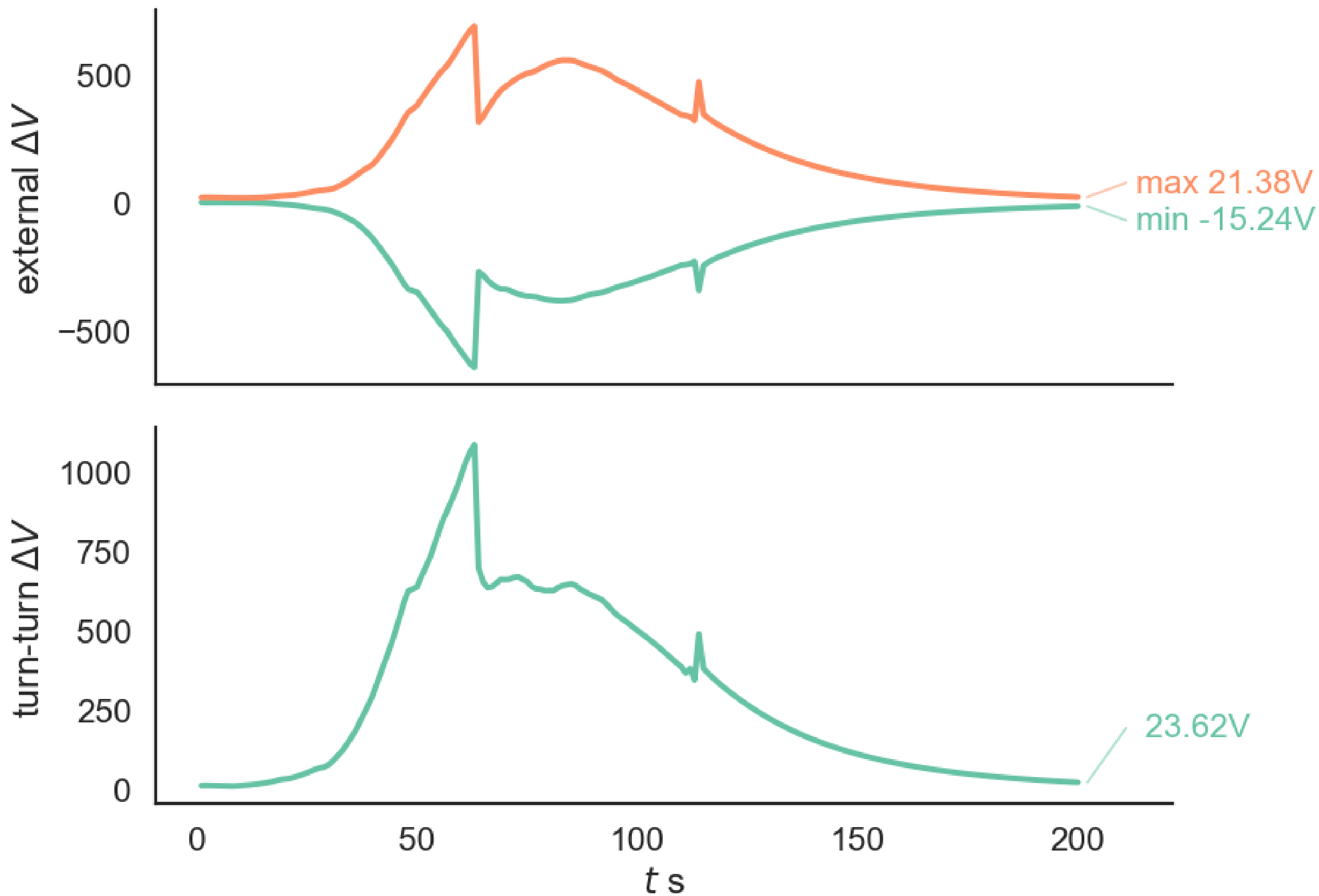
Simulation 7 - PF reference



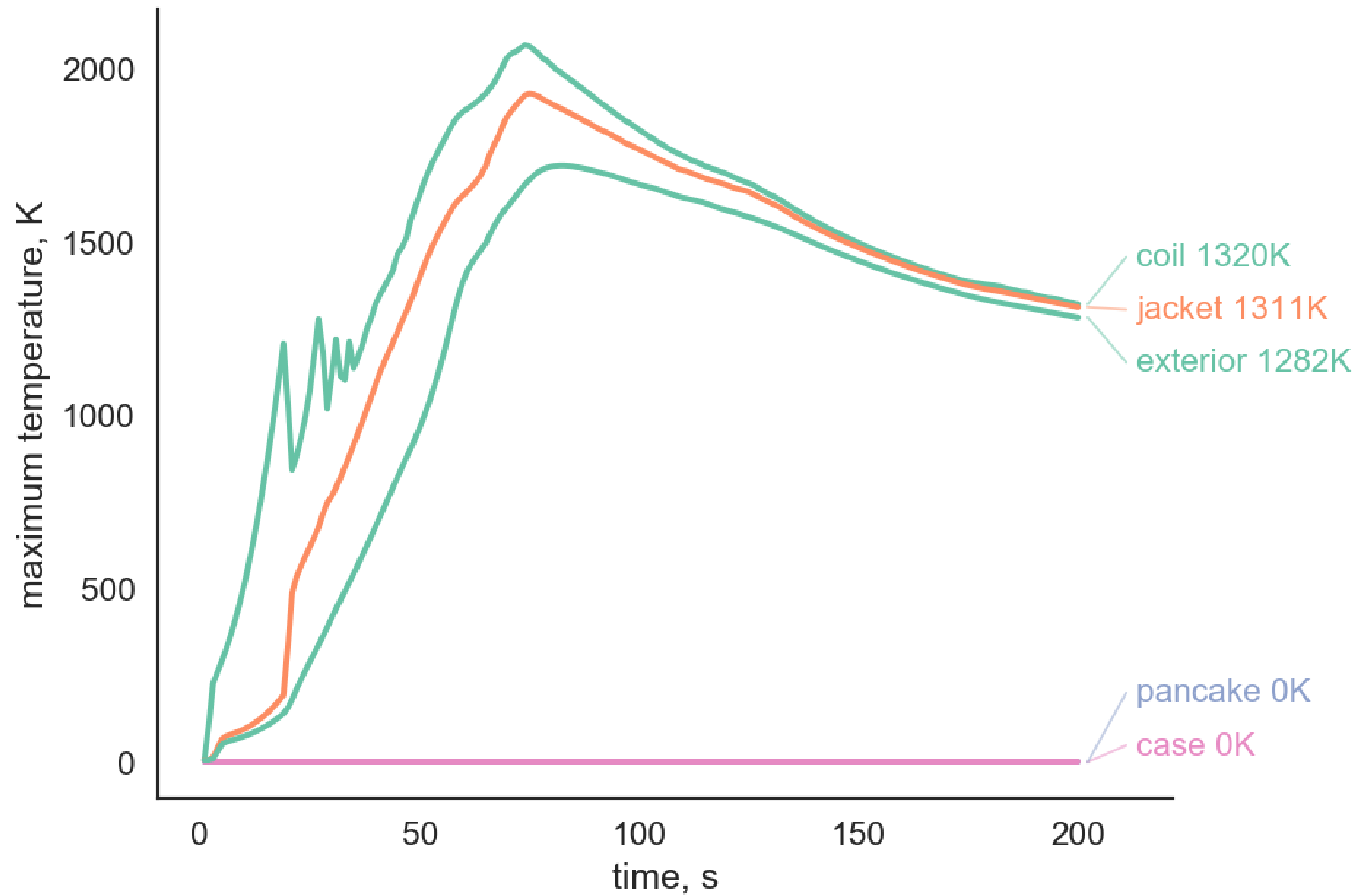
Simulation 7 - PF reference



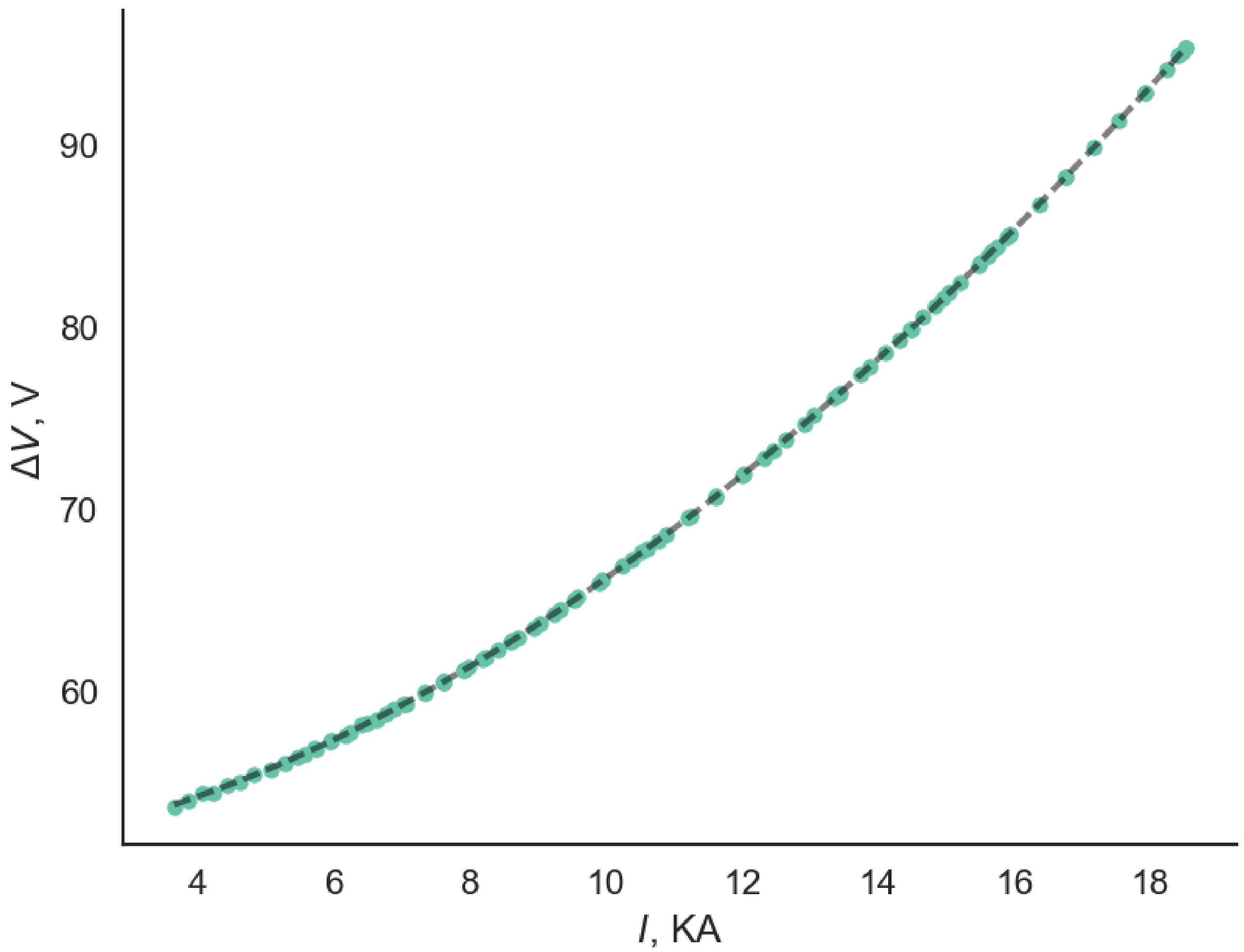
Simulation 7 - PF reference



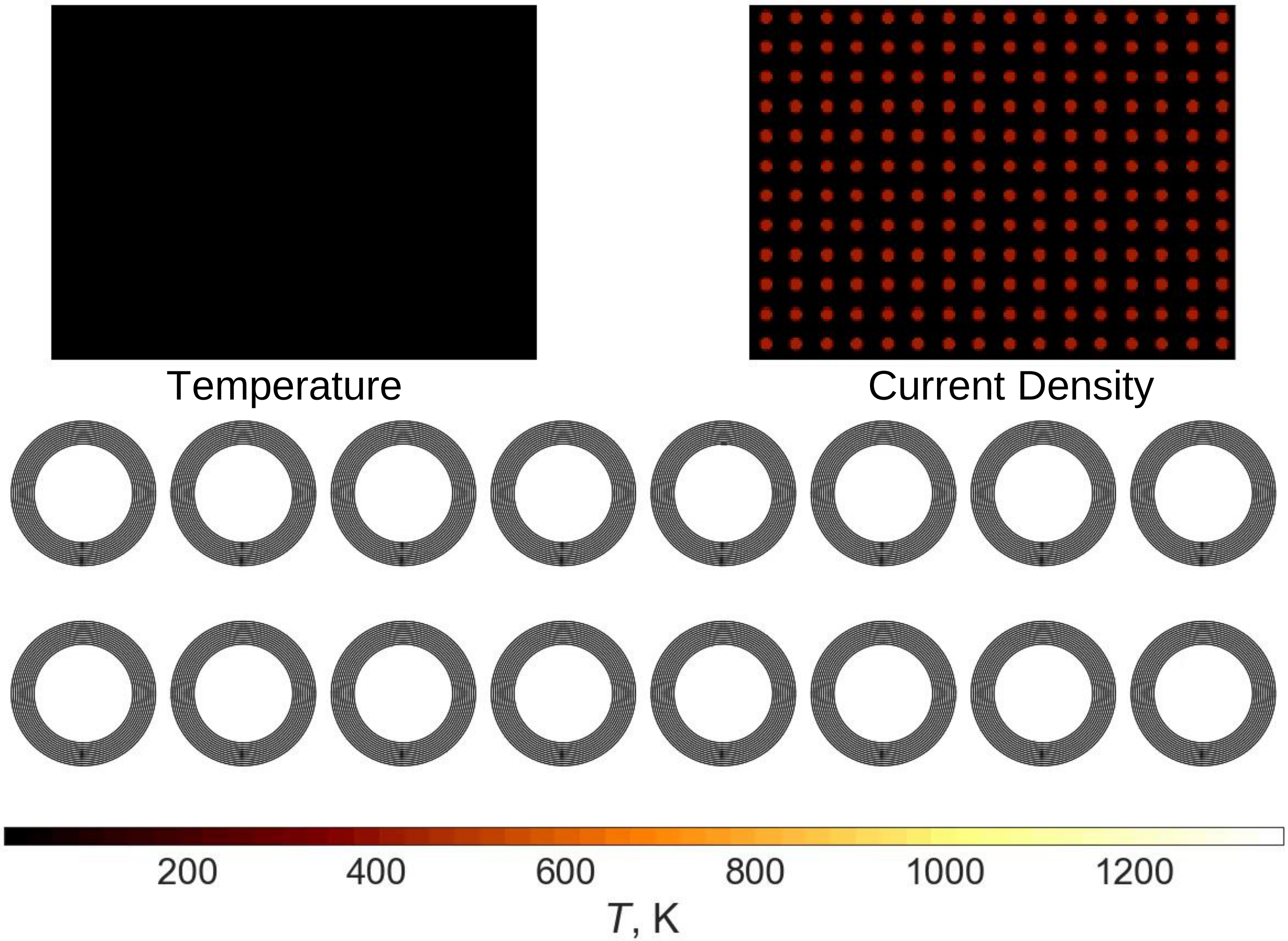
Simulation 7 - PF reference



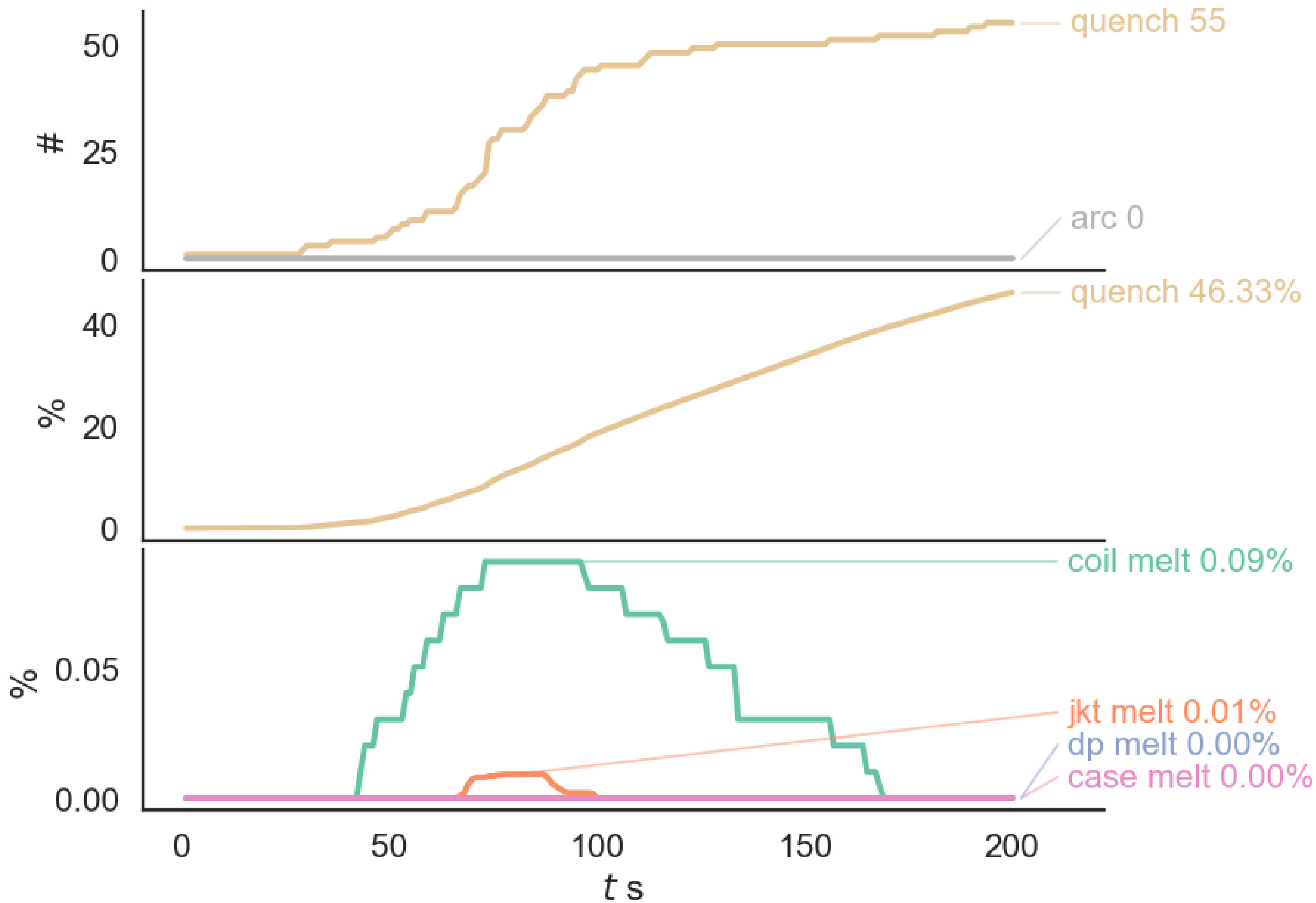
Simulation 7 - PF reference



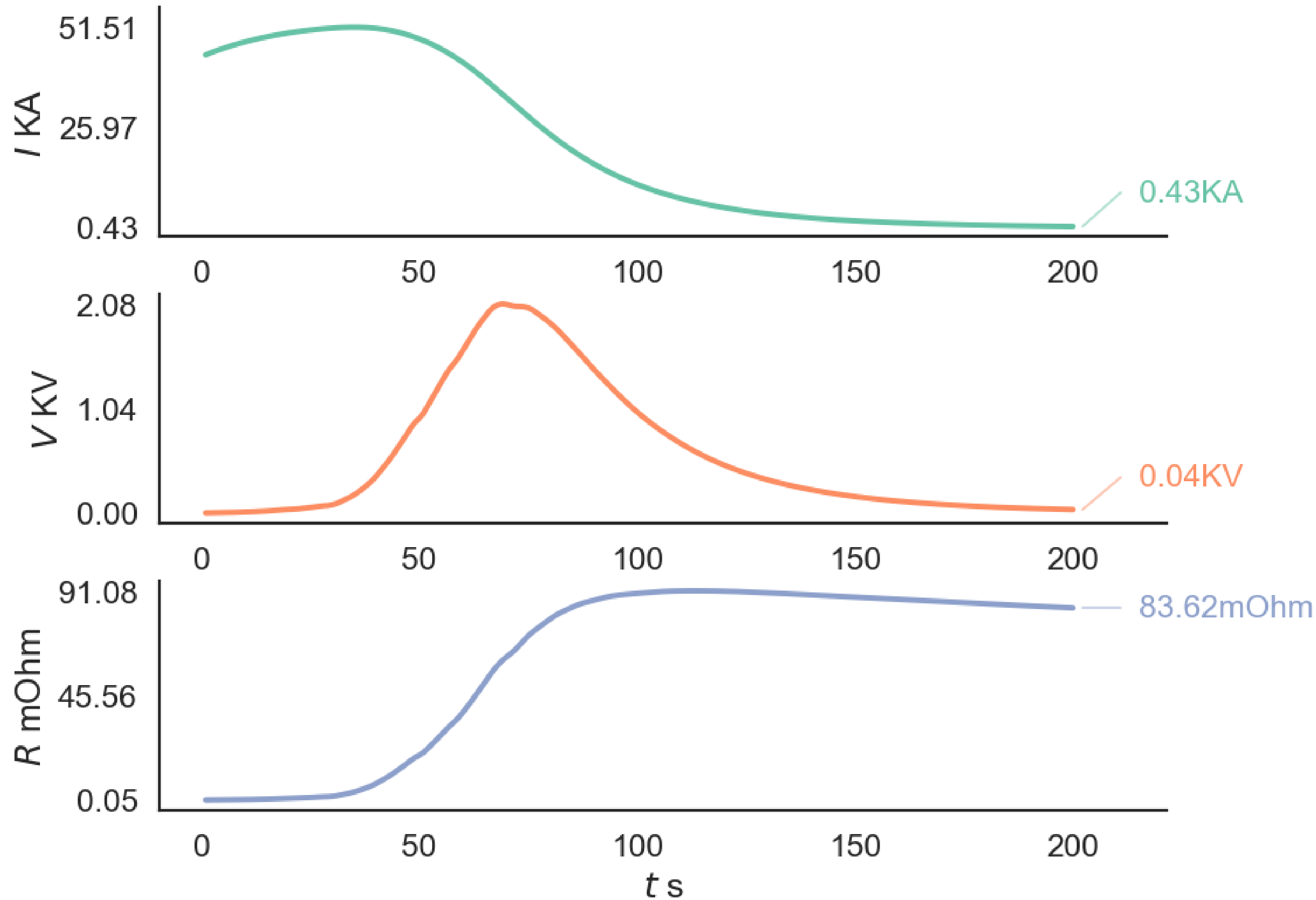
Simulation 8 - PF reference (+ no PDU6)



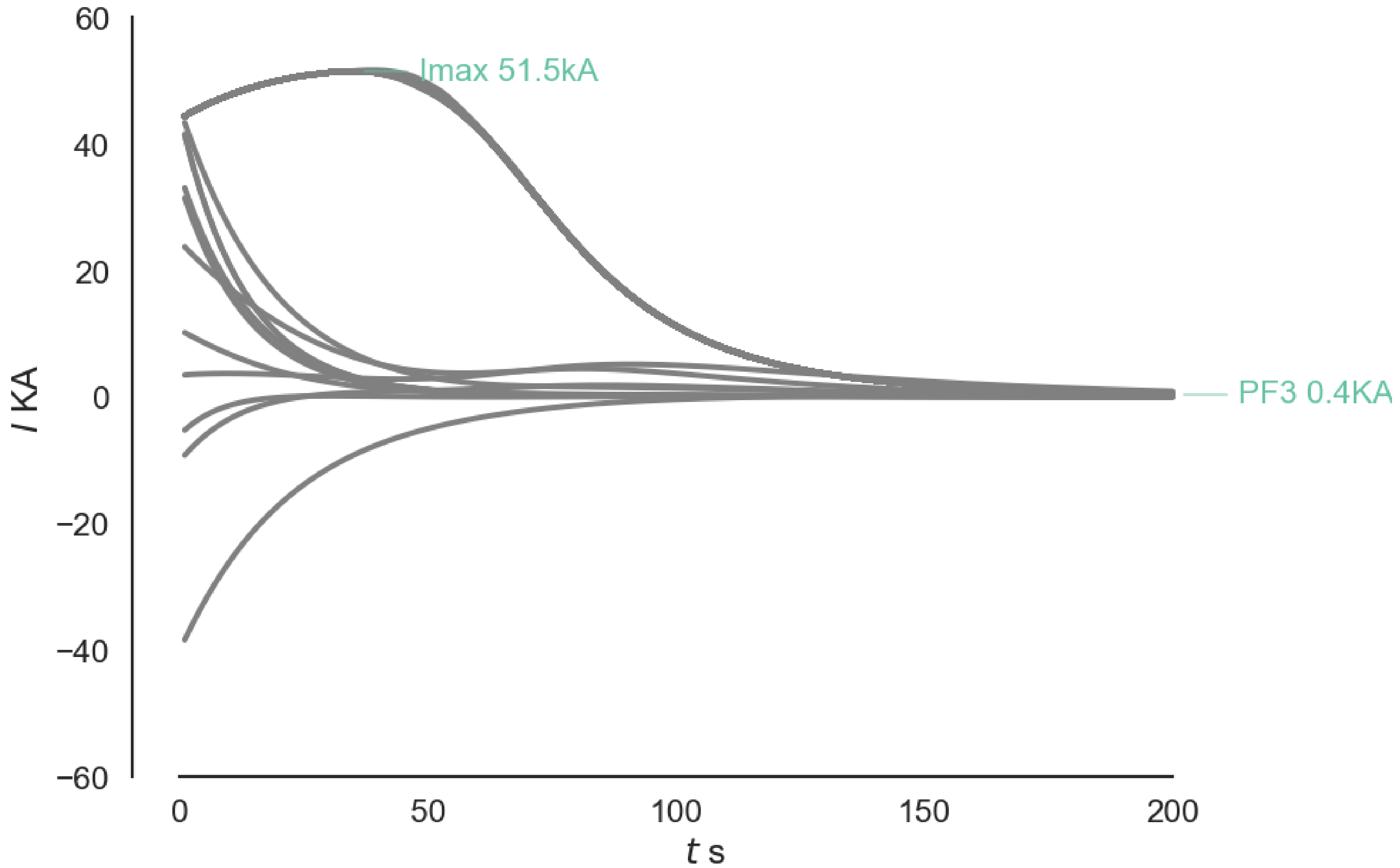
Simulation 8 - PF reference (+ no PDU6)



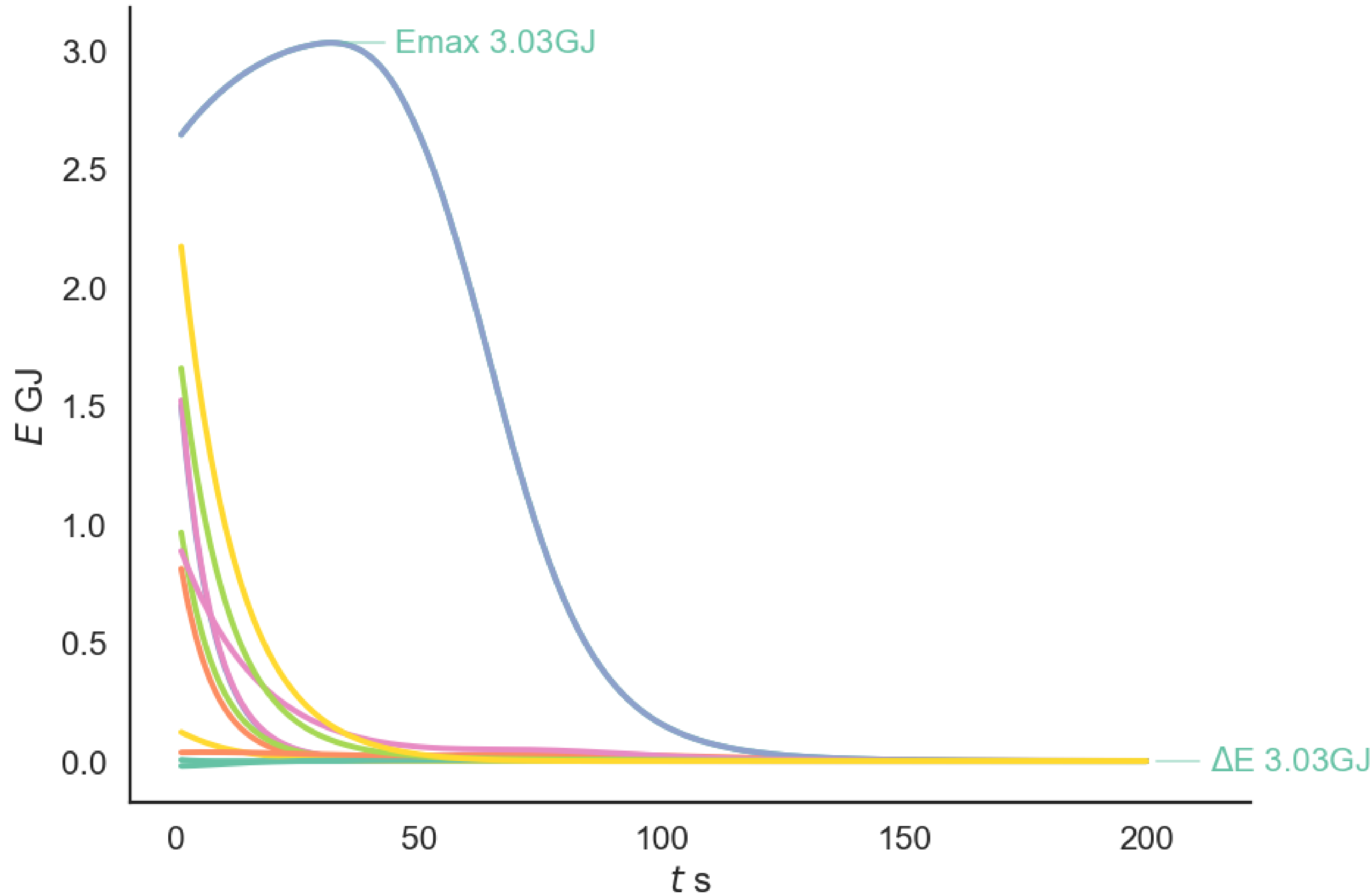
Simulation 8 - PF reference (+ no PDU6)



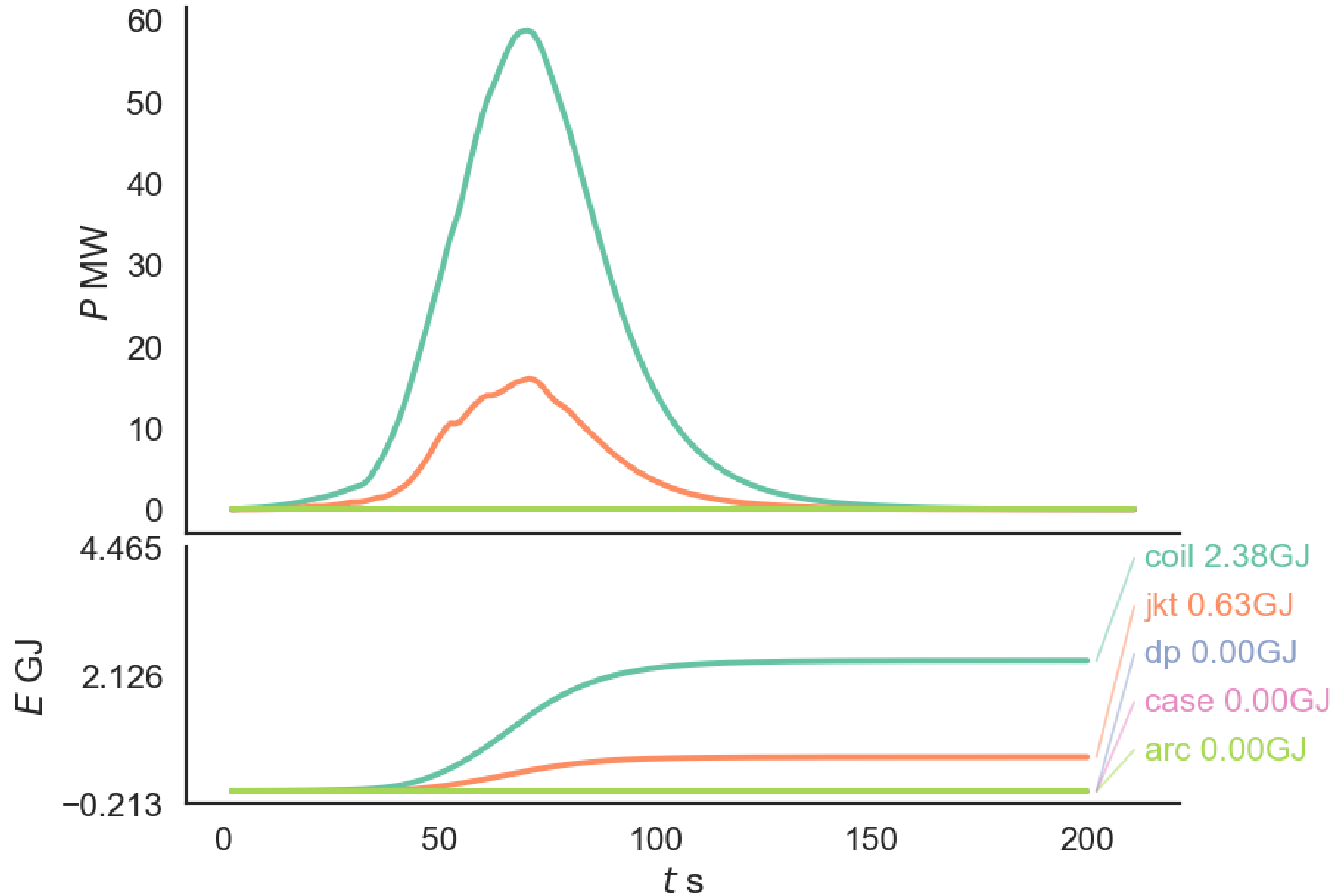
Simulation 8 - PF reference (+ no PDU6)



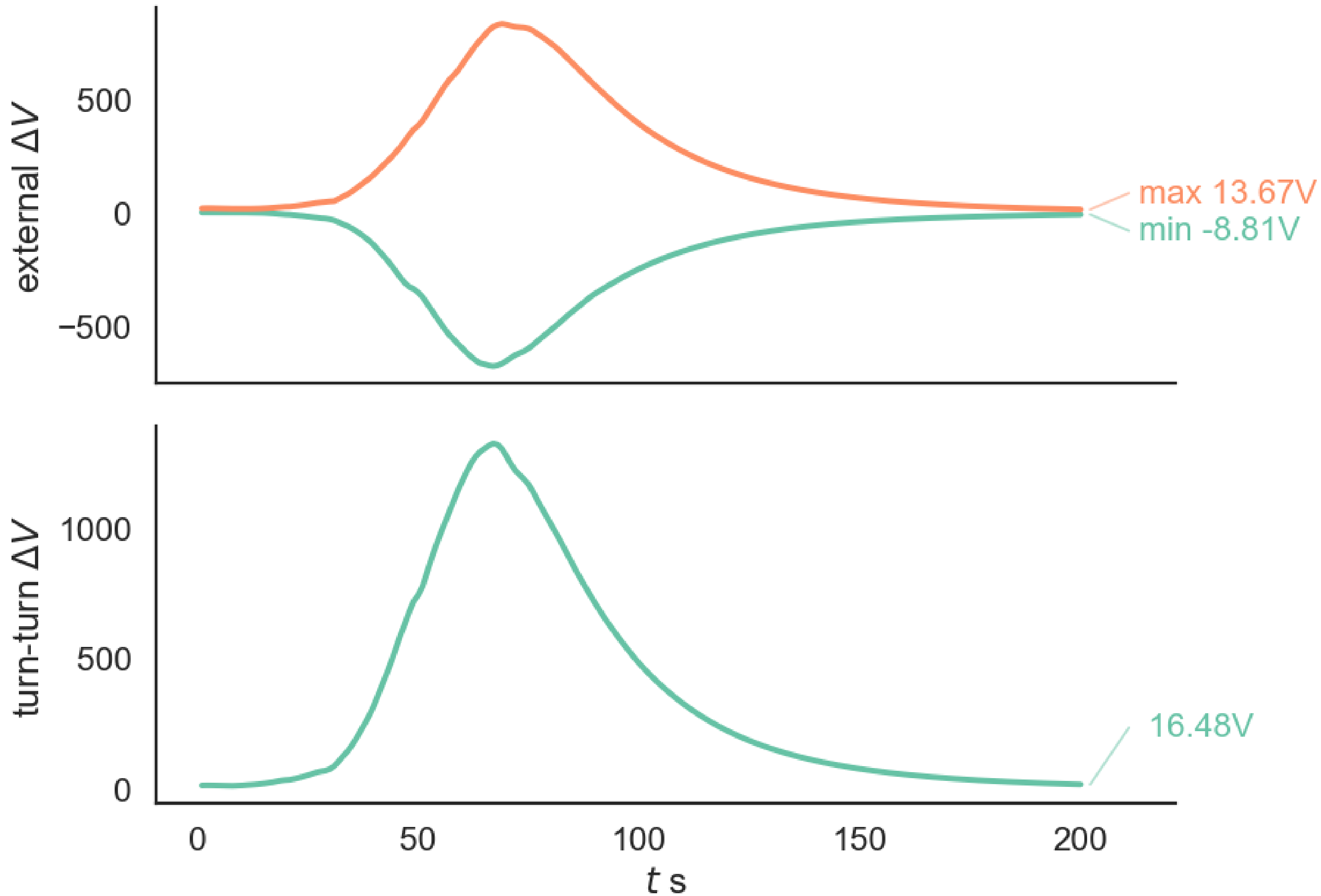
Simulation 8 - PF reference (+ no PDU6)



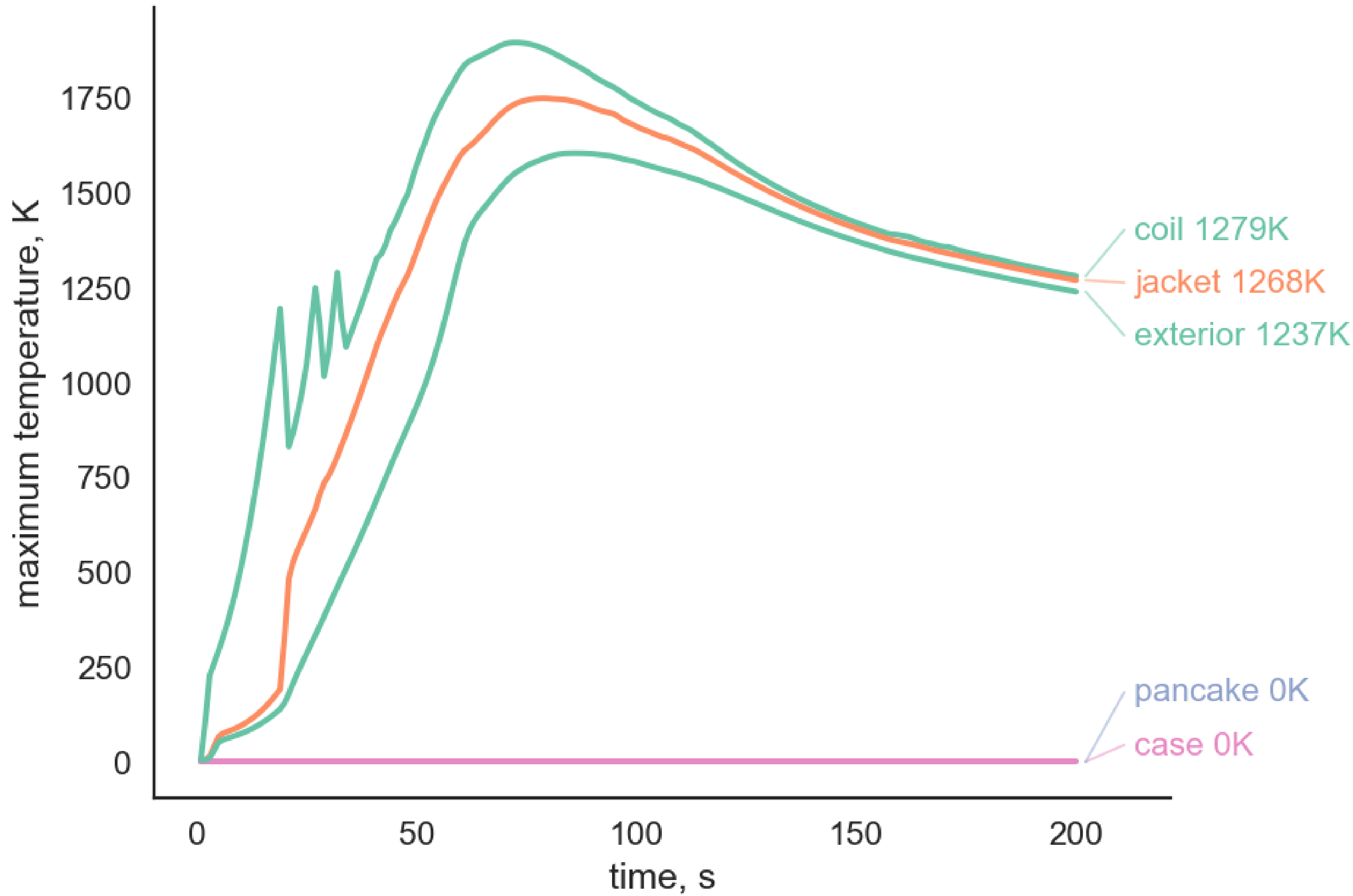
Simulation 8 - PF reference (+ no PDU6)



Simulation 8 - PF reference (+ no PDU6)



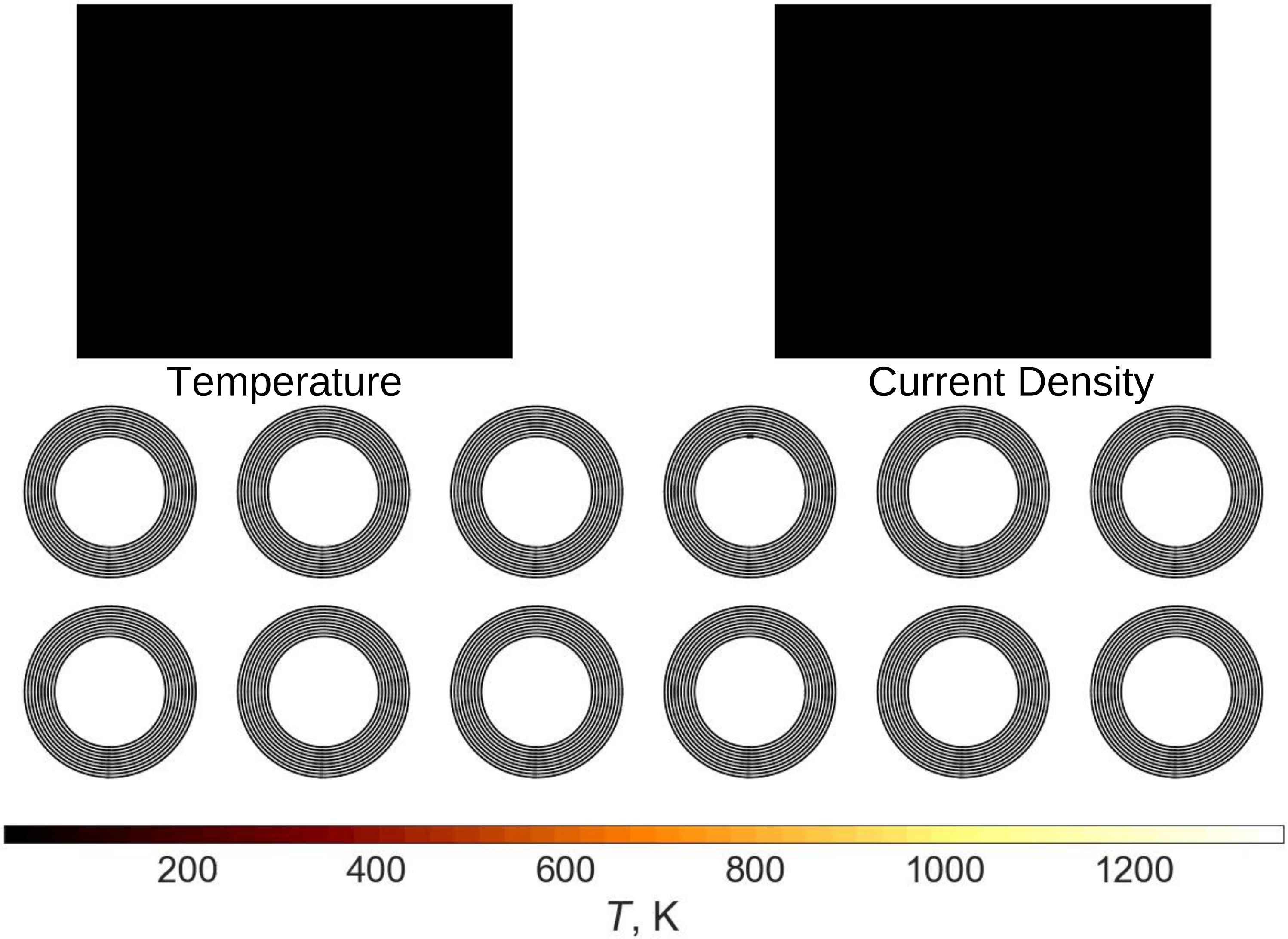
Simulation 8 - PF reference (+ no PDU6)



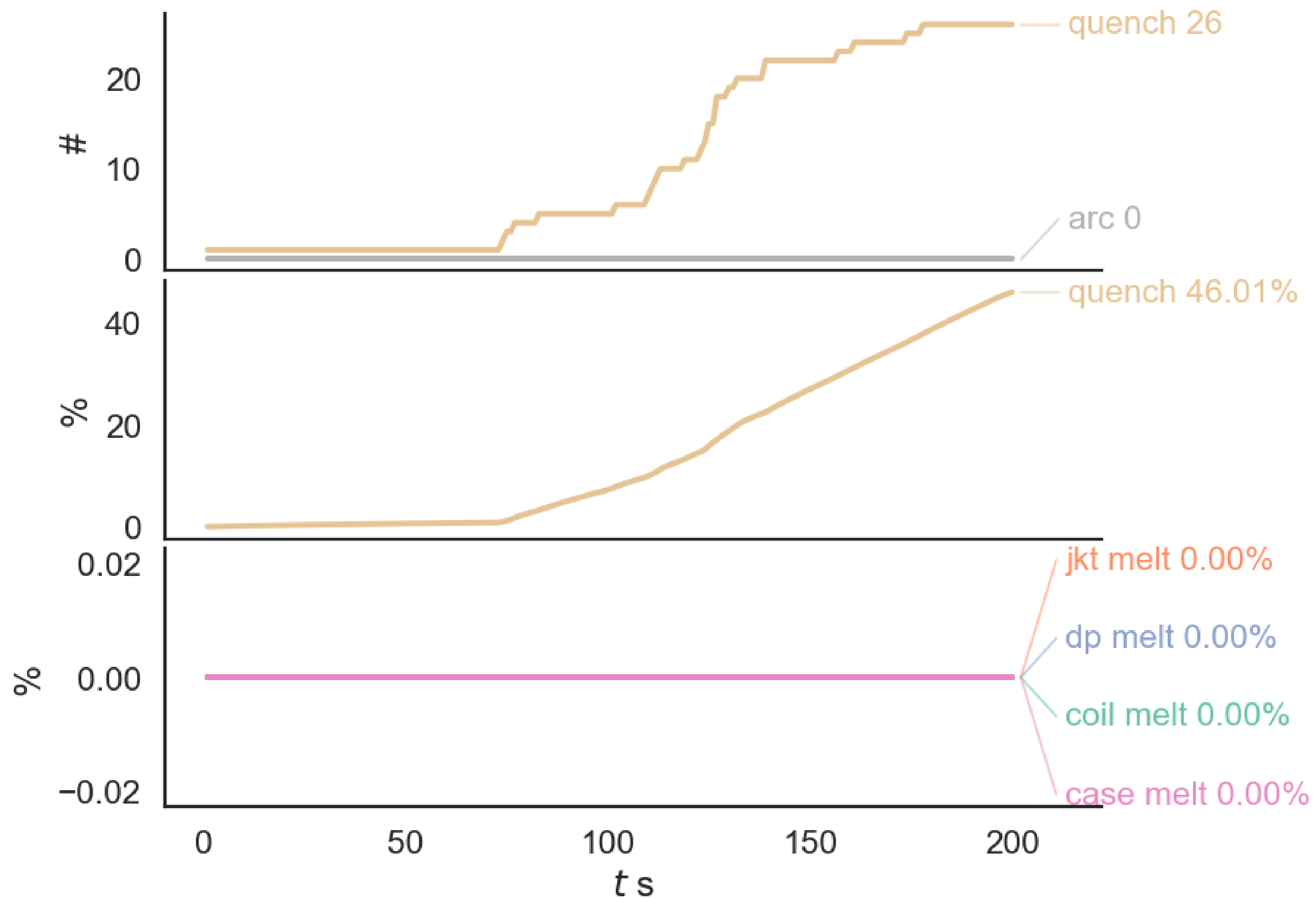
Simulation 8 - PF reference (+ no PDU6)

No Arcs

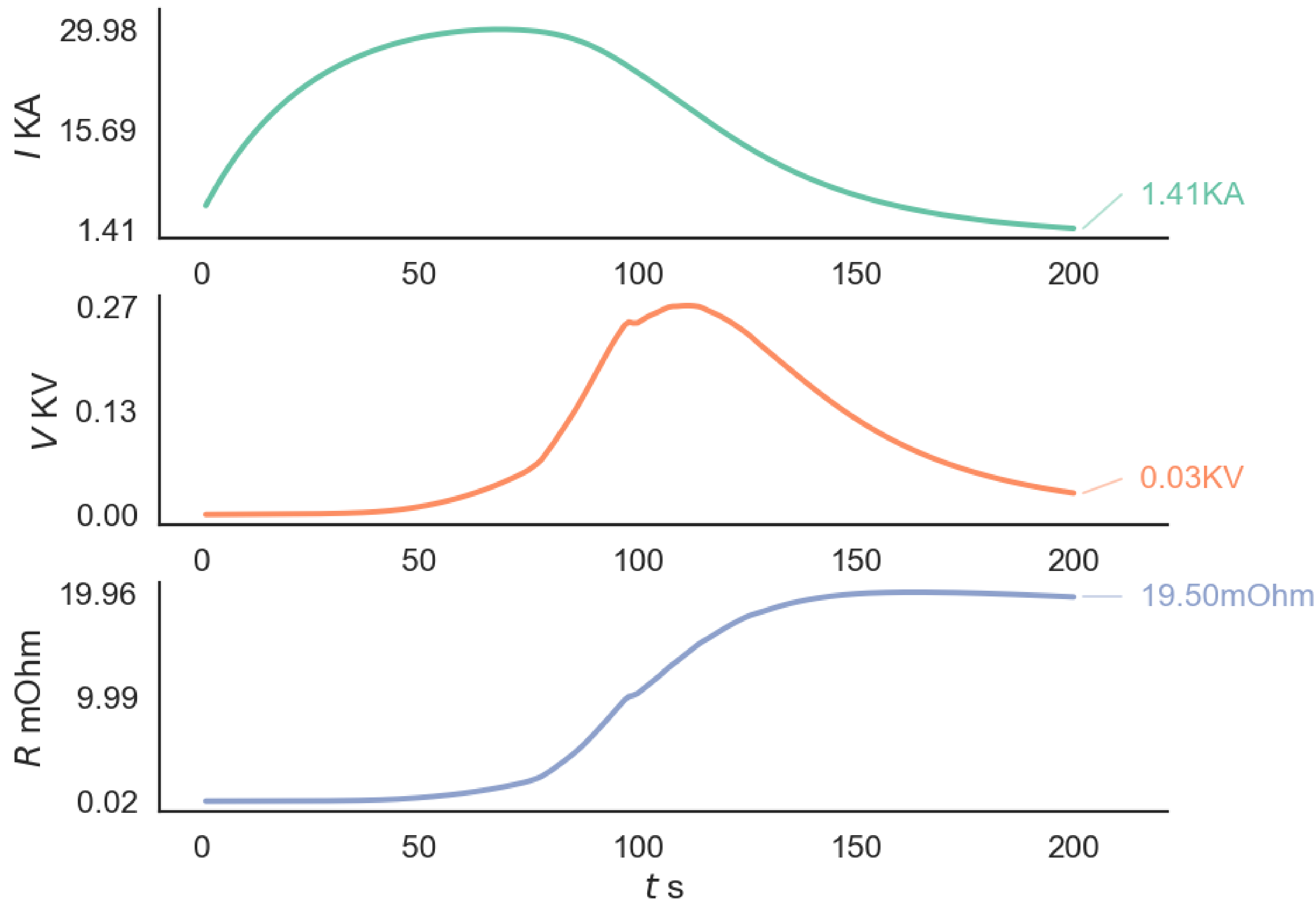
Simulation 9 - PF2



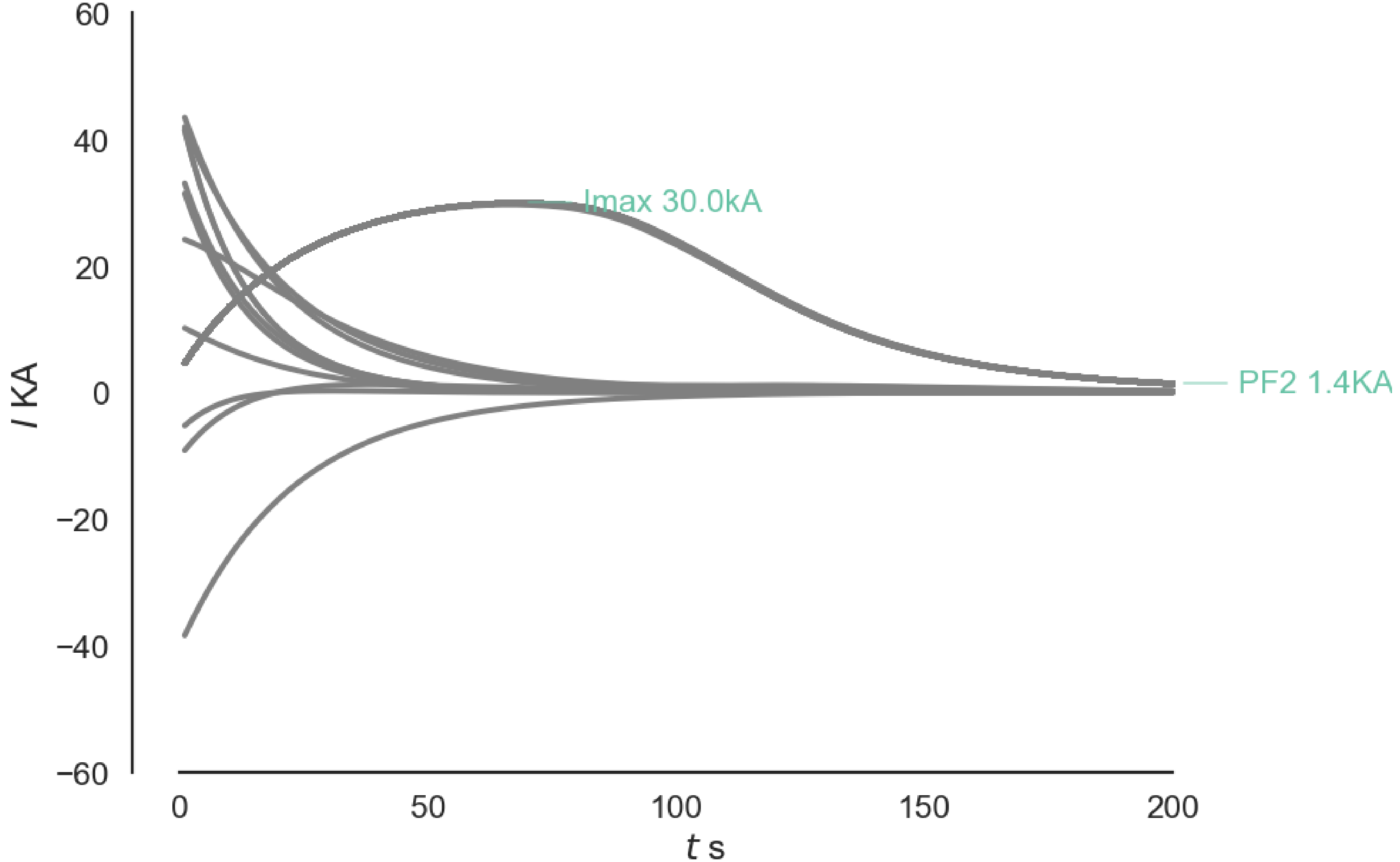
Simulation 9 - PF2



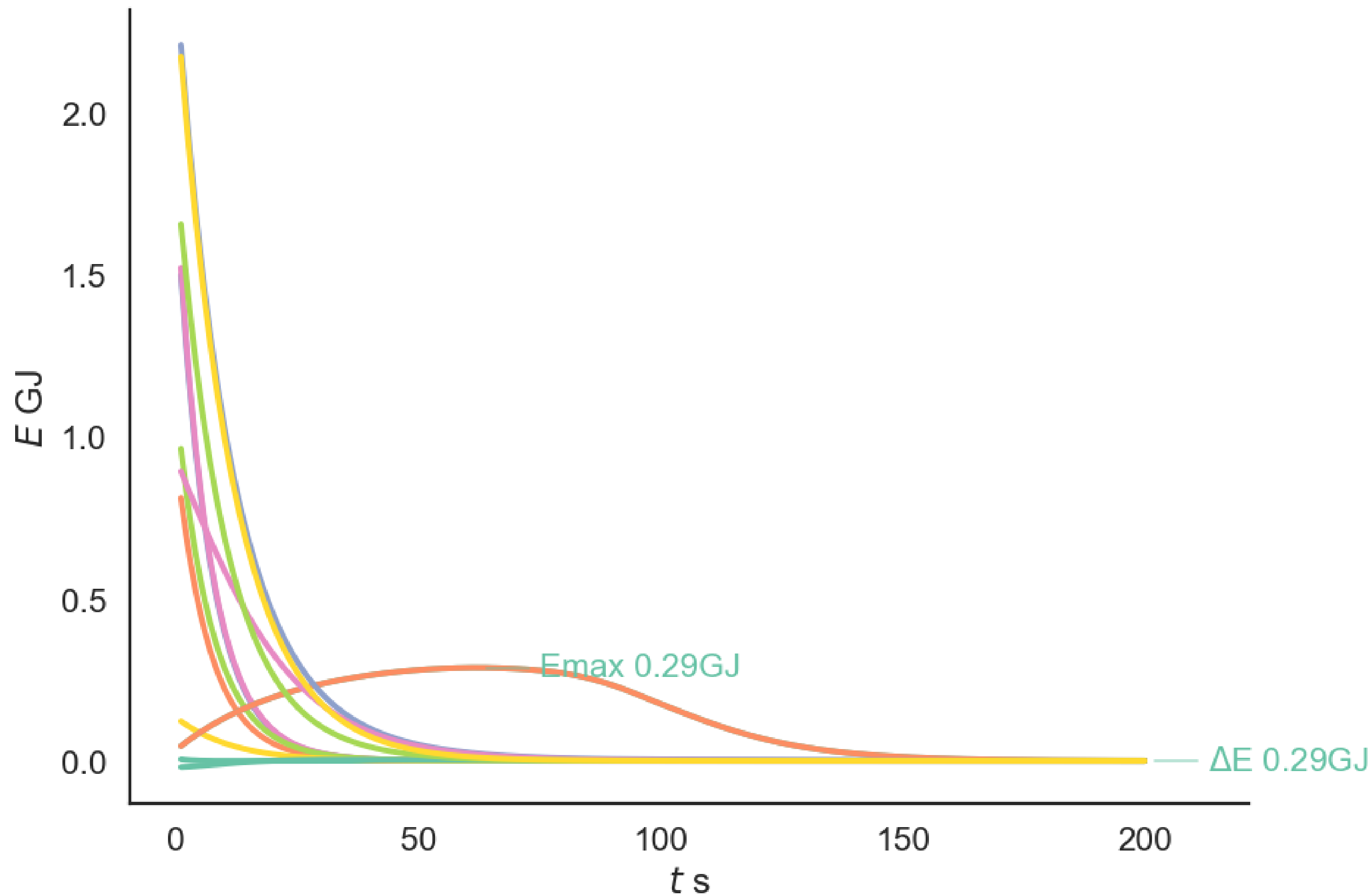
Simulation 9 - PF2



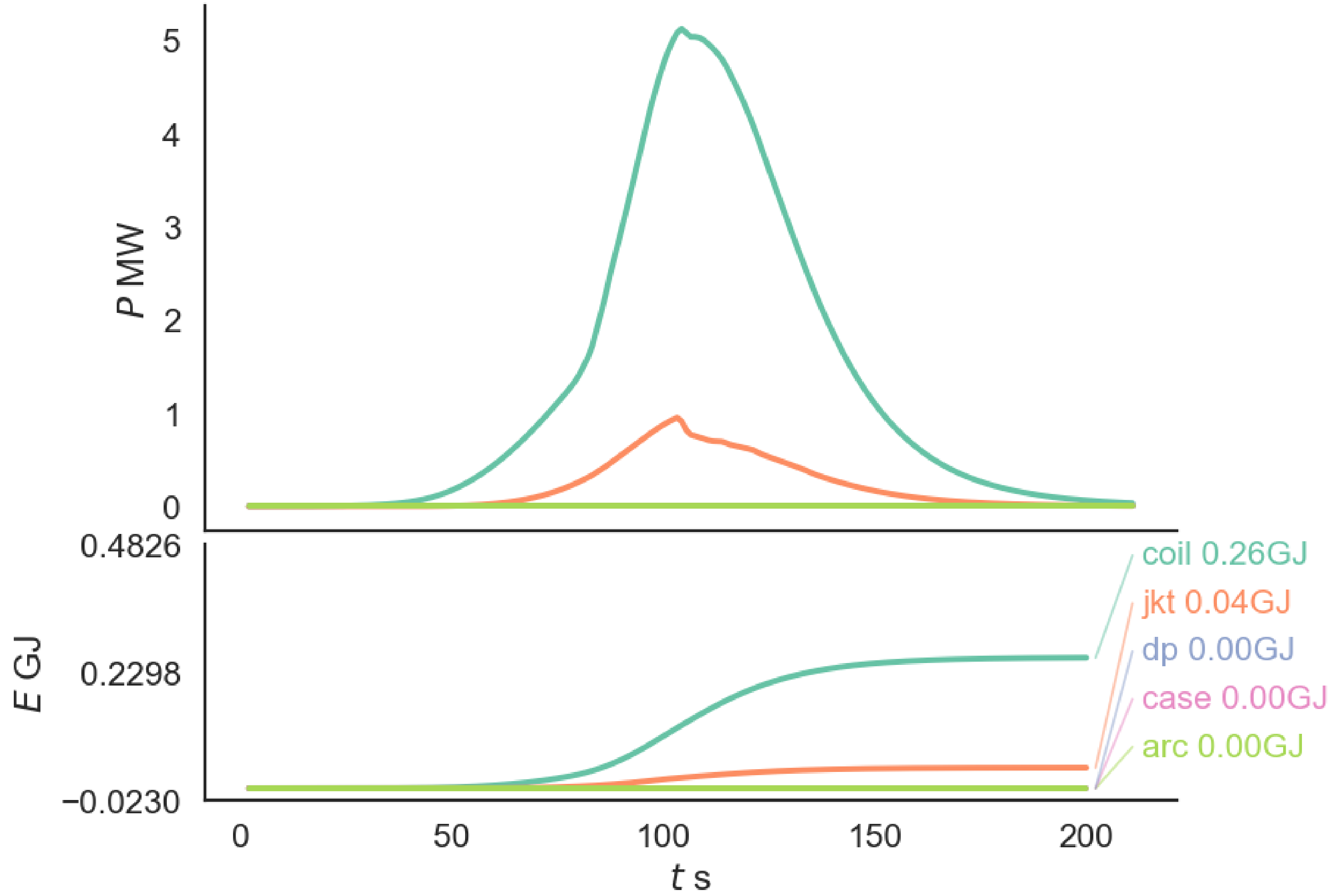
Simulation 9 - PF2



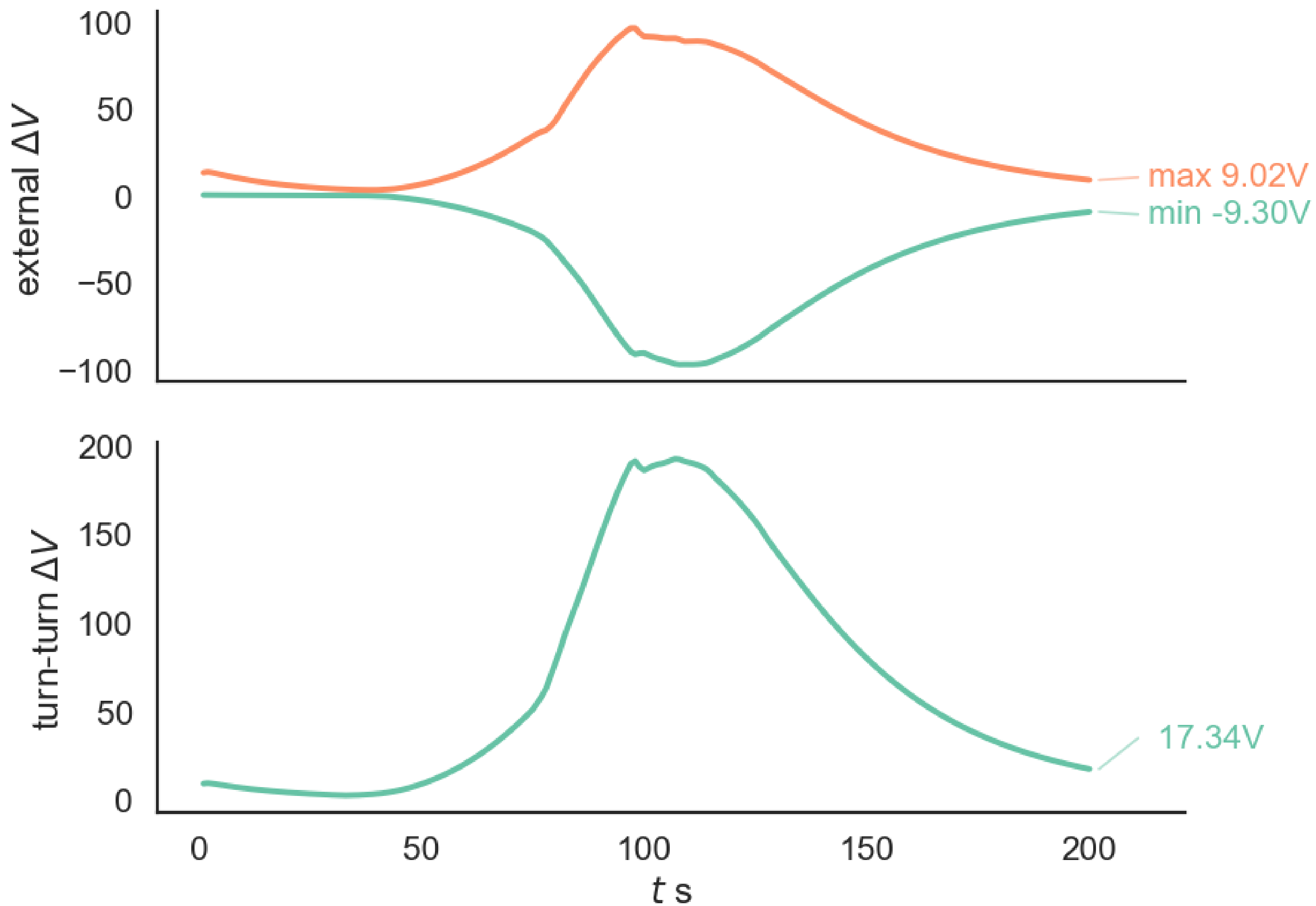
Simulation 9 - PF2



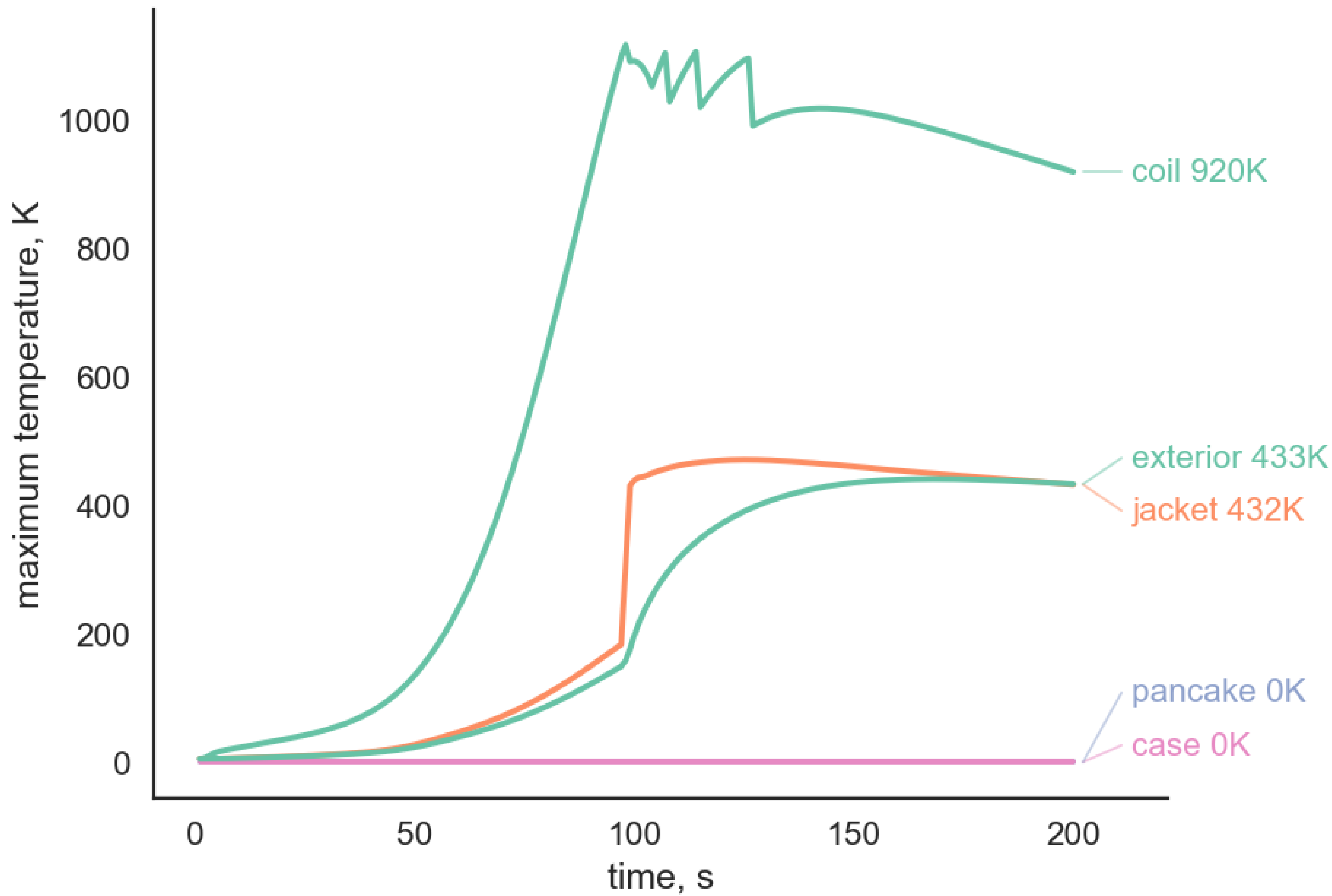
Simulation 9 - PF2



Simulation 9 - PF2



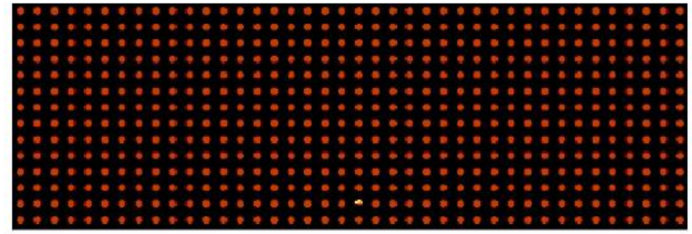
Simulation 9 - PF2



Simulation 9 - PF2

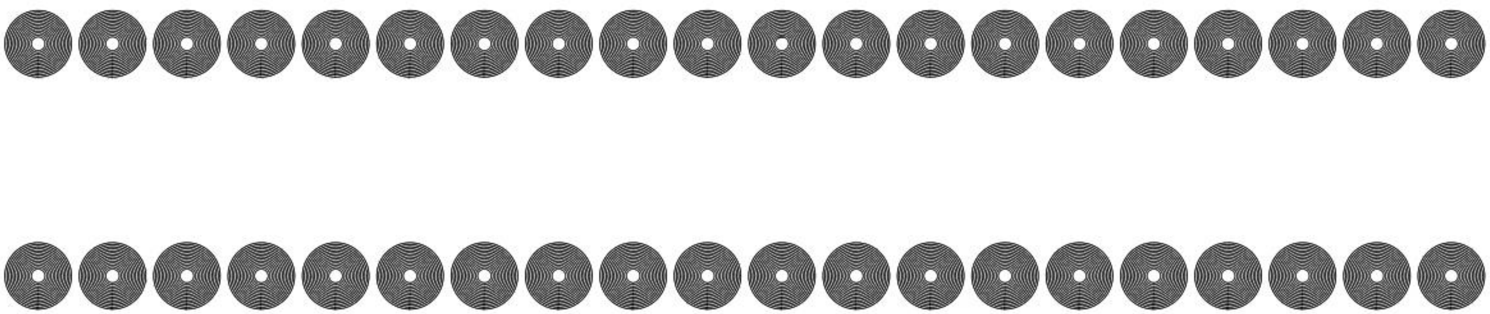
No Arcs

Simulation 10 - CS5

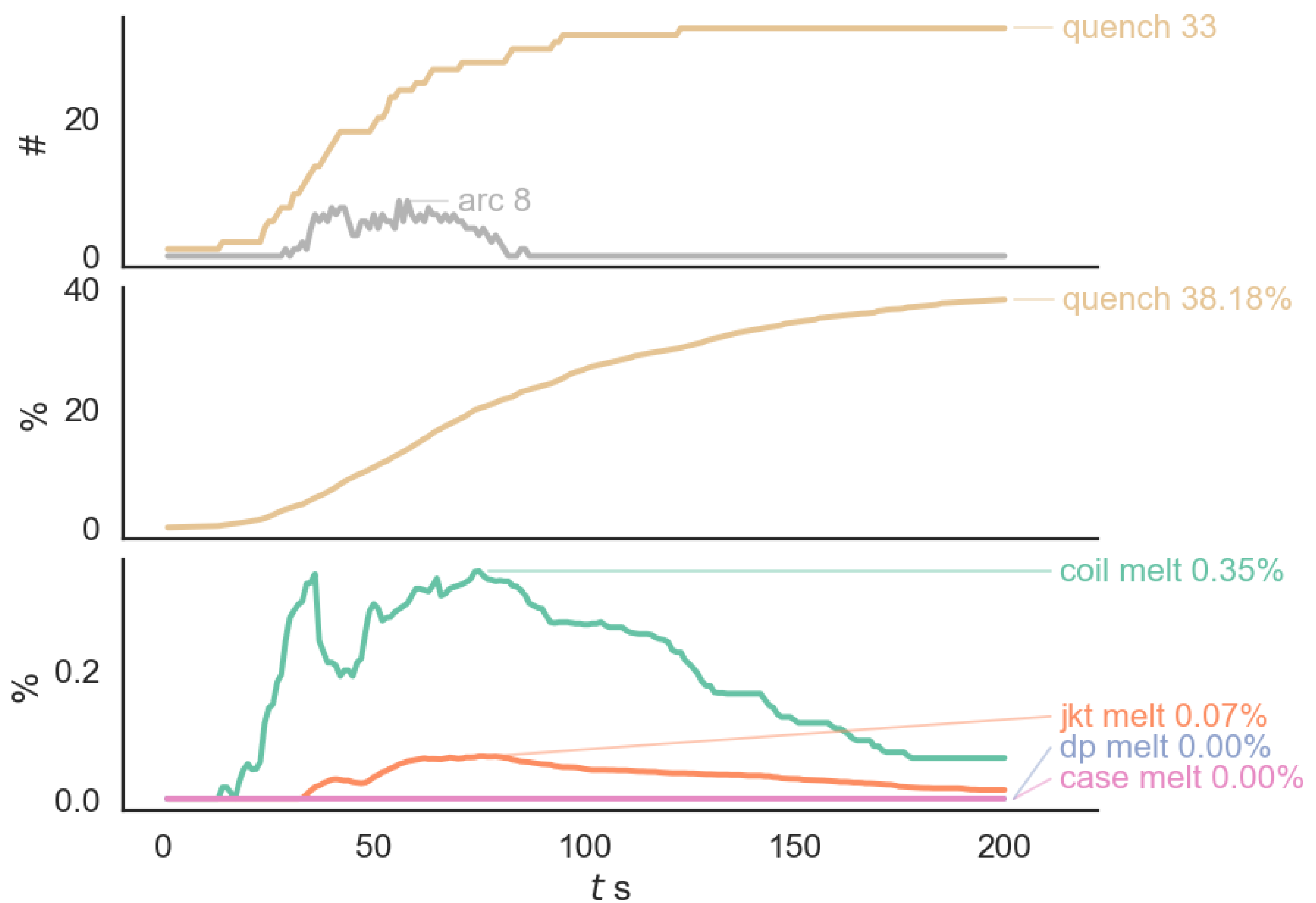


Temperature

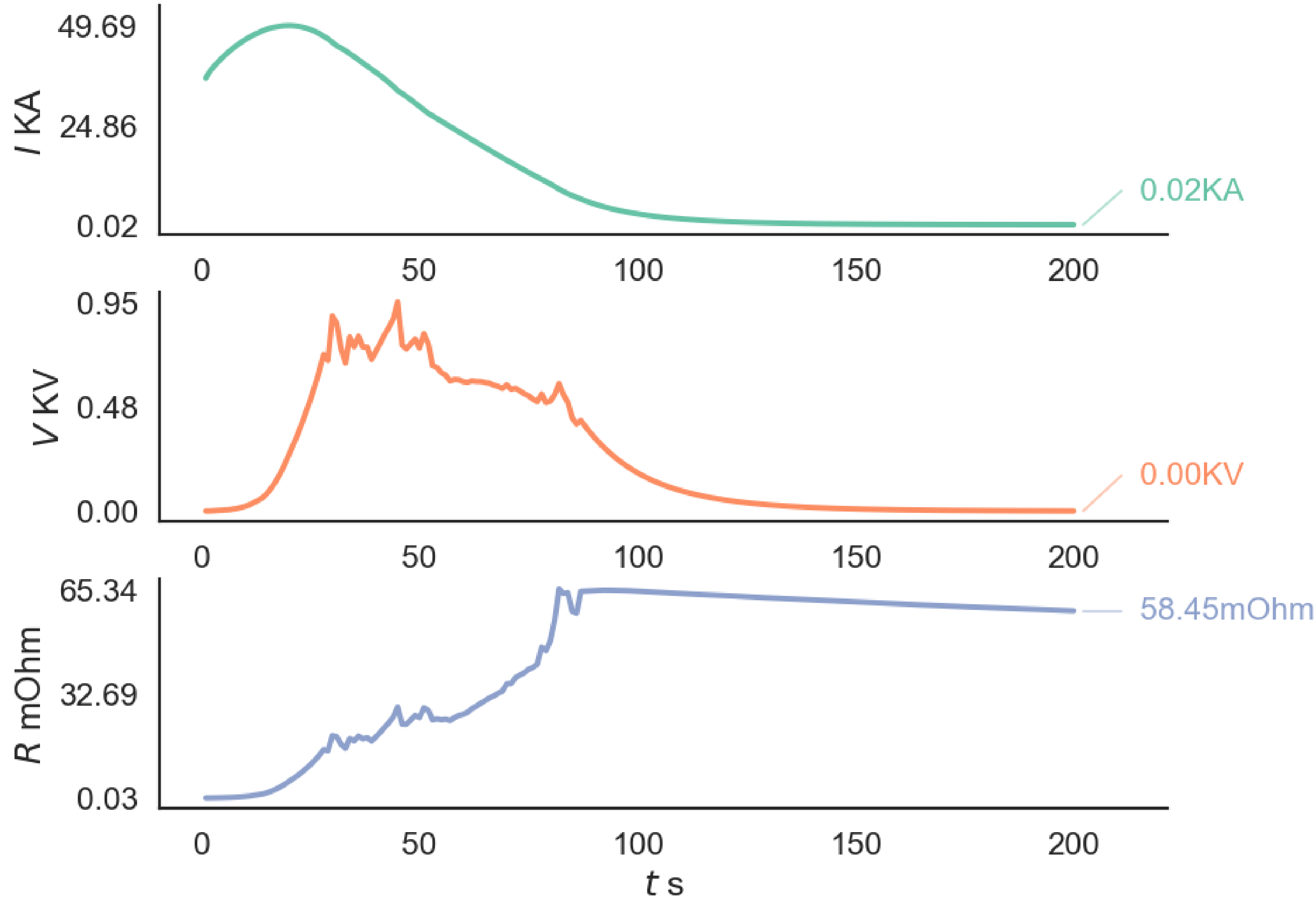
Current Density



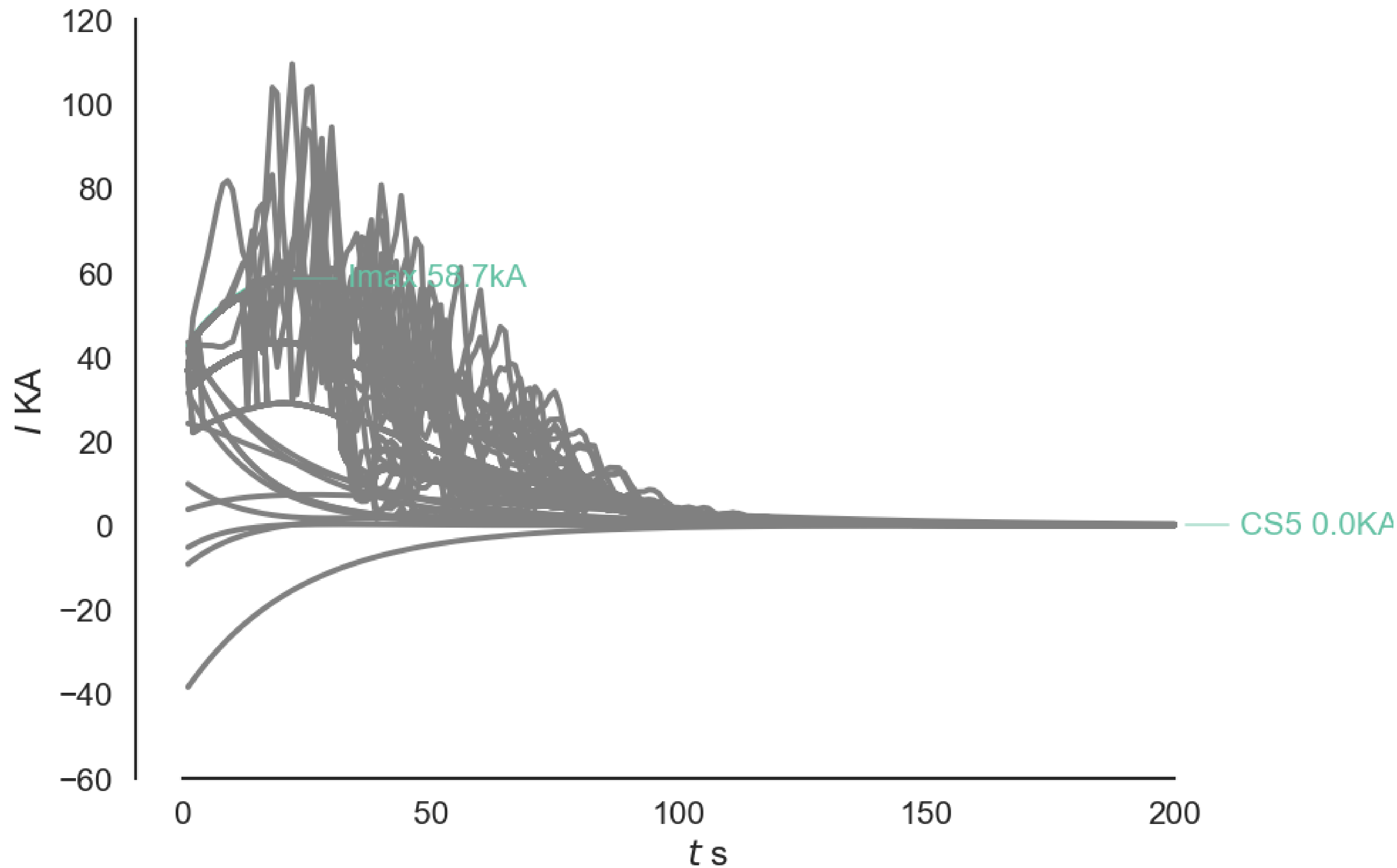
Simulation 10 - CS5



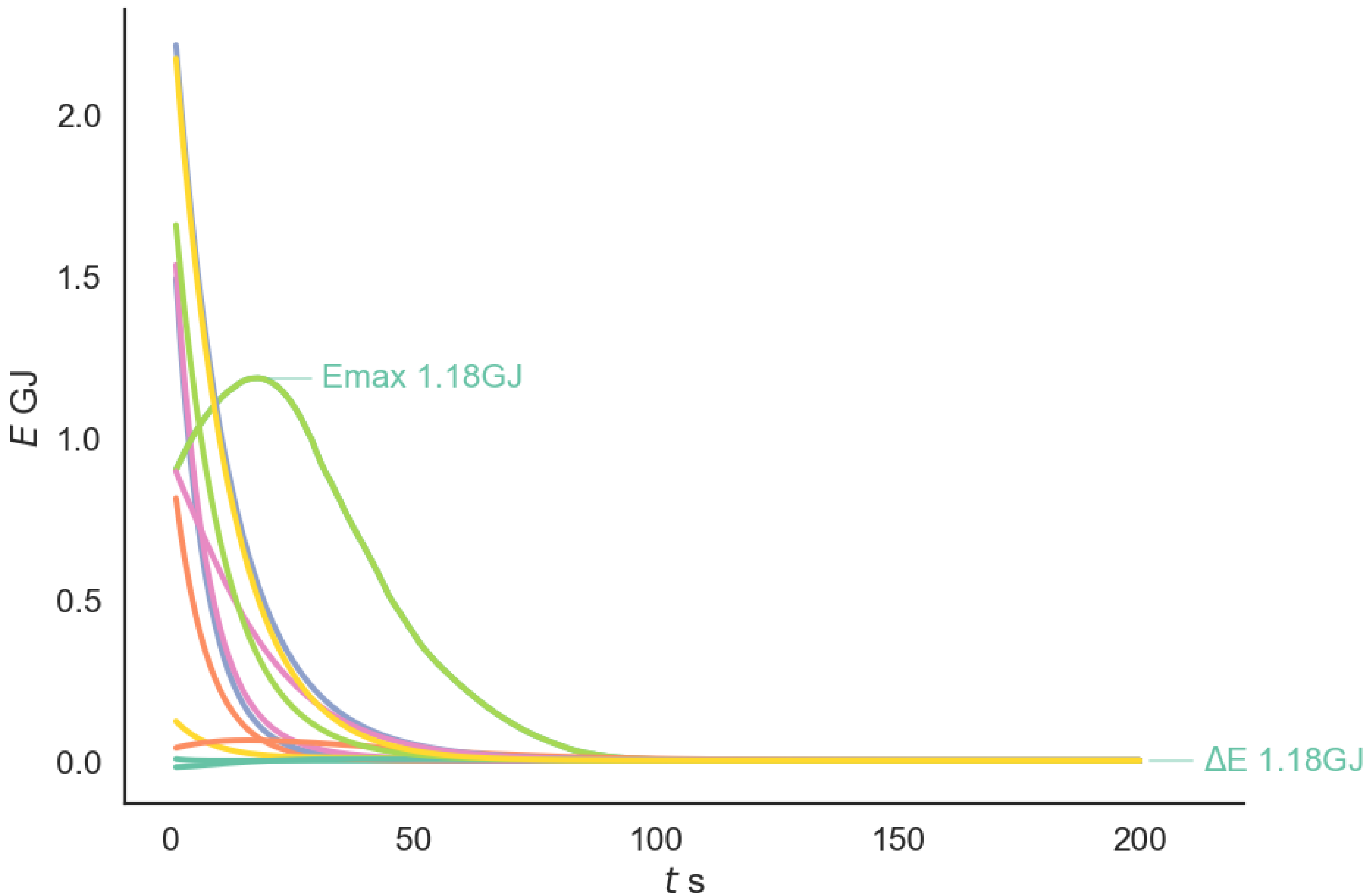
Simulation 10 - CS5



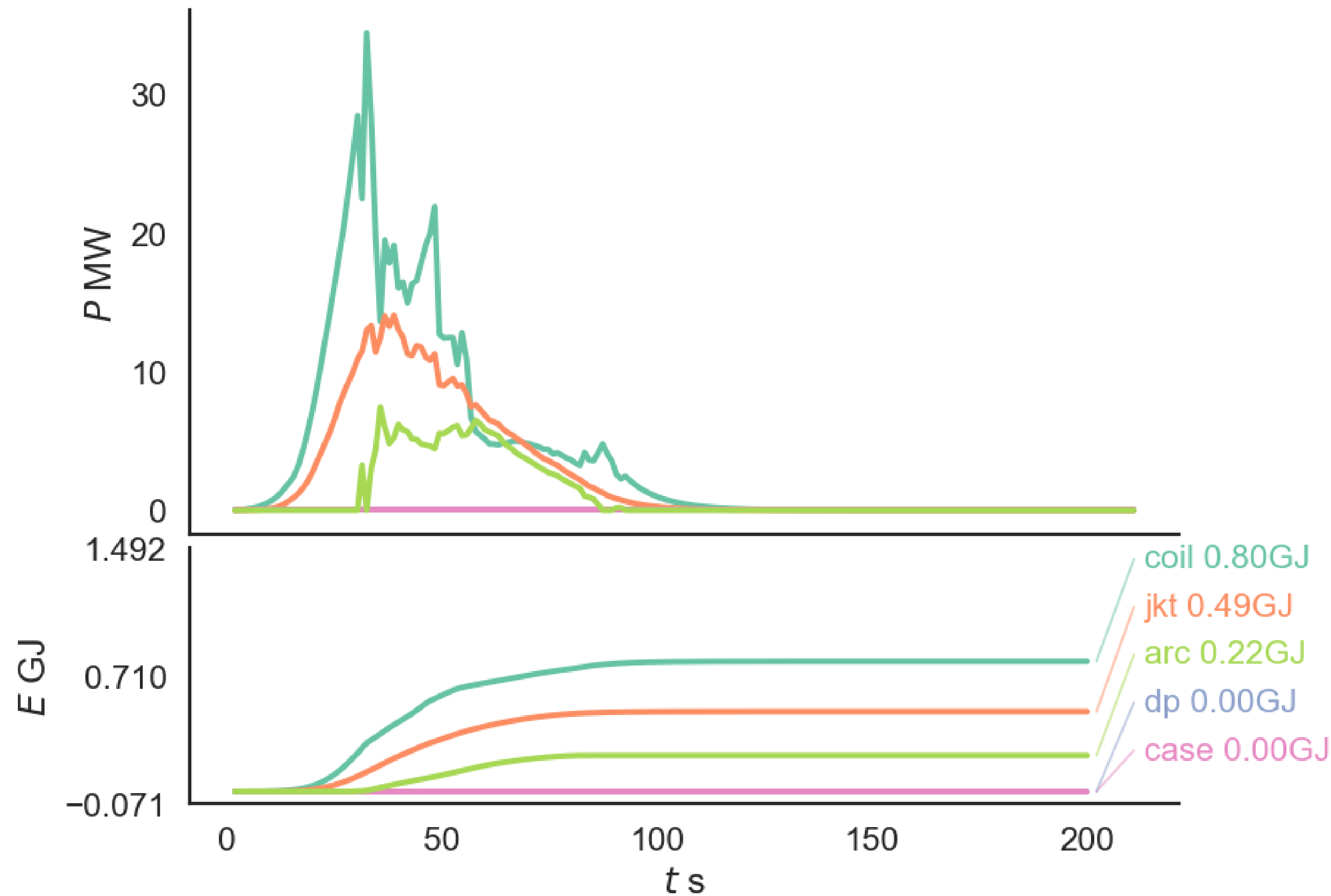
Simulation 10 - CS5



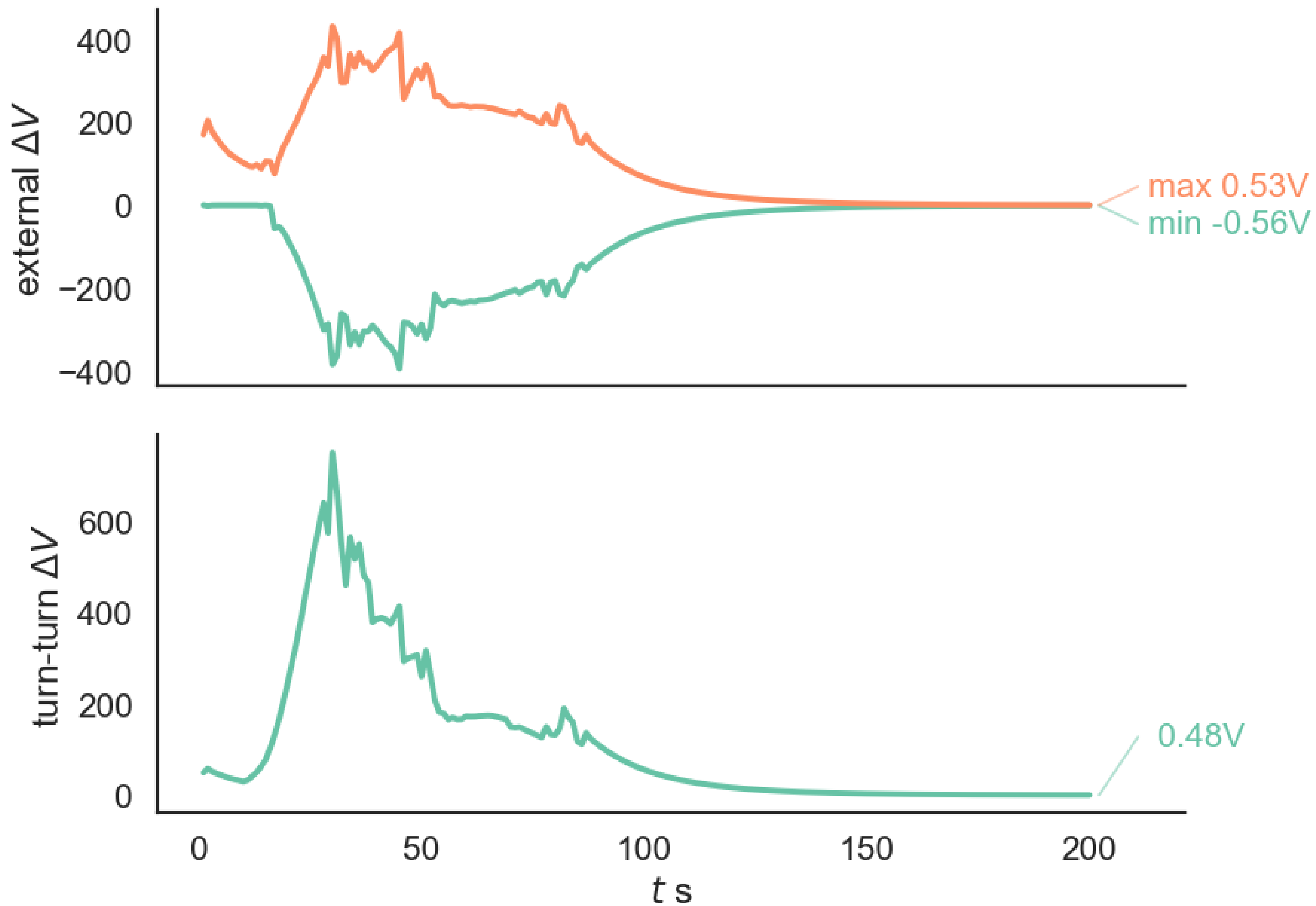
Simulation 10 - CS5



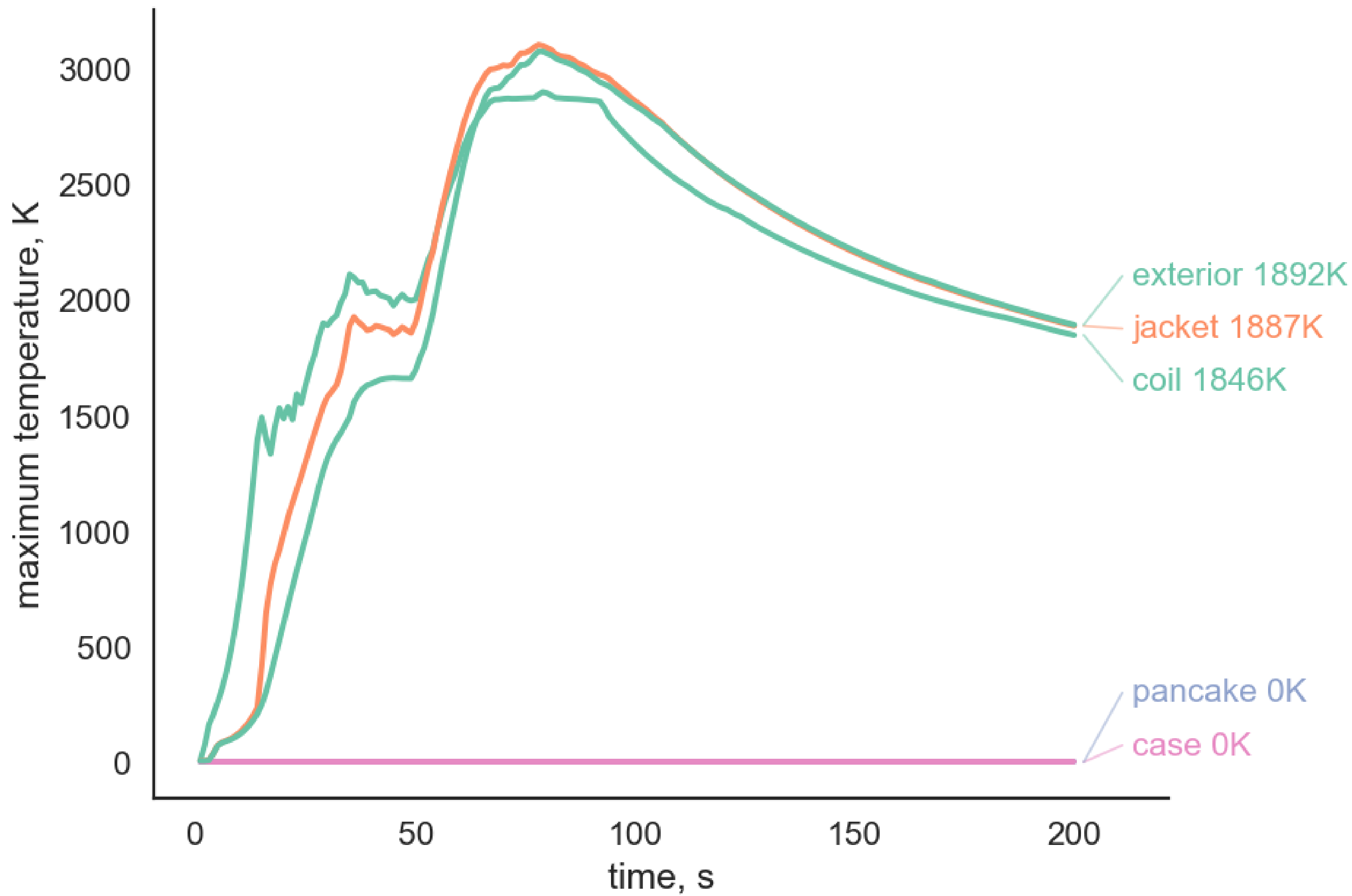
Simulation 10 - CS5



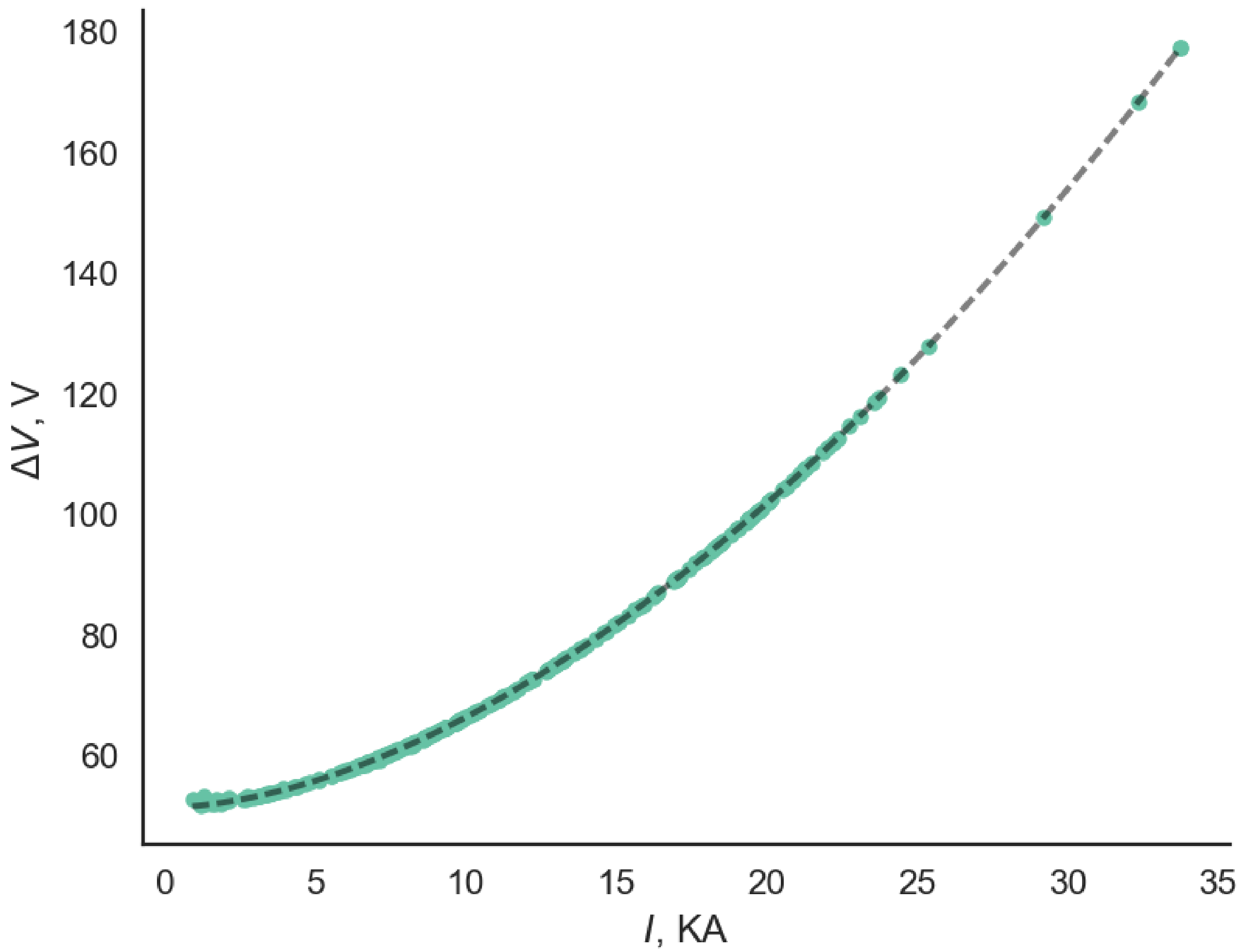
Simulation 10 - CS5



Simulation 10 - CS5

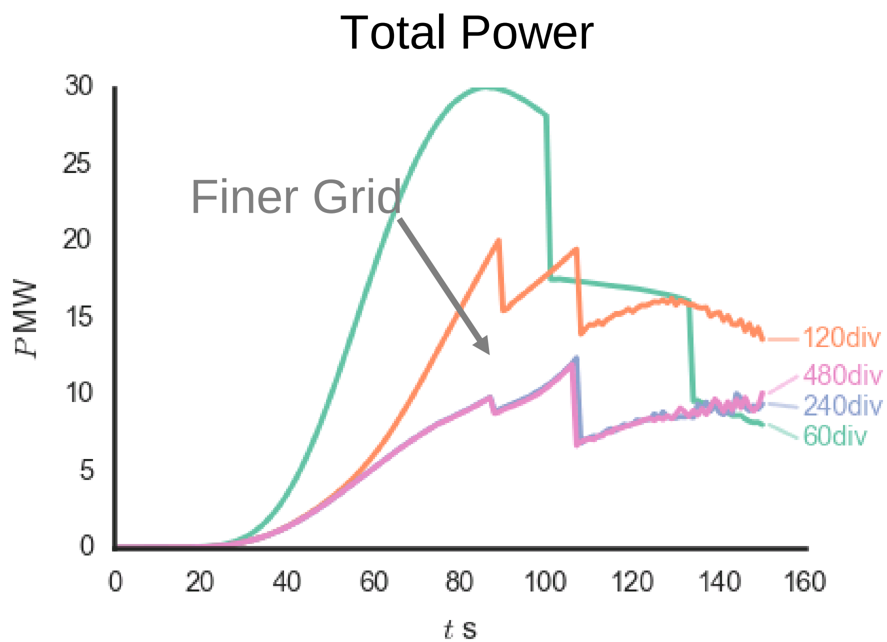


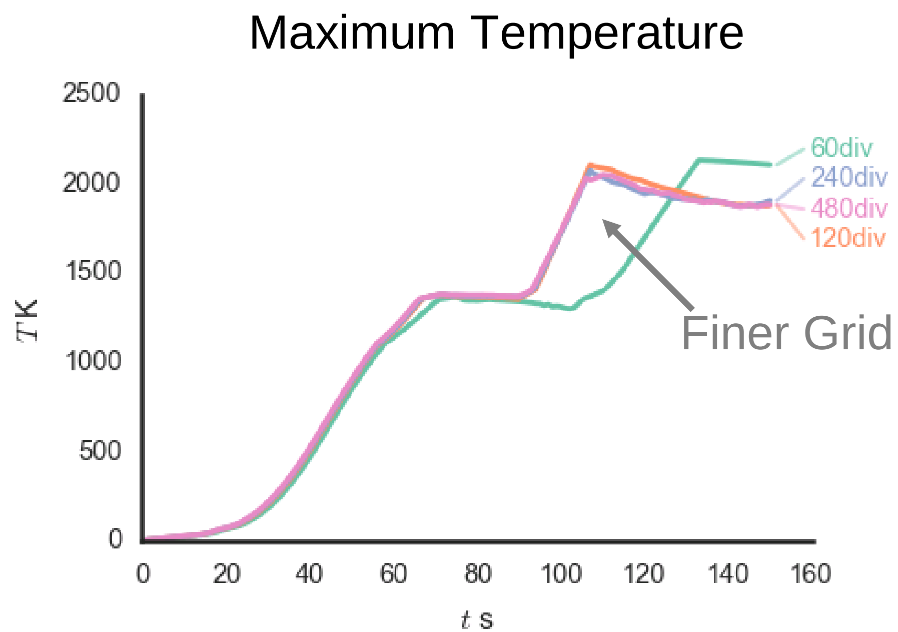
Simulation 10 - CS5



Sensitivity studies

Sensitivity study – grid convergence



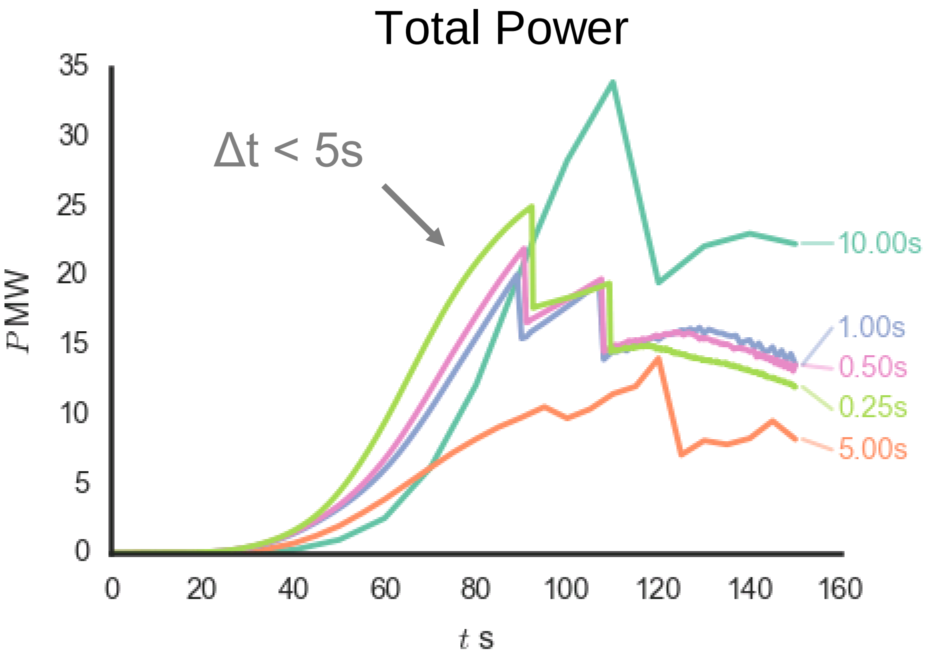


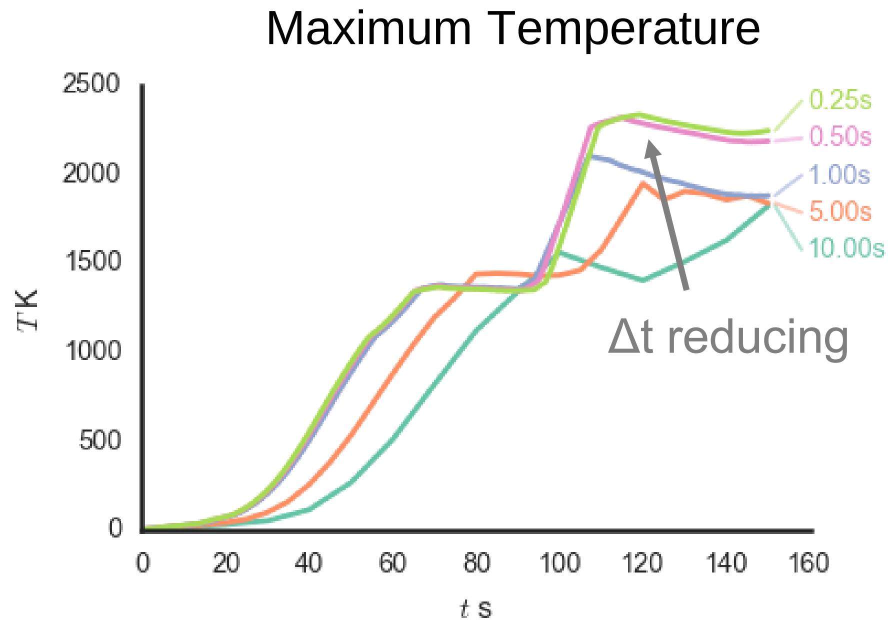
Dependance of time-step on total power on swept FE grid resolution

Simulation data produced using 100 divisions (TF reference)

Sensitivity study – time step convergence

Δt ≡ load-step update (single sub-step)





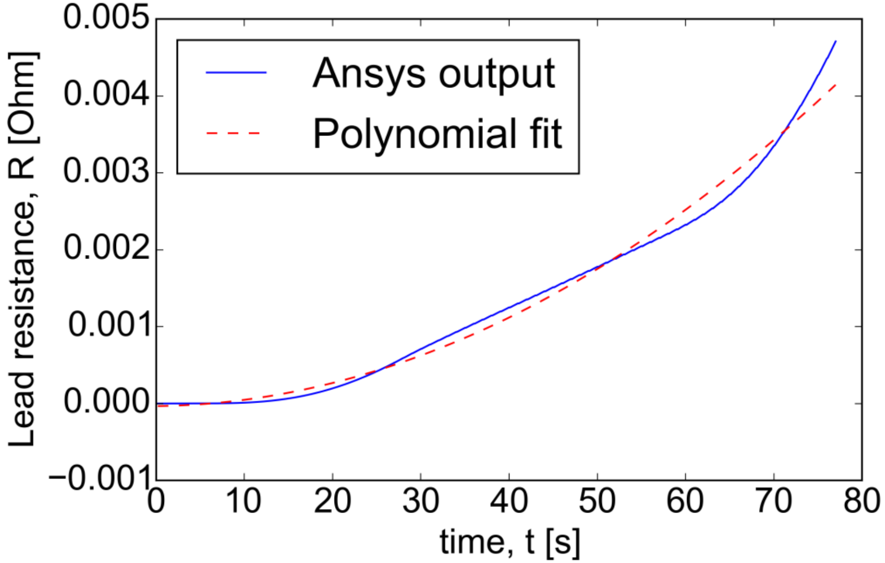
Dependance of time-step on total power and maximum temperature

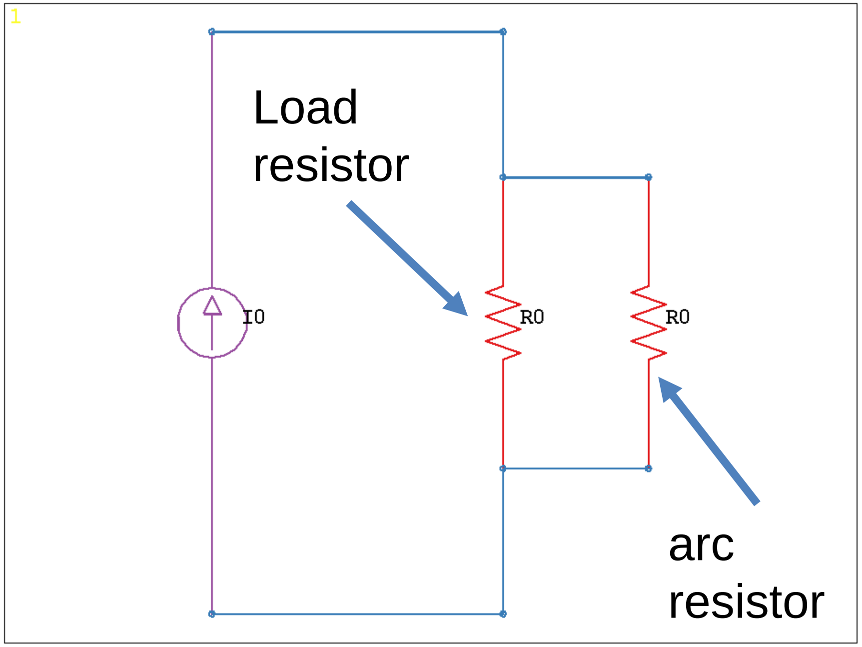
Simulation data produced using Δt=1s

Electrical - arcs (model development)

Electrical - arcs (model development)

Polynomial fit from TF simulation

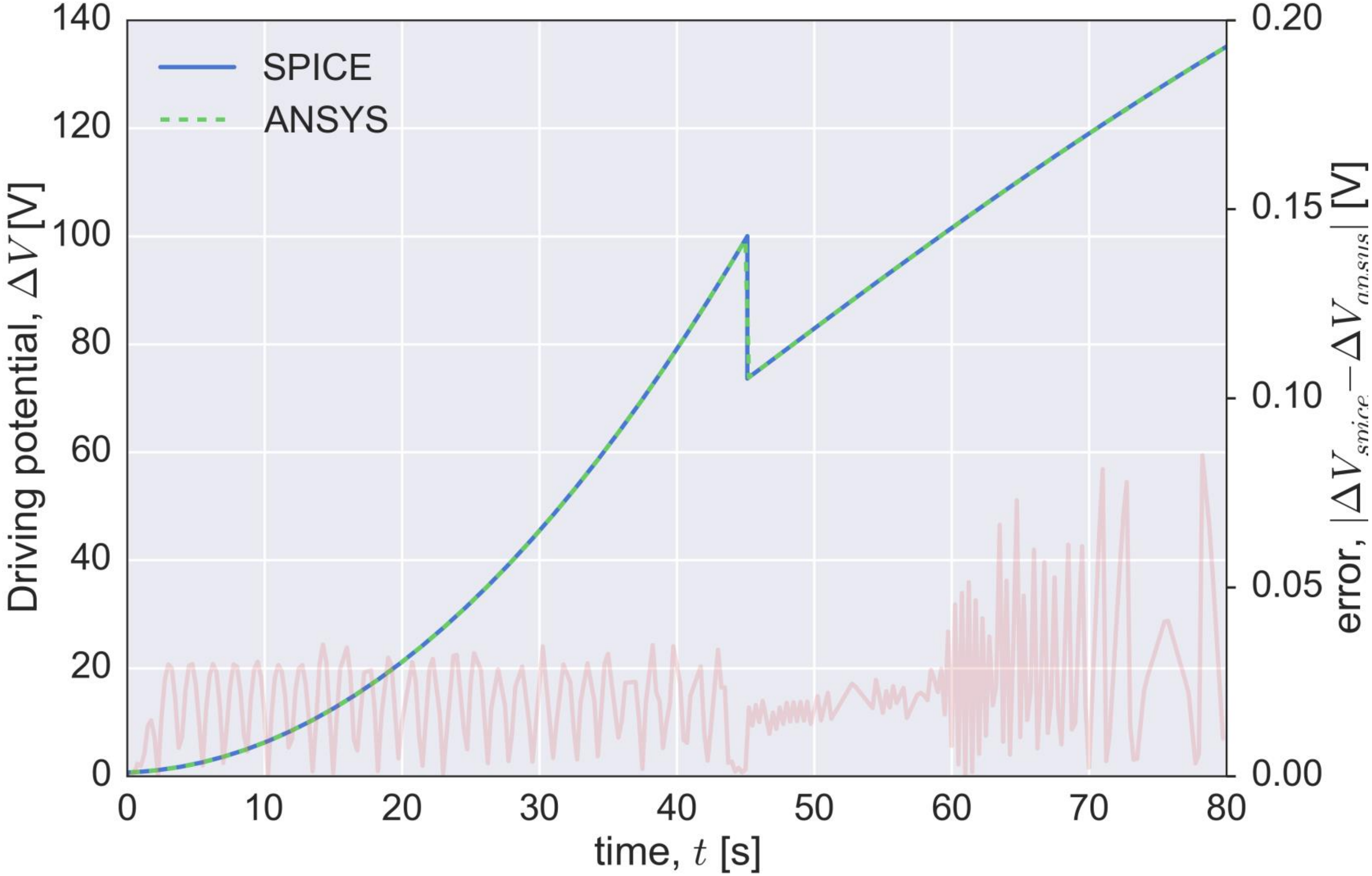




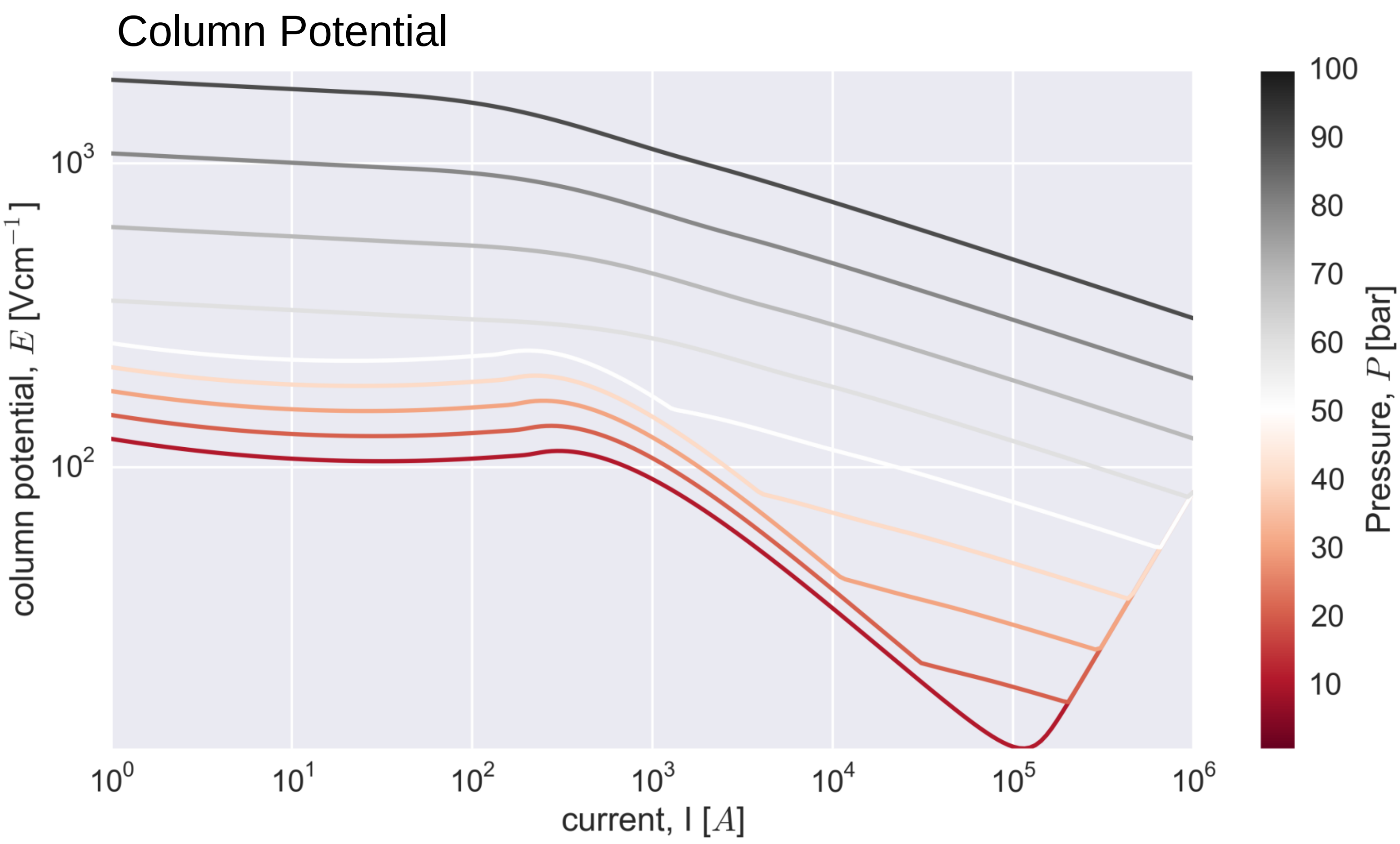
- R(t) applied as load resistor
- Arc enabled when dV>100V
- Kronhart arc verified with SPICE model
- Holmes arc implemented, V *fn* (current, pressure, diameter, temperature)

Electrical - arcs (model development)

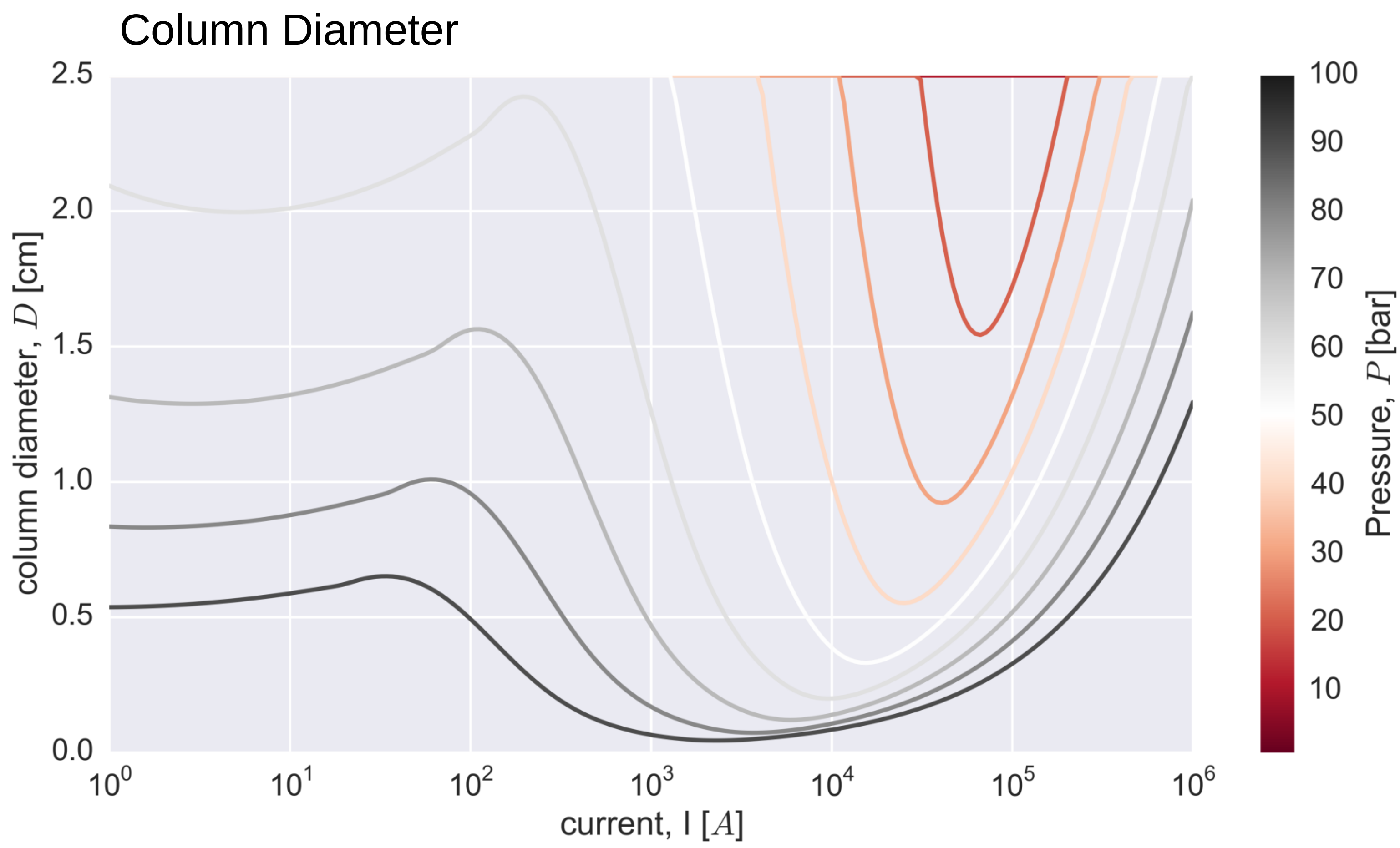
Kronhart model verification



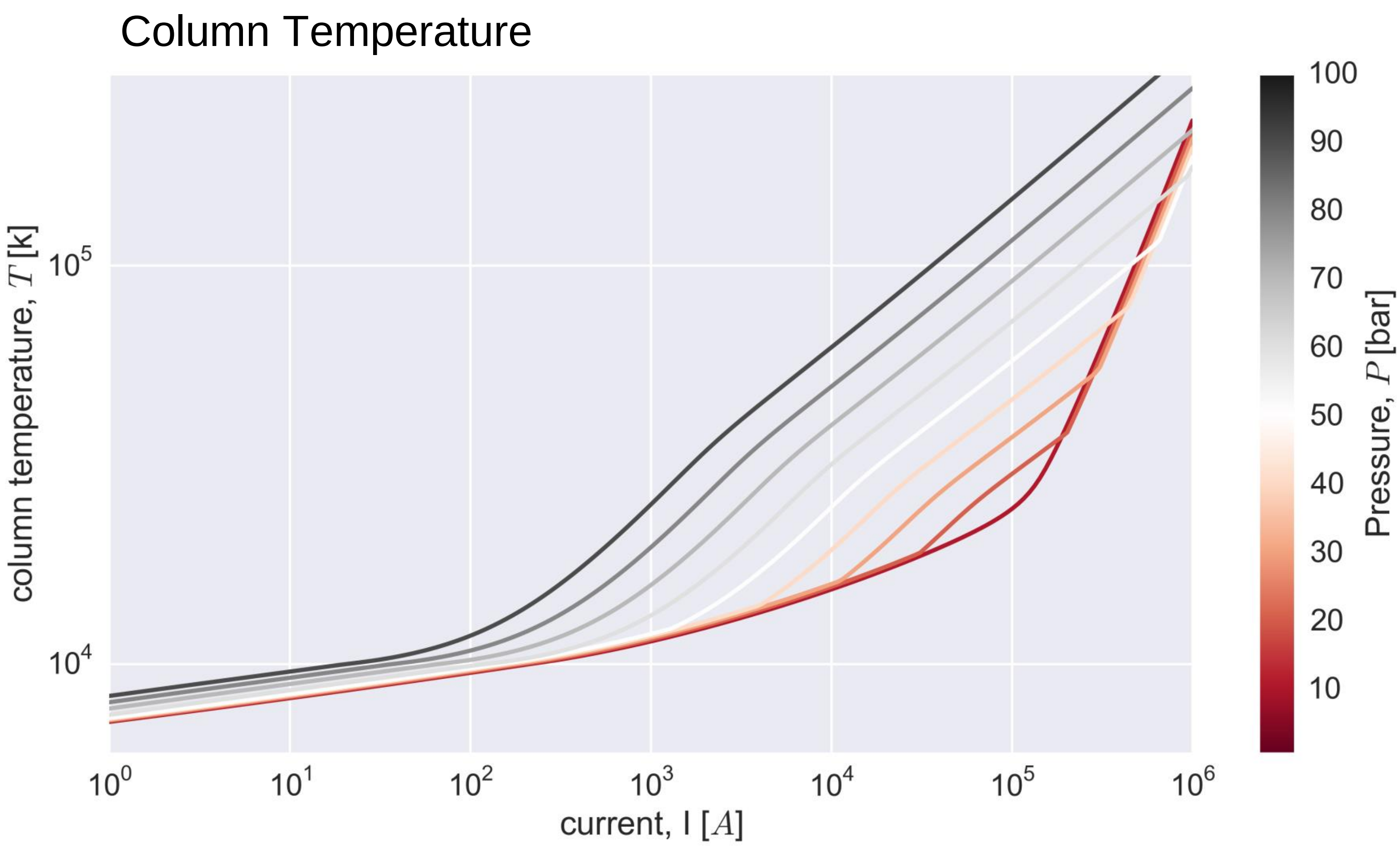
Holmes arc model



Holmes arc model



Holmes arc model



Holmes arc ANSYS test-bench