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# Quench Transient Simulation in a Self-Protecting Magnet with a 3D Finite-Difference Scheme

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19 November 2021

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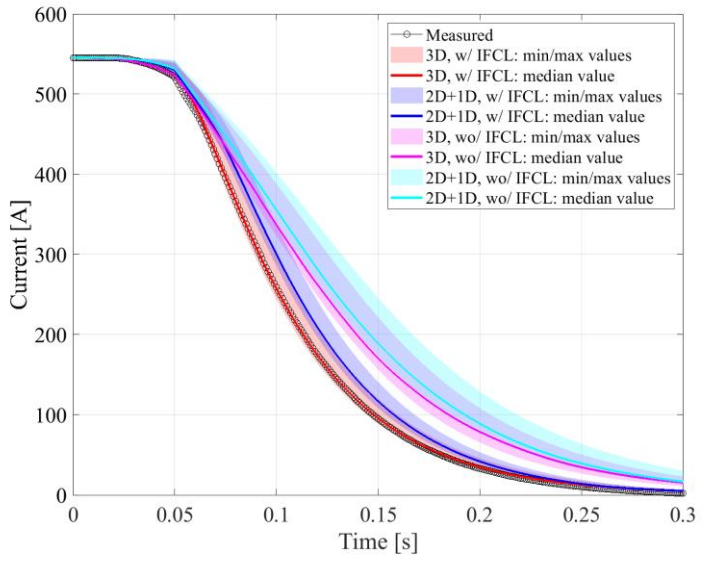


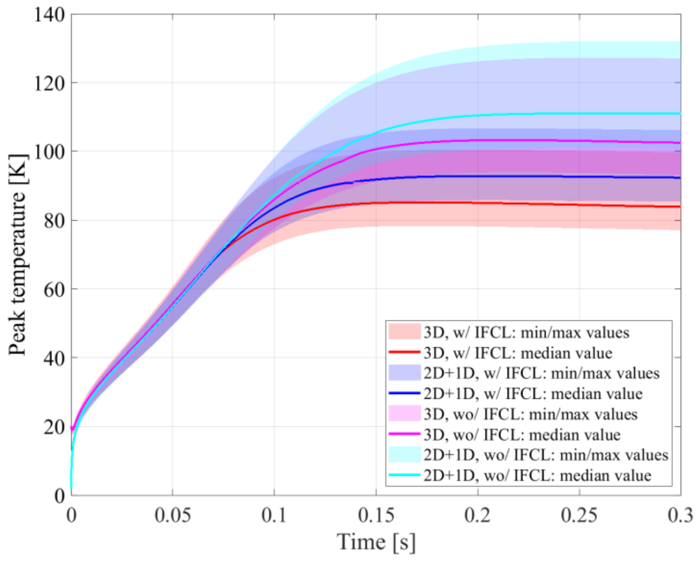


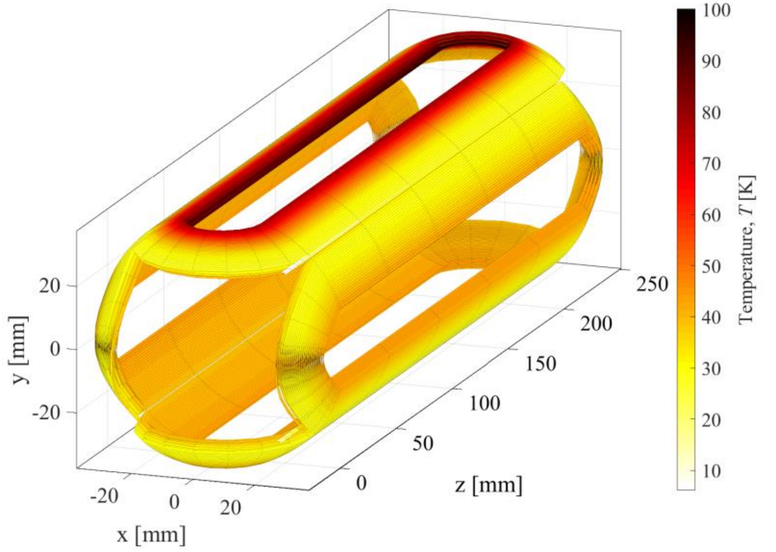

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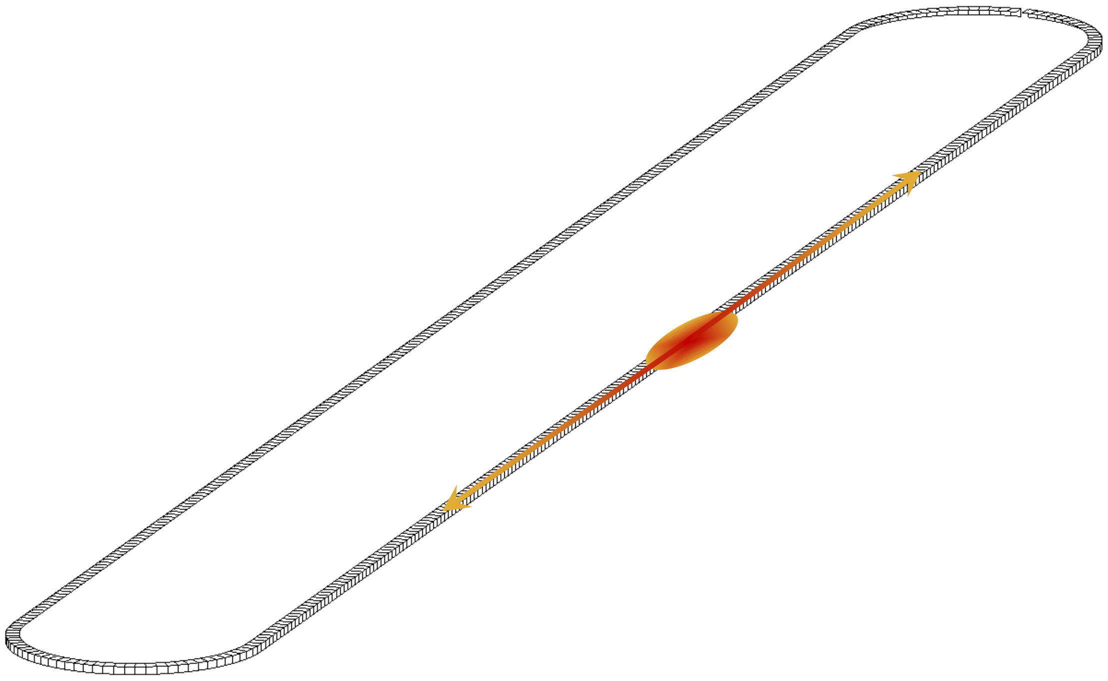
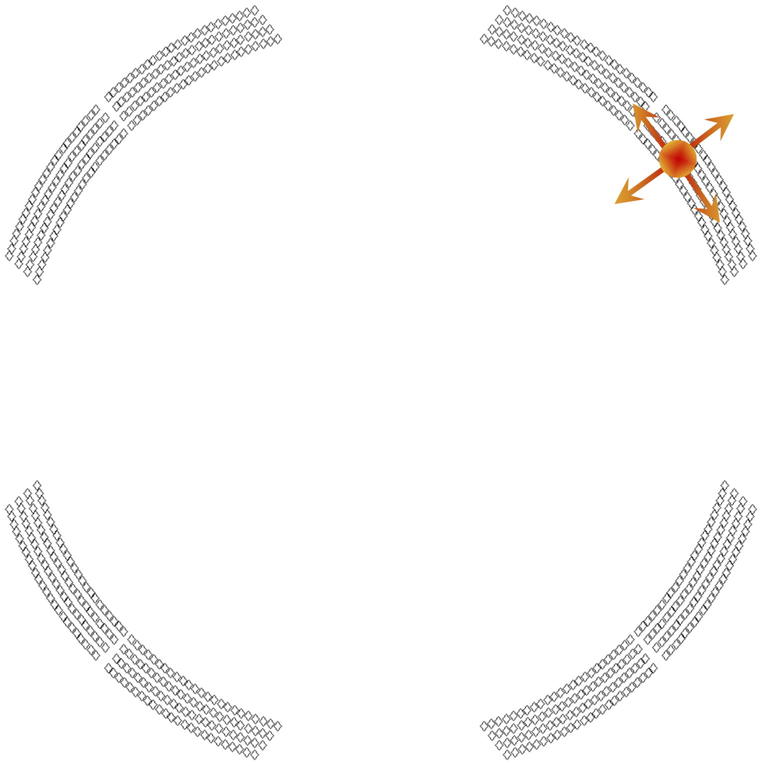
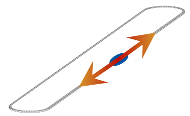


| | |
|---|---|
| 1D | Longitudinal |

# Quench Transient Simulation in a Self-Protecting Magnet with a 3D Finite-Difference Scheme



| | | |
|---|---|---|
|  | 1D | Longitudinal |
| | 2D | Transversal |

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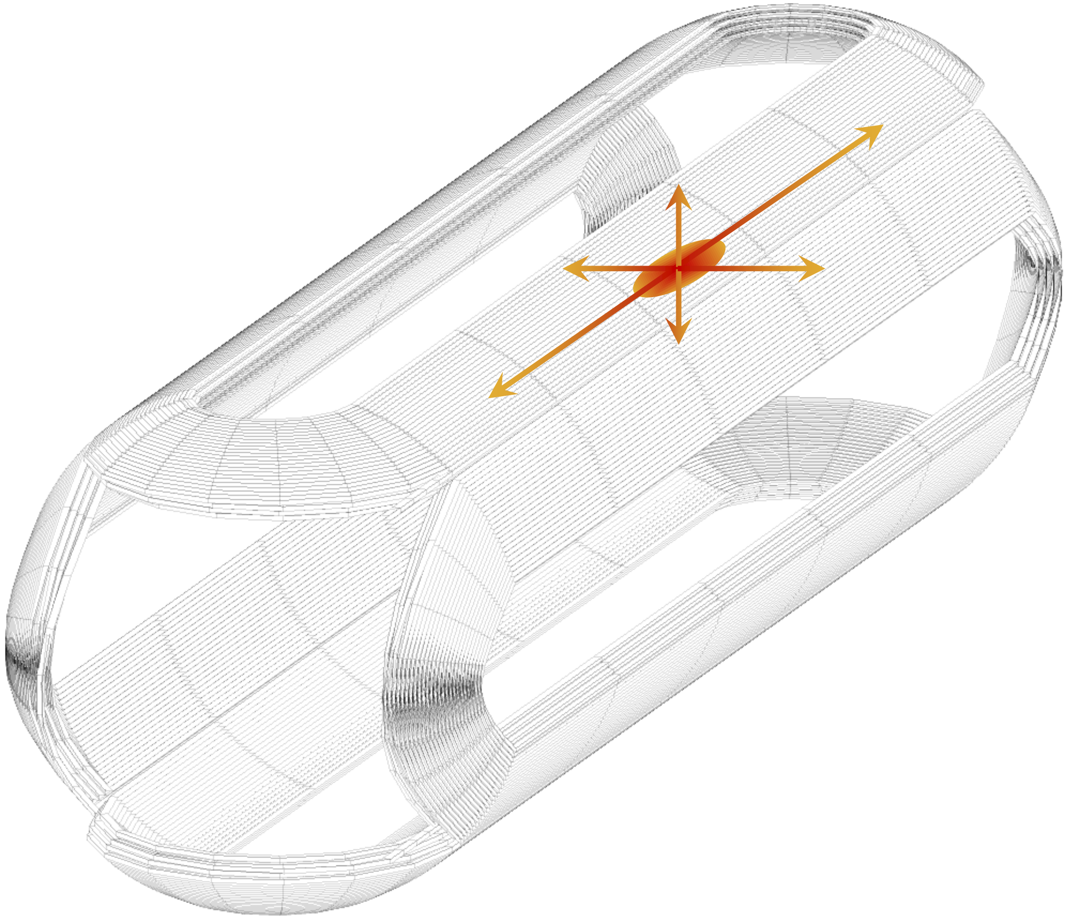
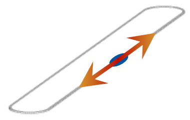
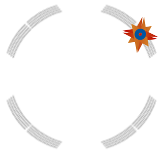
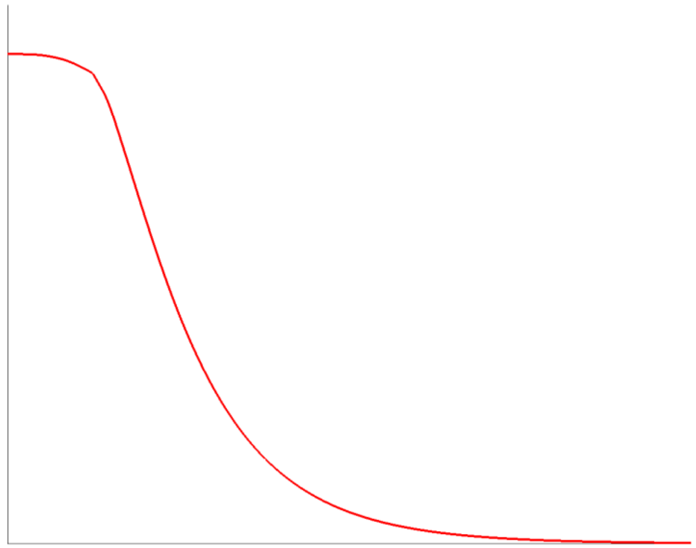


| | | |
|---|---|---|
|  | 1D | Longitudinal |
|  | 2D | Transversal |
| | 3D | Longitudinal and transversal |

# Quench Transient Simulation in a Self-Protecting Magnet with a 3D Finite-Difference Scheme

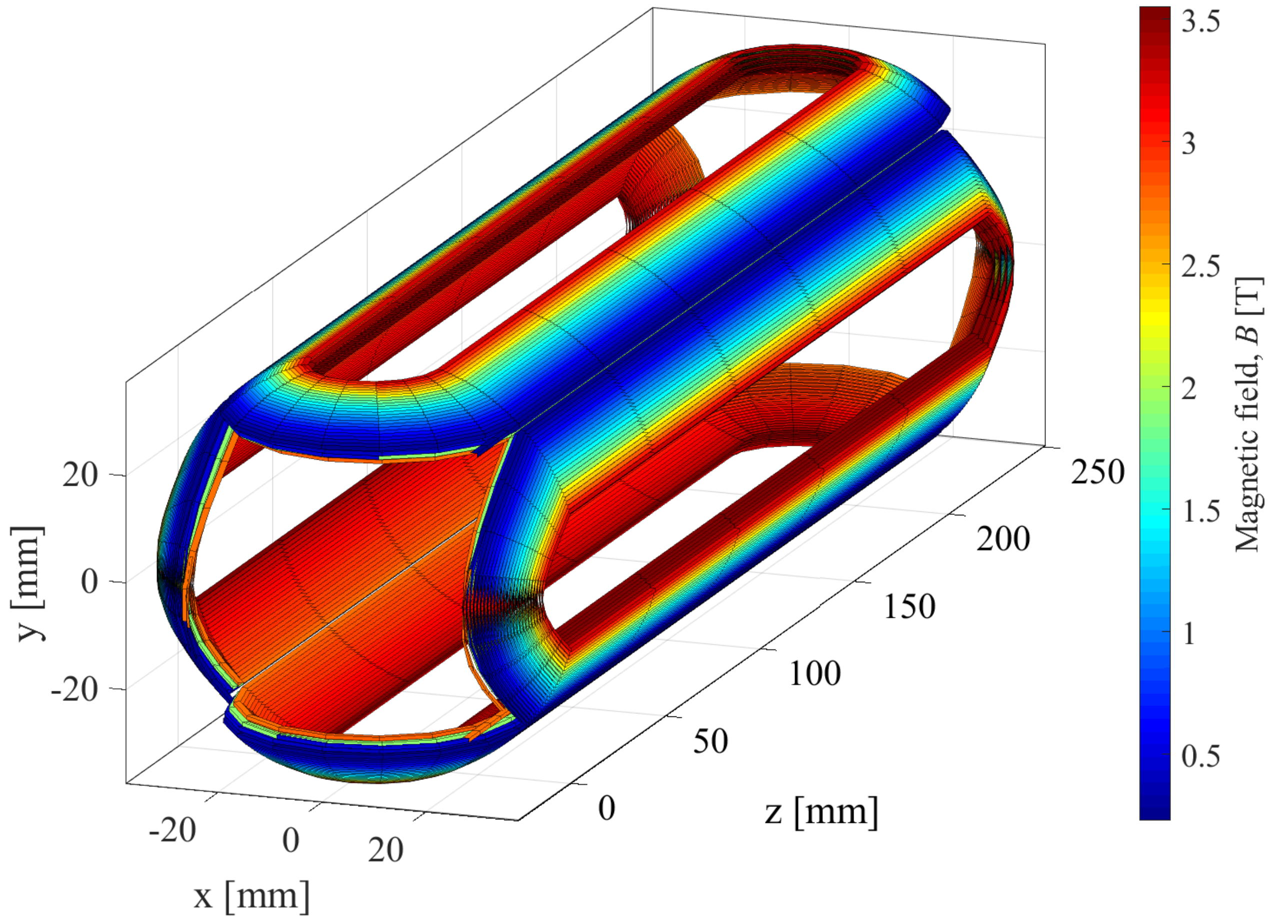
Electrical resistance develops in the coil



Magnet current is discharged

Peak temperature is maintained low

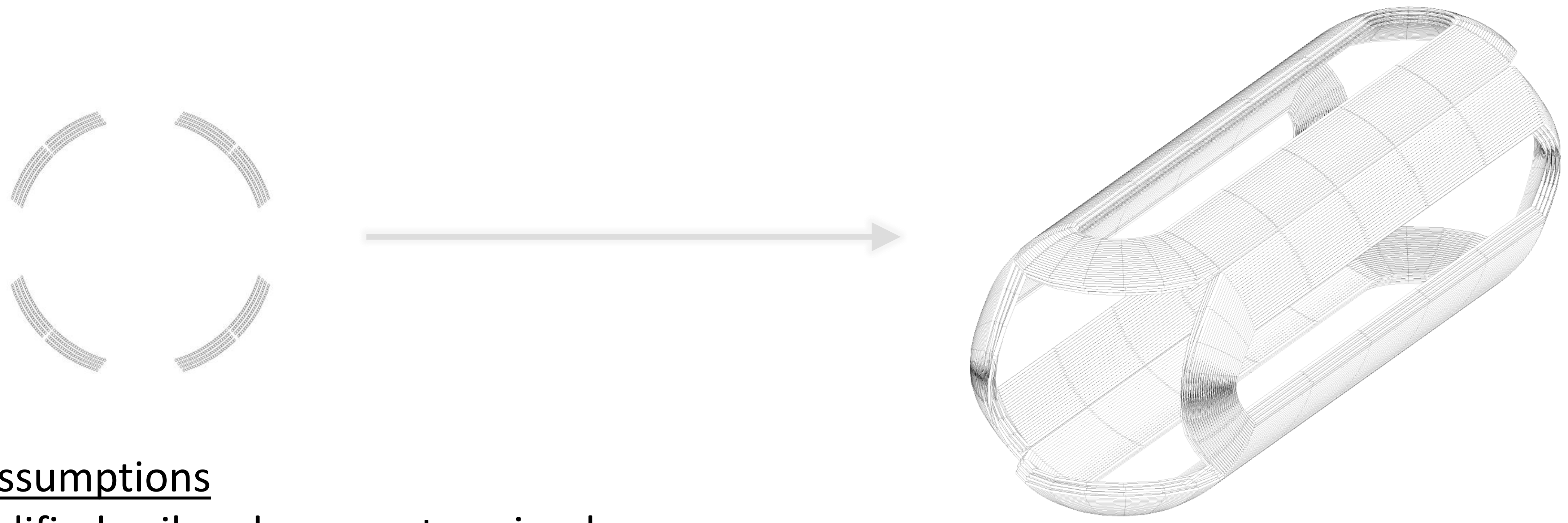
# Quench Transient Simulation in a Self-Protecting Magnet with a 3D Finite-Difference Scheme




| LHC quadrupole magnet [MQSX] | |
|---|---|
| Superconductor | Nb-Ti |
| Operating current | 550 A |
| Operating temperature | 1.9 K |
| Peak field on the conductor | 3.5 T |
| Self-inductance | 14 mH |
| Magnetic length | 223 mm |
| Number of turns | 384 |

*2D magnetic field was calculated with the ROXIE program*

# Quench Transient Simulation in a Self-Protecting Magnet with a 3D Finite-Difference Scheme



<u>Main assumptions</u>

→ Simplified coil ends geometry: simple arcs

→ 2D magnetic field extended to the full turn: no 3D field

✓ Good assumptions for electro-thermal quench simulations

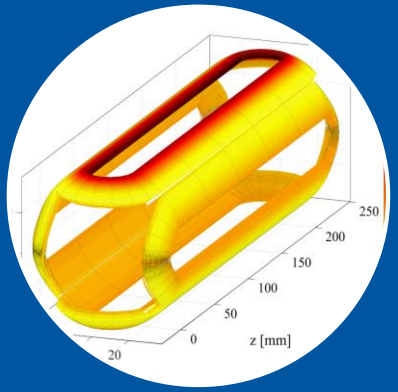
x Not good for other transients (in particular mechanical)

# Quench Transient Simulation in a Self-Protecting Magnet with a 3D Finite-Difference Scheme

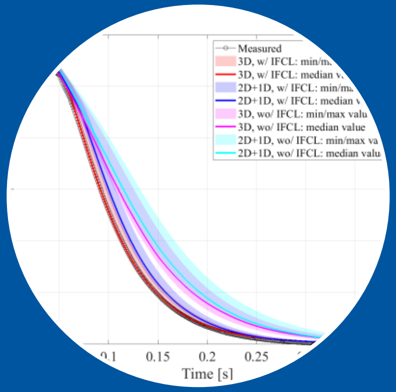
| | A | B | C | D | E |
|---|---|---|---|---|---|
| A | AA | AB | AC | AD | AE |
| B | BA | BB | BC | 0 | 0 |
| C | CA | CB | CC | 0 | 0 |
| D | DA | 0 | 0 | DD | DE |
| E | EA | 0 | 0 | ED | EE |

<u>Thermal balance equation solved in 3D</u>

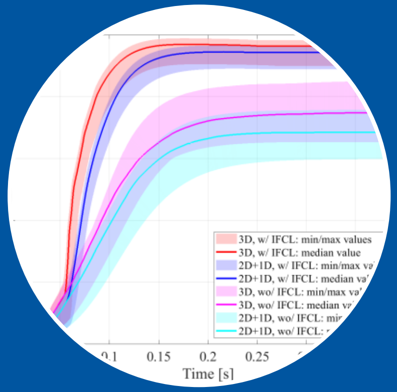
- ✓ Thermal diffusion in 3D
- ✓ Quench state and ohmic loss
- ✓ Inter-Filament Coupling Loss (IFCL)




Effect of quench location

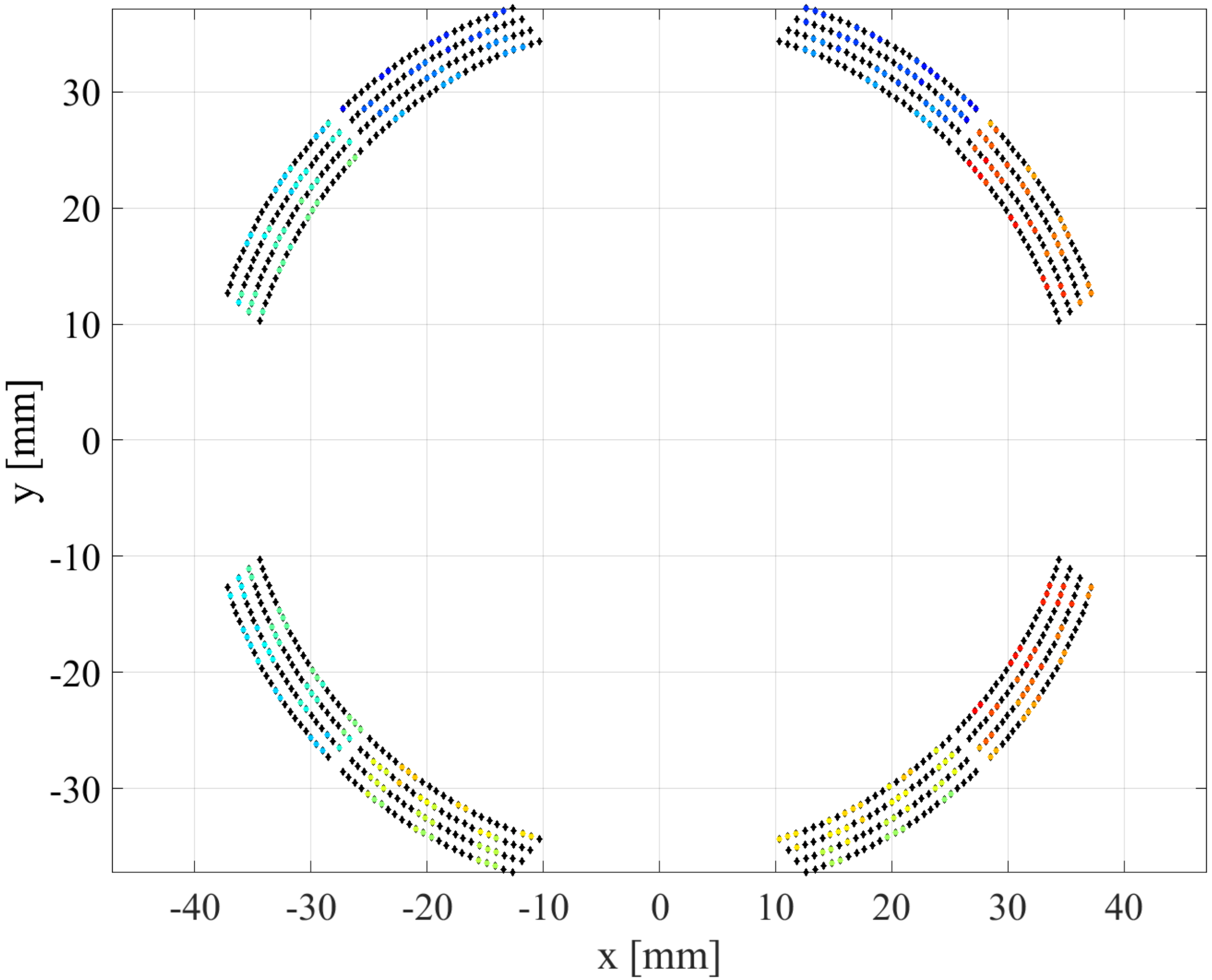



3D simulation compared to 2D+1D




Effect of Inter-Filament Coupling Loss (IFCL)

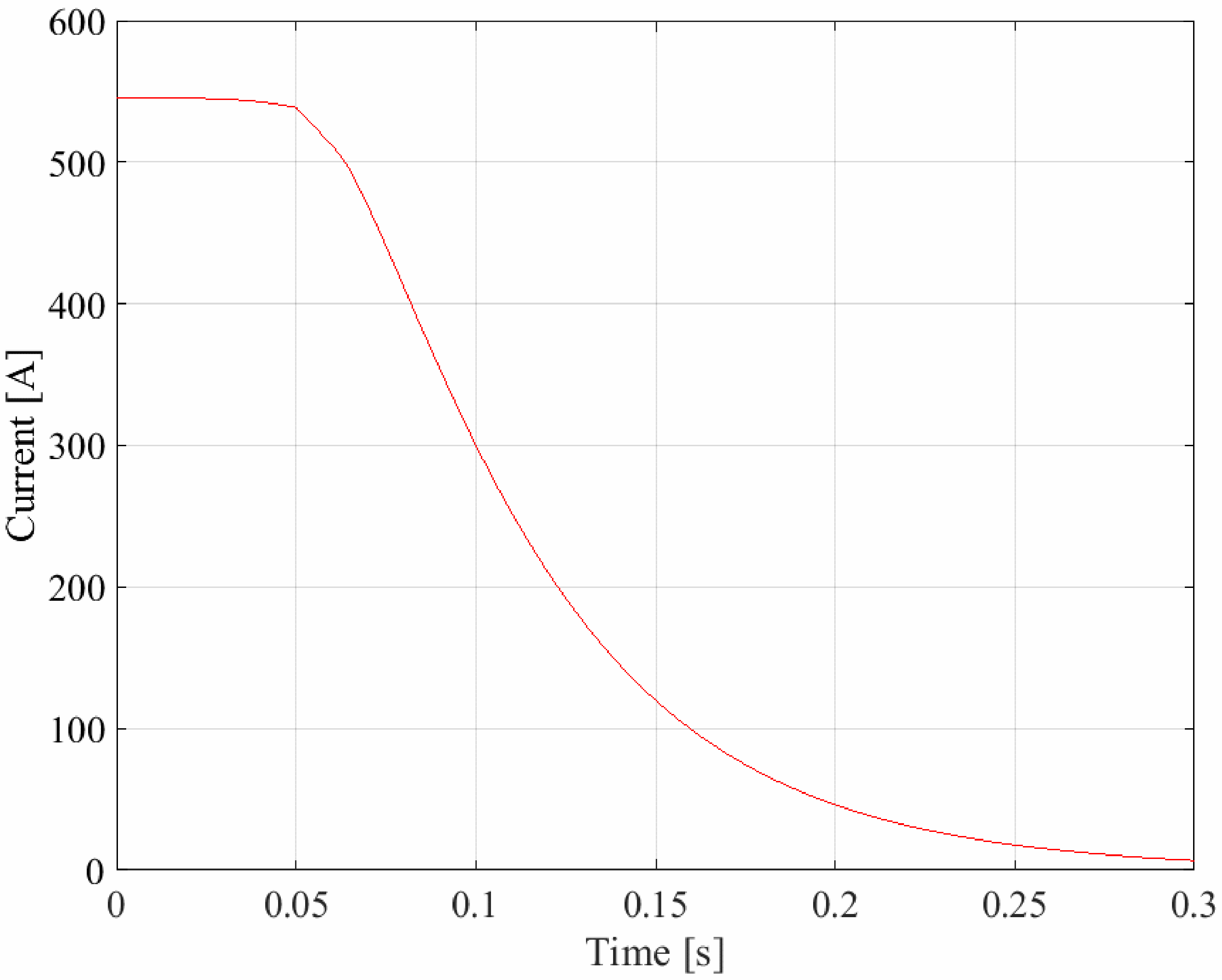
# Analyzed quench locations




Different quench locations

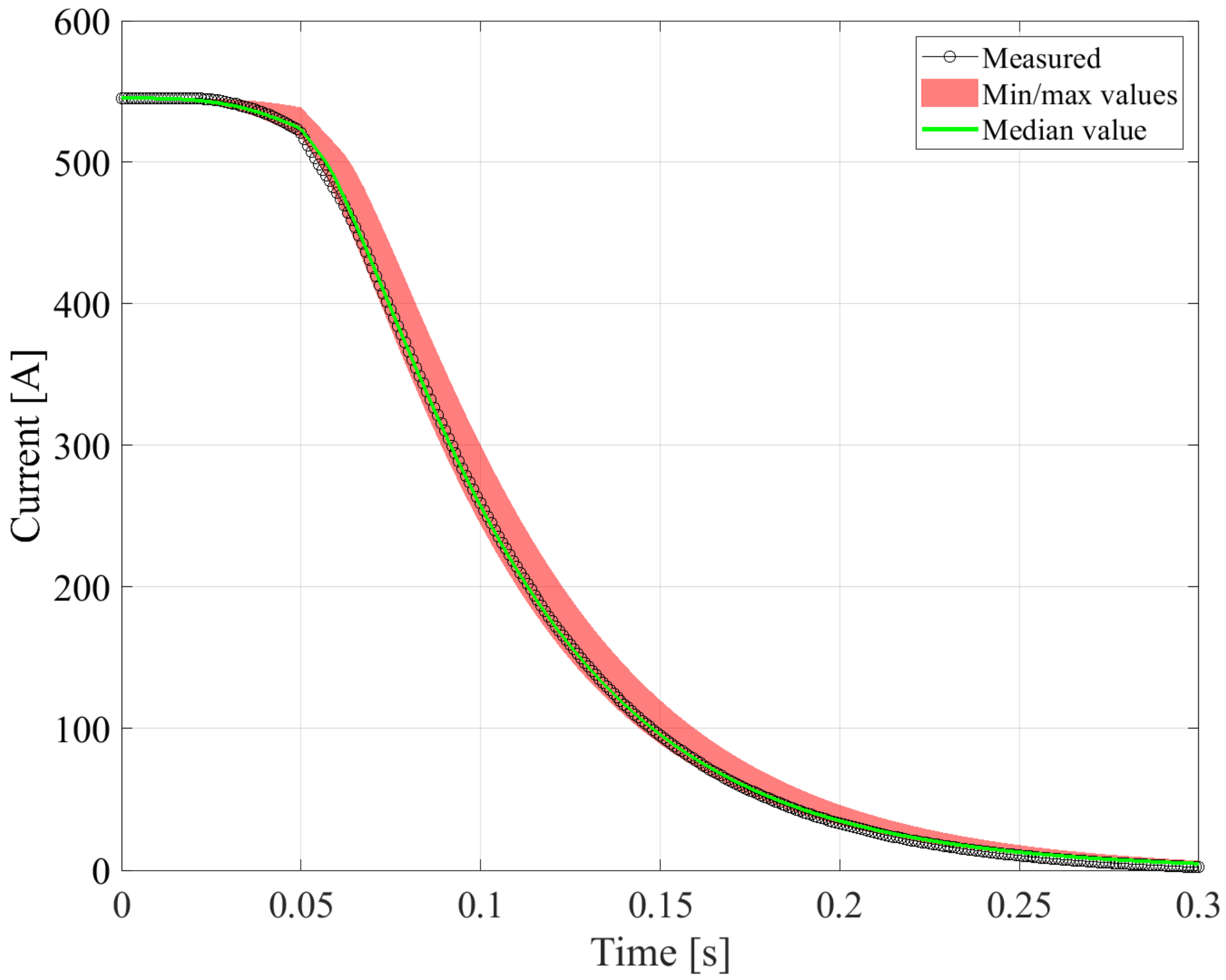
→ Different magnetic field
→ Different longitudinal locations
→ Different number of adjacent turns

# Simulated current discharge for different quench locations



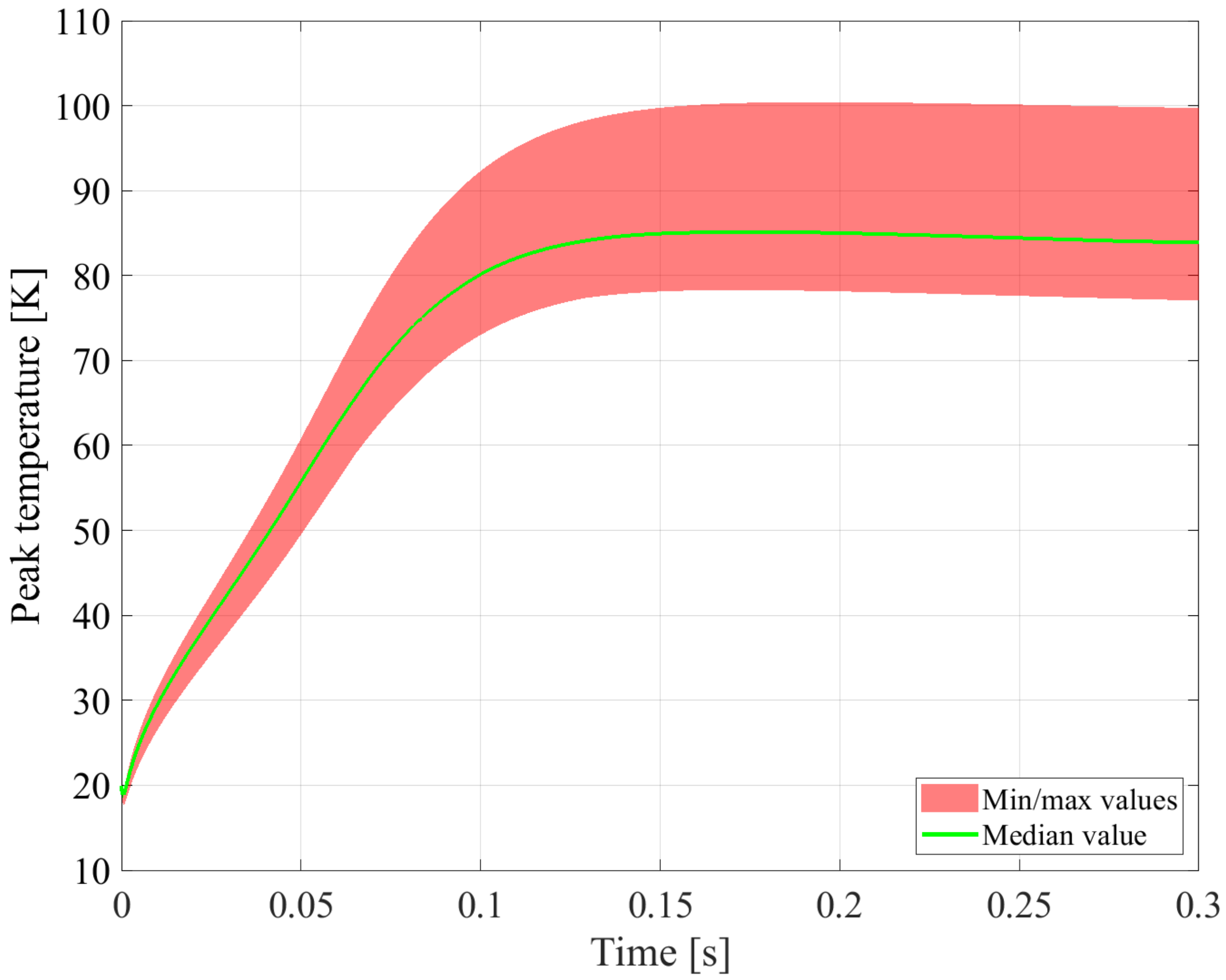

→ Median value represents the most typical expected discharge current

# Comparison to current discharge measured during LHC operation




→ 3D quench simulation reproduces very well the experimental curve

# Simulated peak coil temperature for different quench locations

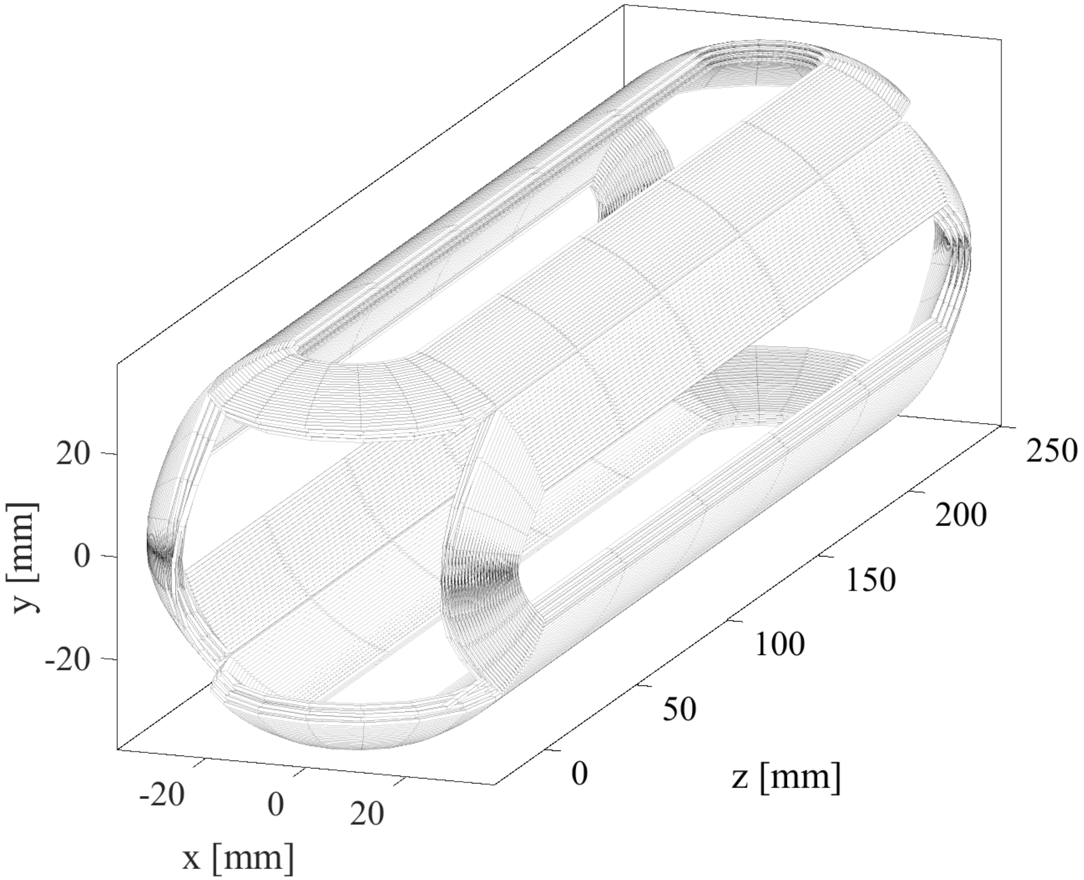



→ Peak coil temperature below 100 K (self-protecting magnet)

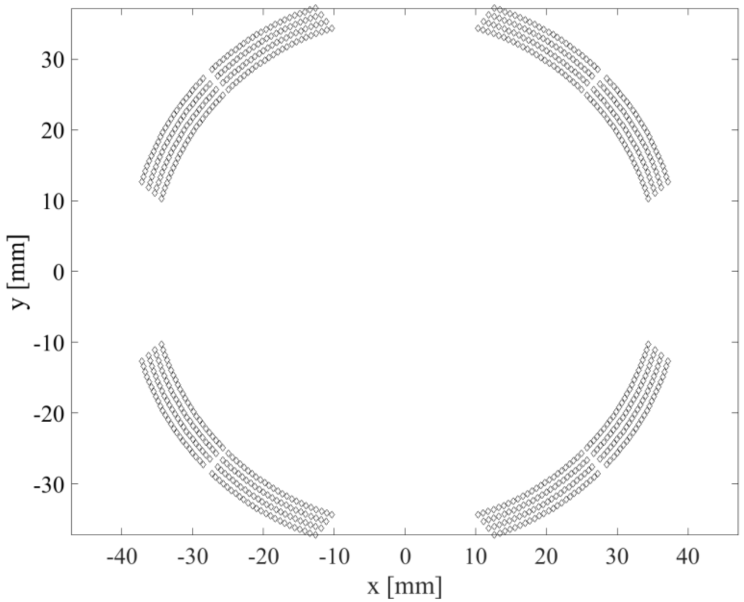
→ Uncertainty in quench location results in ~25 K uncertainty

3D

2D+1D

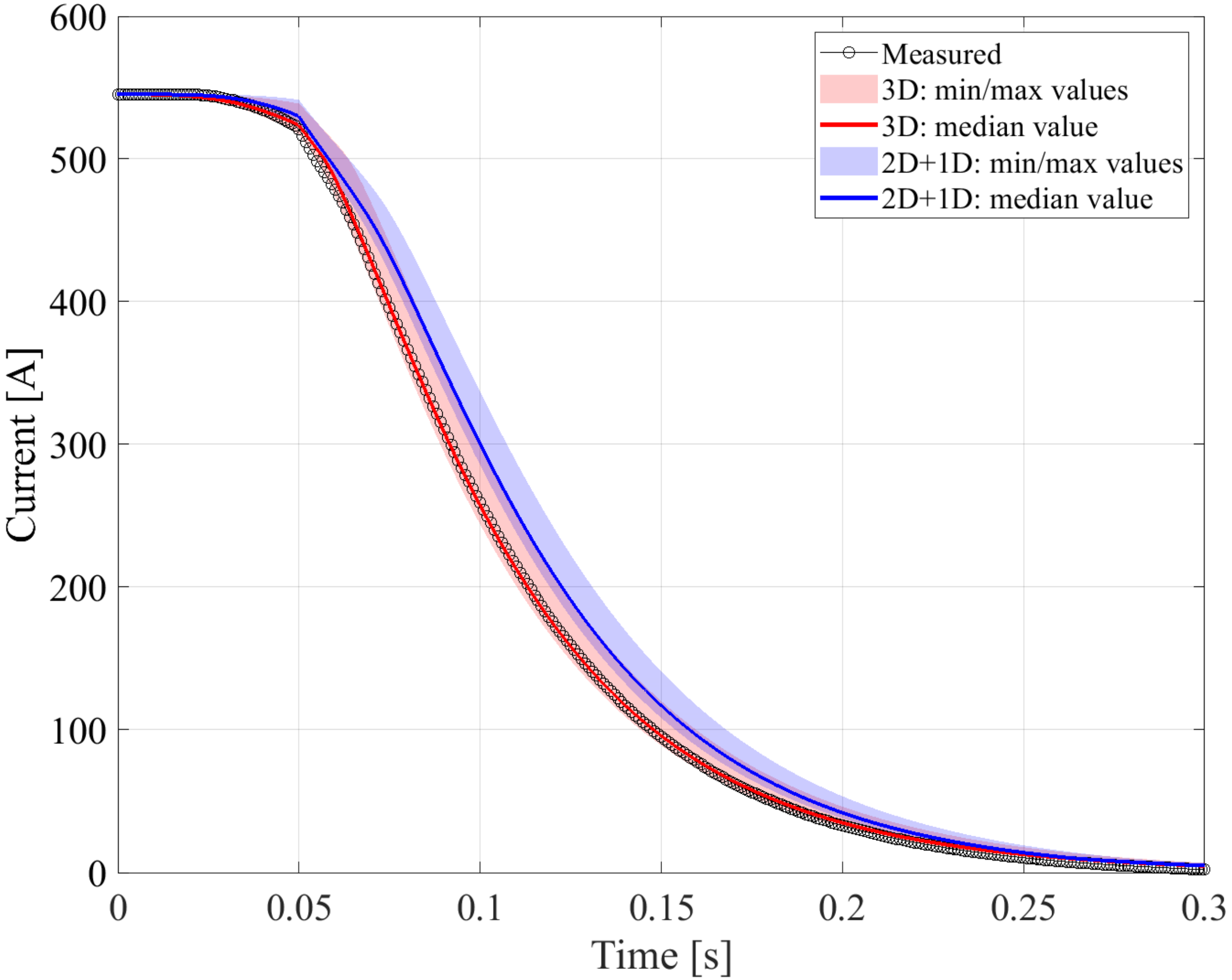


20
0
-20
y [mm]
-20
0
20
x [mm]
0
50
100
150
200
250
z [mm]

30
20
10
0
-10
-20
-30
y [mm]
-40
-30
-20
-10
0
10
20
30
40
x [mm]

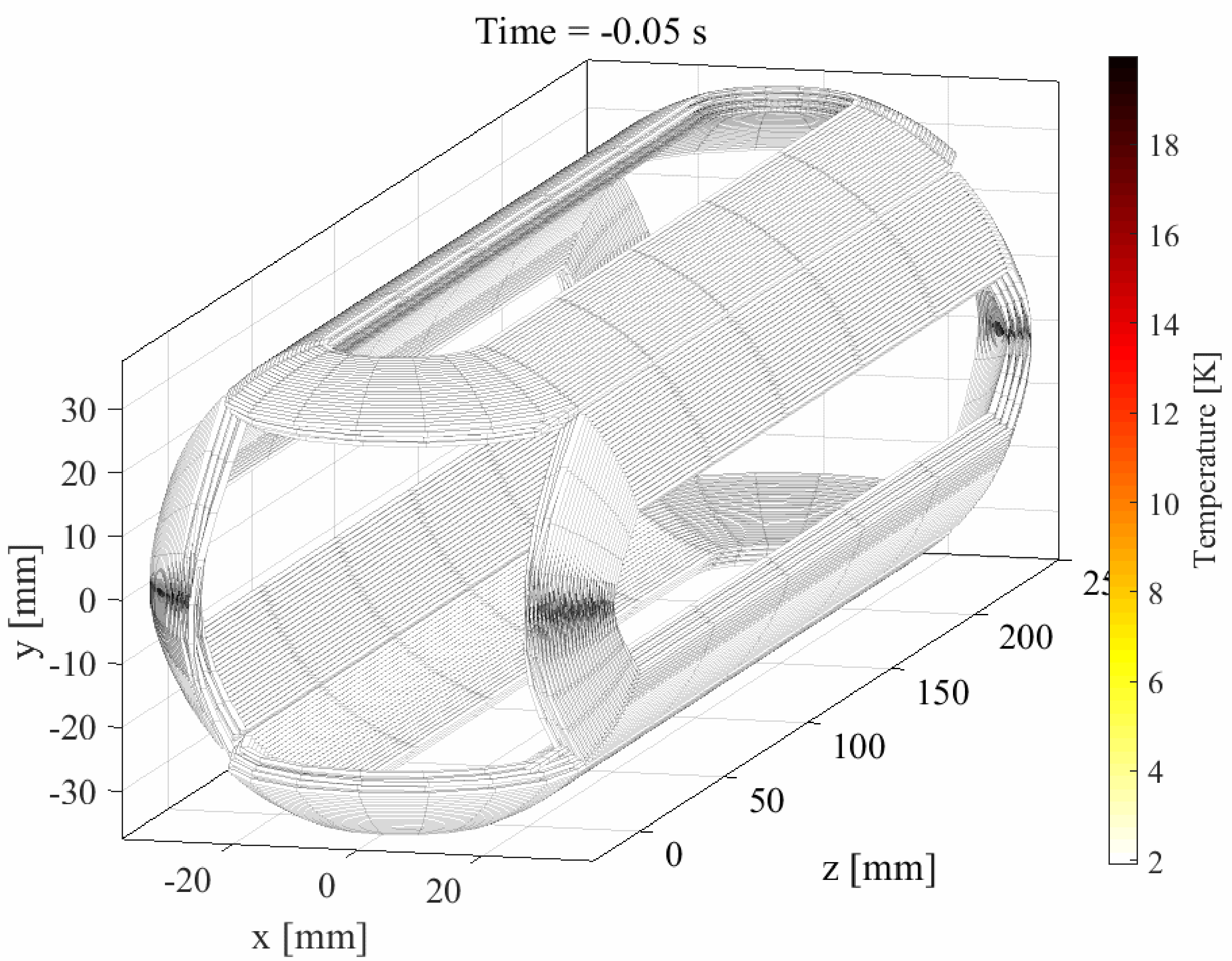
# Current discharge simulated with 3D and 2D+1D models

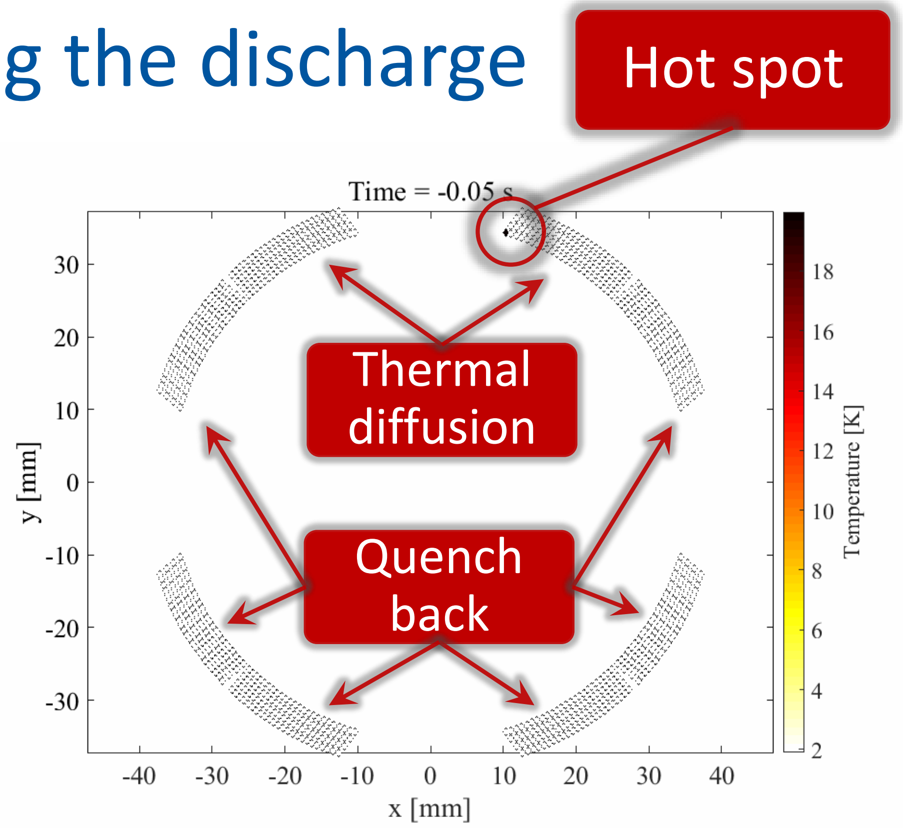



→ 2D+1D model qualitatively reproduces the transient

→ 3D model matches measurements more accurately

# Simulated 3D temperature distribution during the discharge

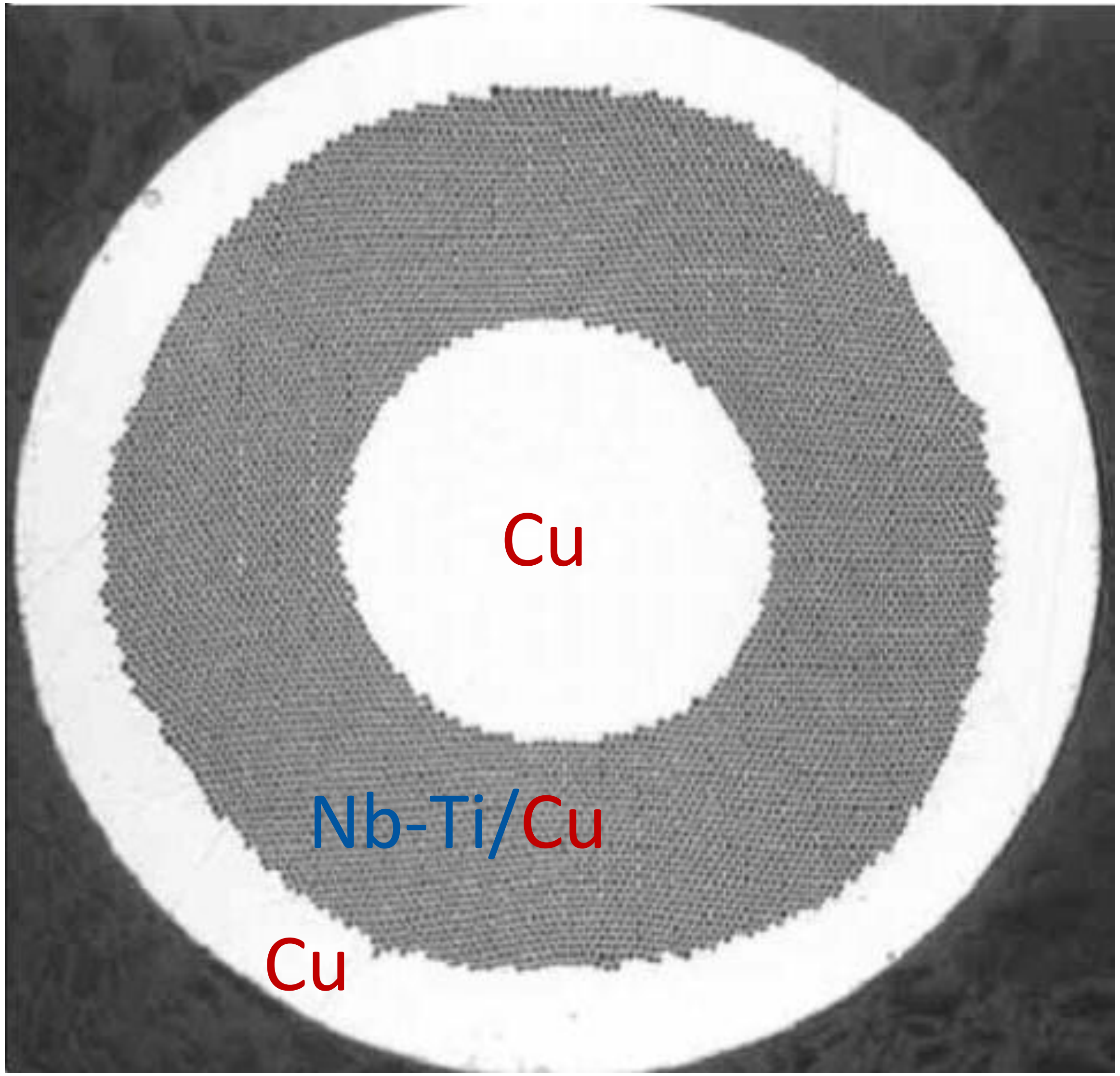


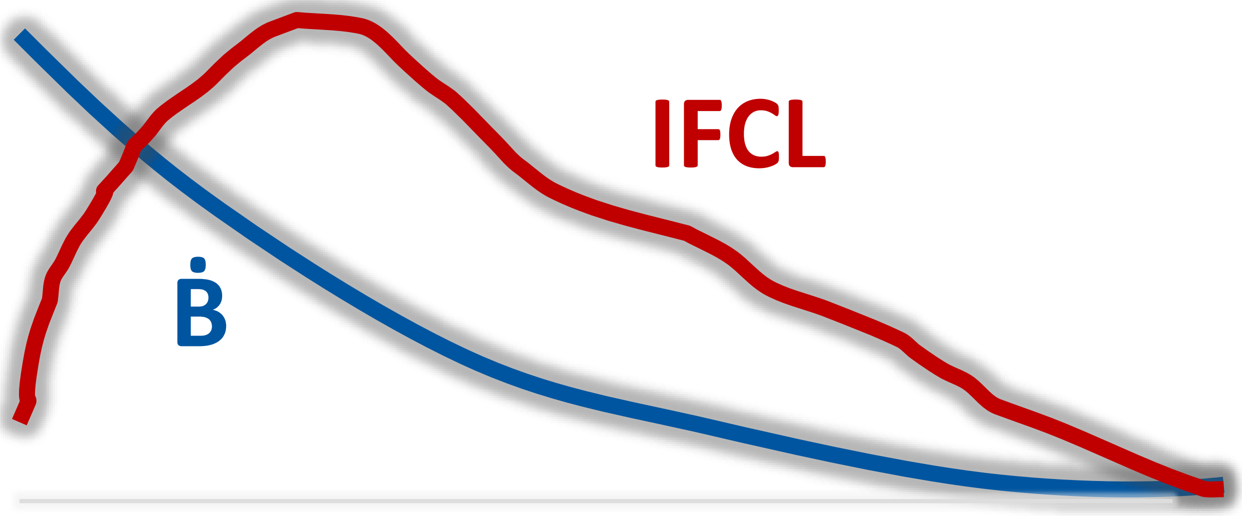




→ Animations provide useful insights in the quench behavior

→ Quench-back is caused by inter-filament coupling loss (IFCL)

# Inter-Filament Coupling Loss (IFCL)

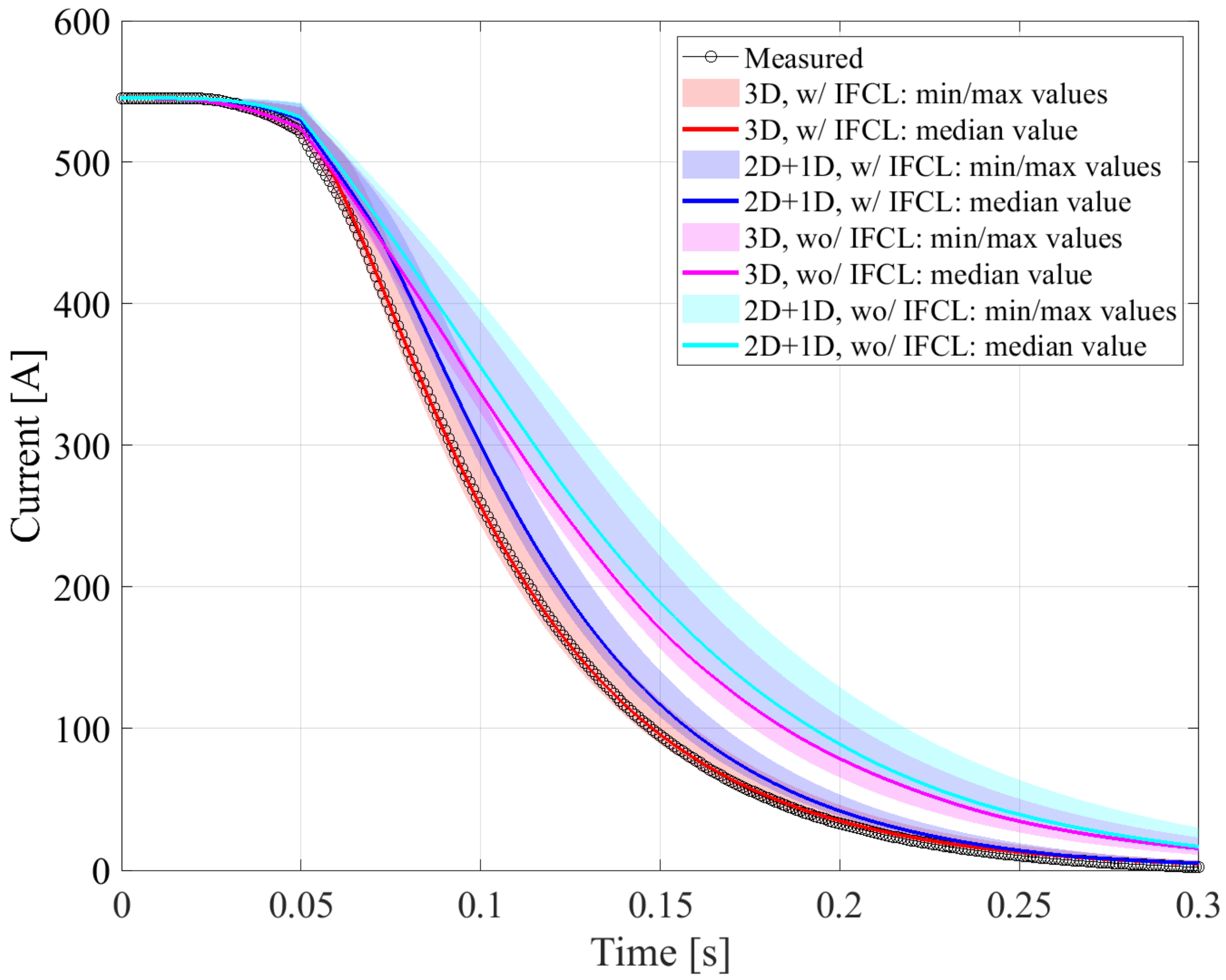



→ Caused by coupling currents between twisted superconducting filaments

→ IFCL is roughly proportional to $(dB/dt)^2$

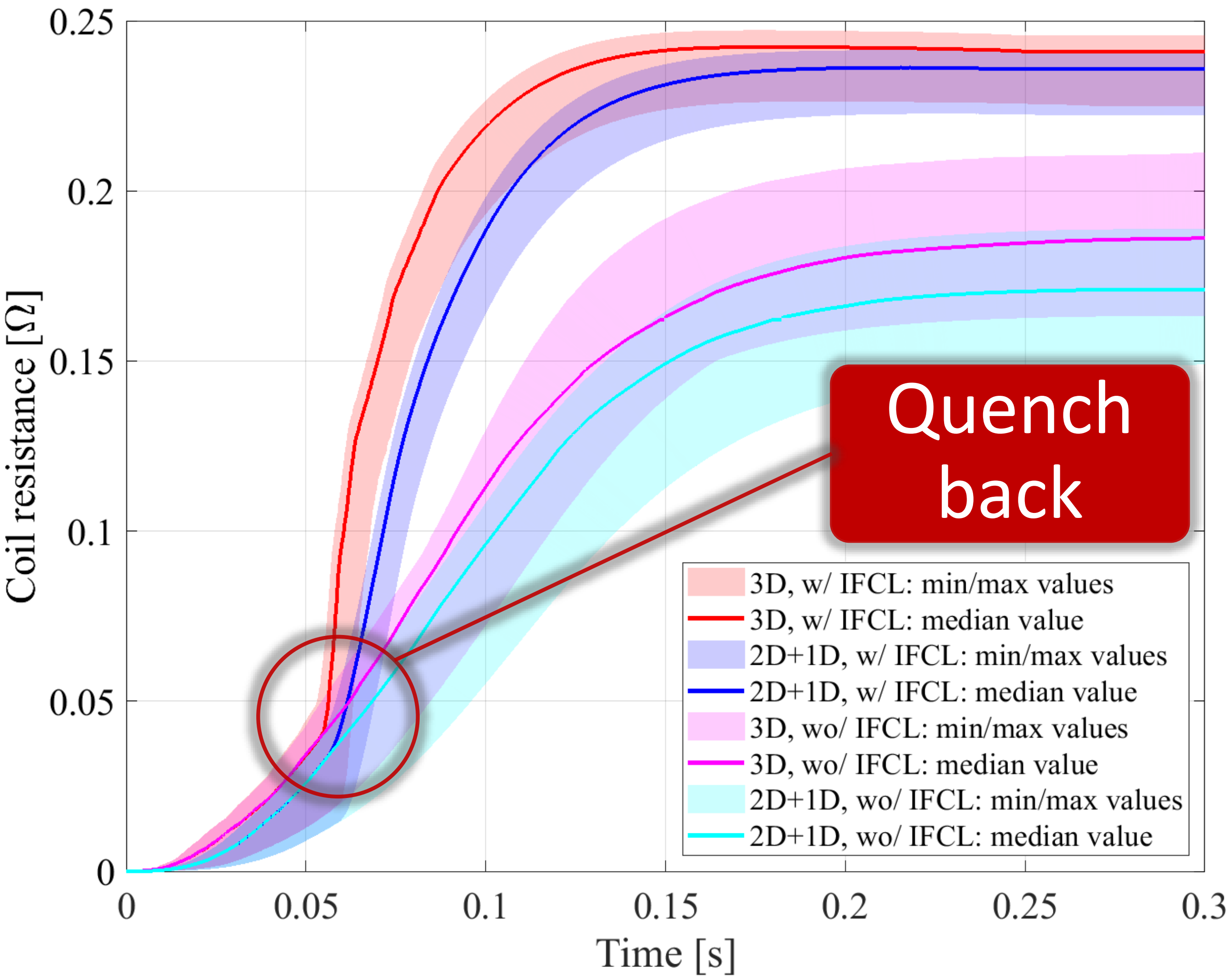
# Current discharge simulated with and without IFCL

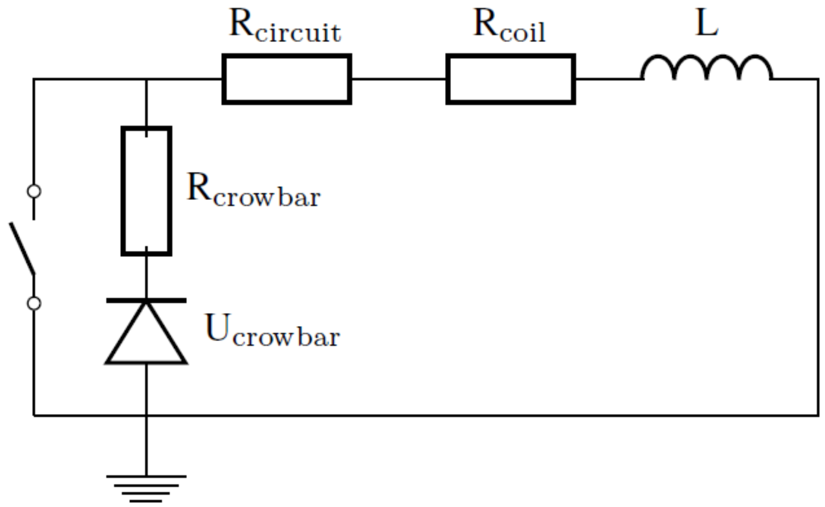



→ IFCL needs to be included in the simulation to reproduce satisfactorily this transient

| Simulated case | RMSE divided by initial current |
|---|---|
| 3D with IFCL | <0.5% |
| 2D+1D with IFCL | 4% |
| 3D without IFCL | 9% |
| 2D+1D without IFCL | 11% |

# Coil resistance simulated with and without IFCL

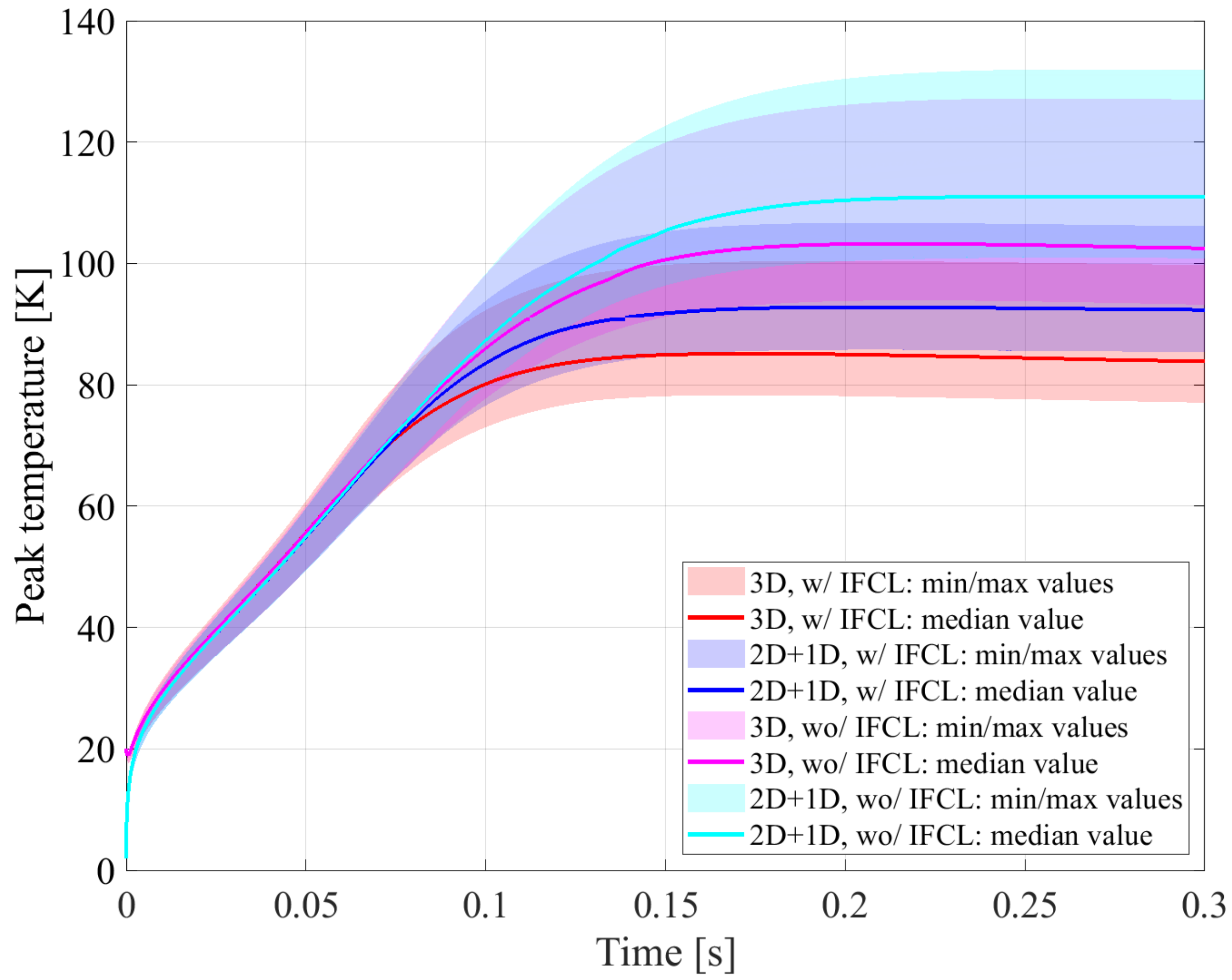



→ At t=50 ms, the current is forced through an 80 mΩ crowbar

→ Quench-back soon occurs and rapidly increases the coil resistance

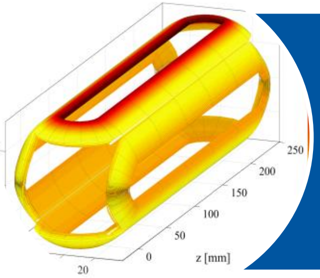
# Peak coil temperature simulated with and without IFCL



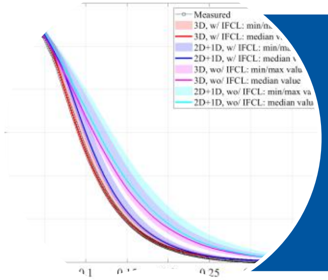

→ Neglecting IFCL the temperature is overestimated by ~30 K

→ For other magnets, the difference might be more critical

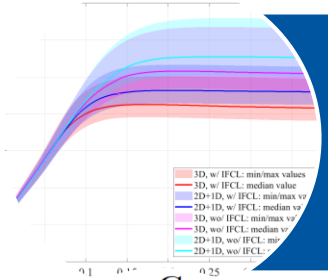
# Main takeaways



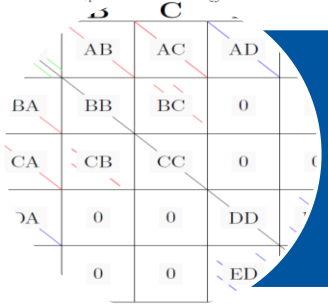

Quench transient in a 3D full-scale magnet geometry successfully simulated



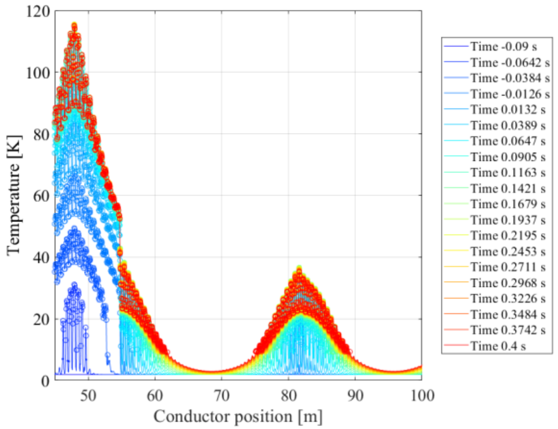
Excellent agreement with experimental results collected during LHC operation

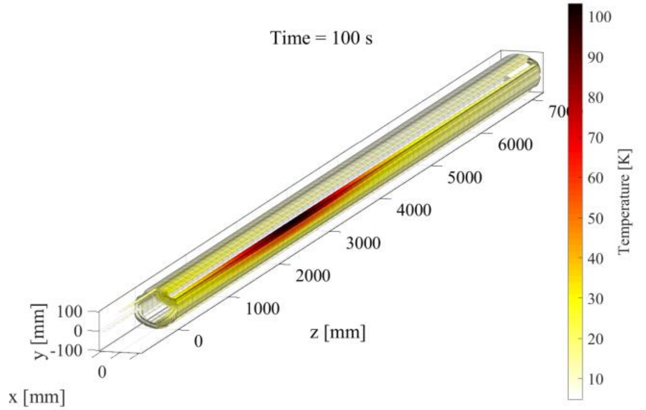


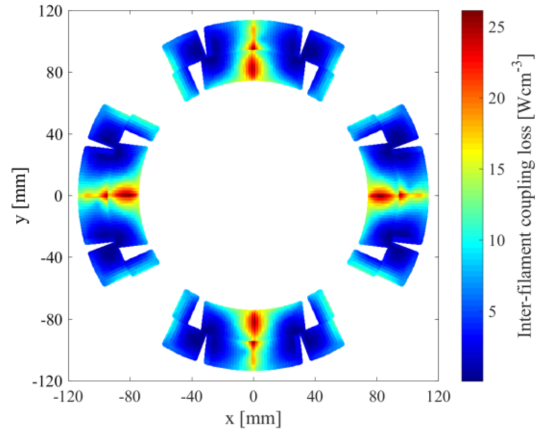
The effect of quench location and inter-filament coupling loss are quantified

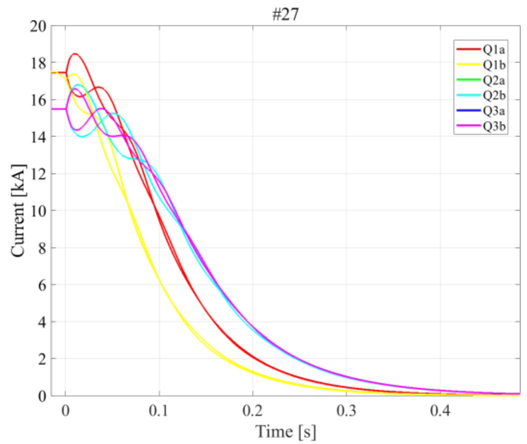



Simulation of the full transient requires <15 minutes



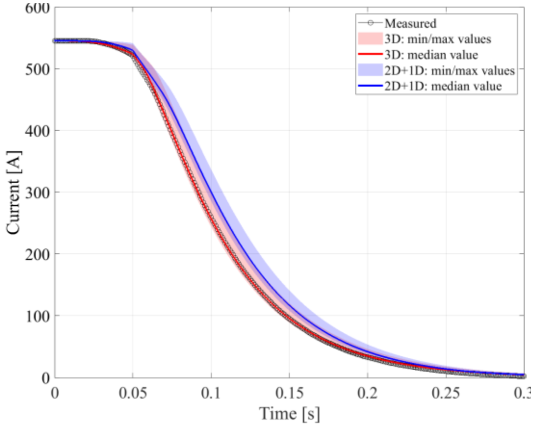



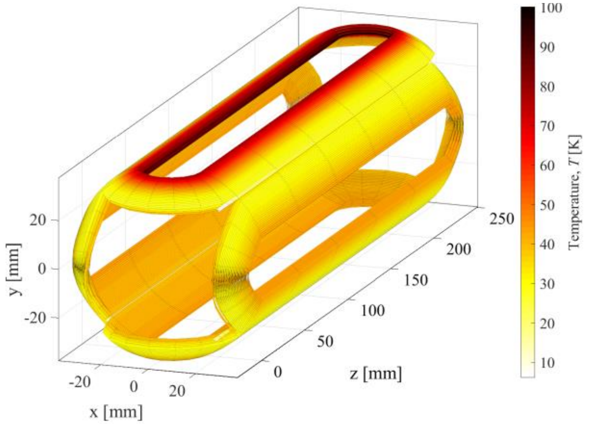



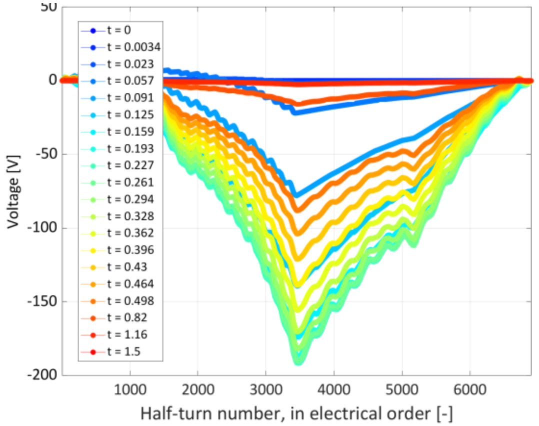



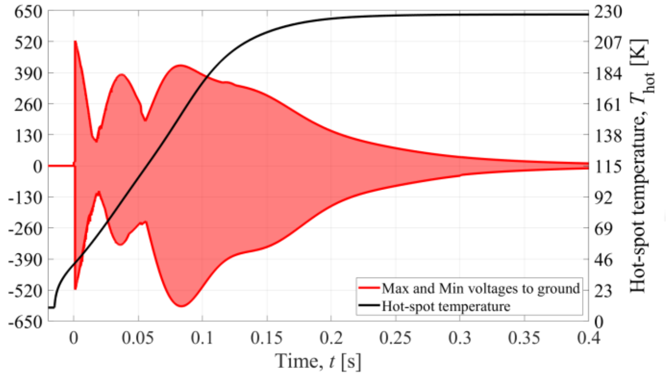

All simulations presented today were performed with LEDET,
a program that is part of the STEAM framework developed at CERN

All STEAM programs are available free of charge for the community
Interested? Visit us → https://espace.cern.ch/steam or Contact us → steam-team@cern.ch



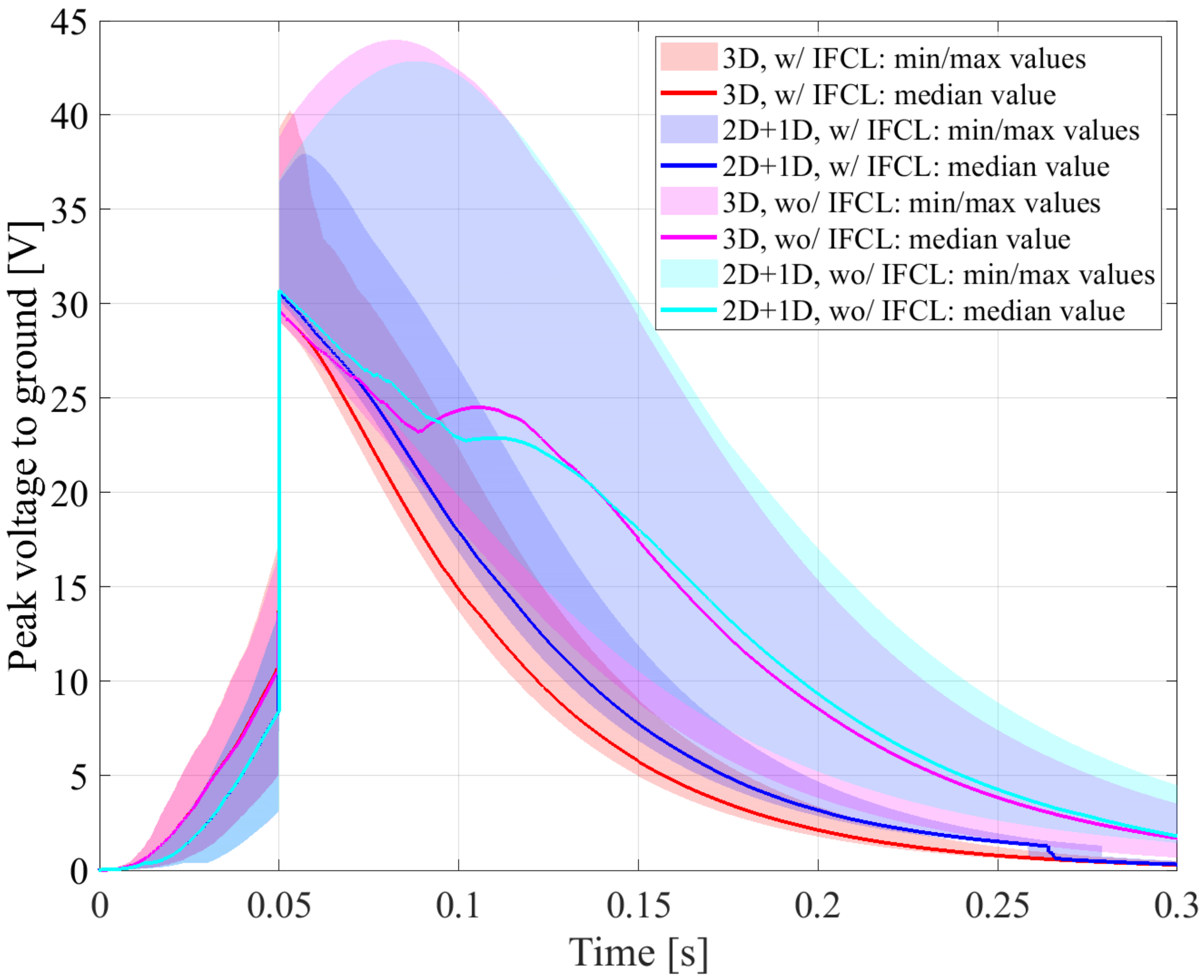



# Annex

# Peak voltage to ground simulated with and without IFCL



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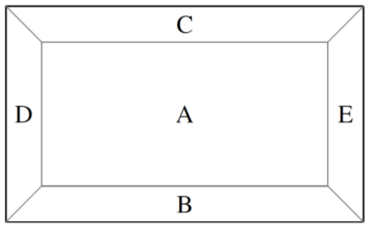


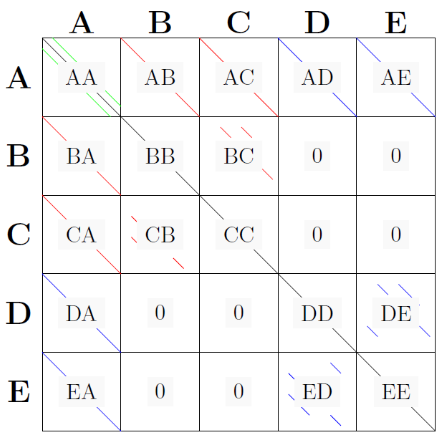


## Physics implemented

- Thermal diffusion in 3D
- Quench state and ohmic loss
- Inter-Filament Coupling Loss (IFCL)

## Finite-Difference Method

- Thermal diffusion equation solved in 3D with a semi-implicit scheme
- Implicit scheme guarantees numerical convergence
- With an explicit scheme with 1 mm mesh size: <1 μs would be needed!

## Method not fully implicit because

- Material properties from previous time step
- Ohmic loss from previous time step

Work is not over yet...

We‘re constantly developing new features!

If you have ideas, wishes & feedback,
we‘re interested!

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https://espace.cern.ch/steam/

steam-team@cern.ch

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