Electro-thermal coupling model of quench protection with nonlinear quench-back for DCT&CCT type magnets

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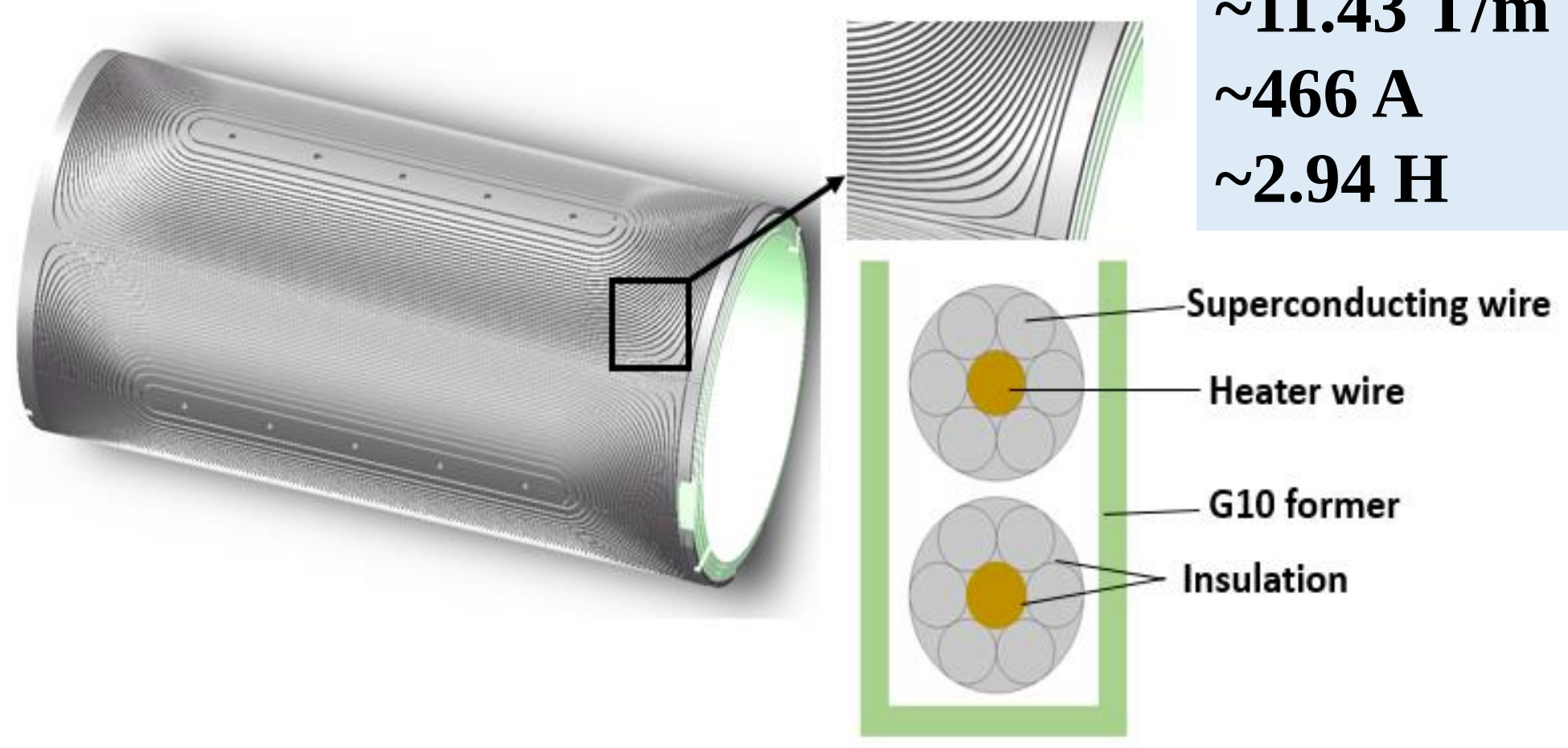
■ Abstract

As promising magnet types, discrete-cosine-theta and canted-cosine-theta (DCT&CCT) superconducting magnets are designed for the HFRS, a fragmention separator of the HIAF in IMP. Quench protection is one of the key issues for DCT&CCT superconducting magnet due to low thermal conductivity between each turns and slow transverse quench propagation. Thermal quench-back triggered by the center cooper wire as a heater automatically is a feasible quench protection option for the magnet wound with 6+1 type superconducting cables (six NbTi/Cu wires and one center cooper wire). An electro-thermal coupling model is developed and validated to deal with the dynamic coupling behaviors of electrical and temperature field inside the superconducting magnets during quench protection process. By comparing with the experimental measurements, the quench-back mechanism is revealed and the baselines of the quench protection of a prototype are analyzed and predicted further.

■ Introduction

- **In the HIAF-HFRS, DCT&CCT superconducting magnets are designed and fabricated by winding the 6+1 cable on G10 former with the slots produced by 3D printing technique.**
- **The quench protection is a key problem for DCT&CCT magnets due to the slow transverse quench propagation.**
- **To protect the magnets properly, a quench protection with non-linear quench-back is used, in which the coil can be heated by the center cooper wire in 6+1 type cable as a heater automatically.**
- **In this work, an electro-thermal coupling model is developed and validated to analyze the quench-back effect and electro-thermal coupling behaviors of a DCT&CCT magnet during quench protection process.**

DCT quadrupole magnets wound with 6+1 type cables



■ Model theory and validation

Thermal model

$$\rho c(T)\frac{\partial T}{\partial t} = -\nabla\cdot\mathbf{q} + Q_{tr} + Q_{hw} + Q_j$$

$$\mathbf{q} = -\mathbf{K}(T,B)\nabla T \qquad Q_j = \frac{I_m^{\ 2}}{S_0^{\ 2}\sigma_m(T,B)}$$

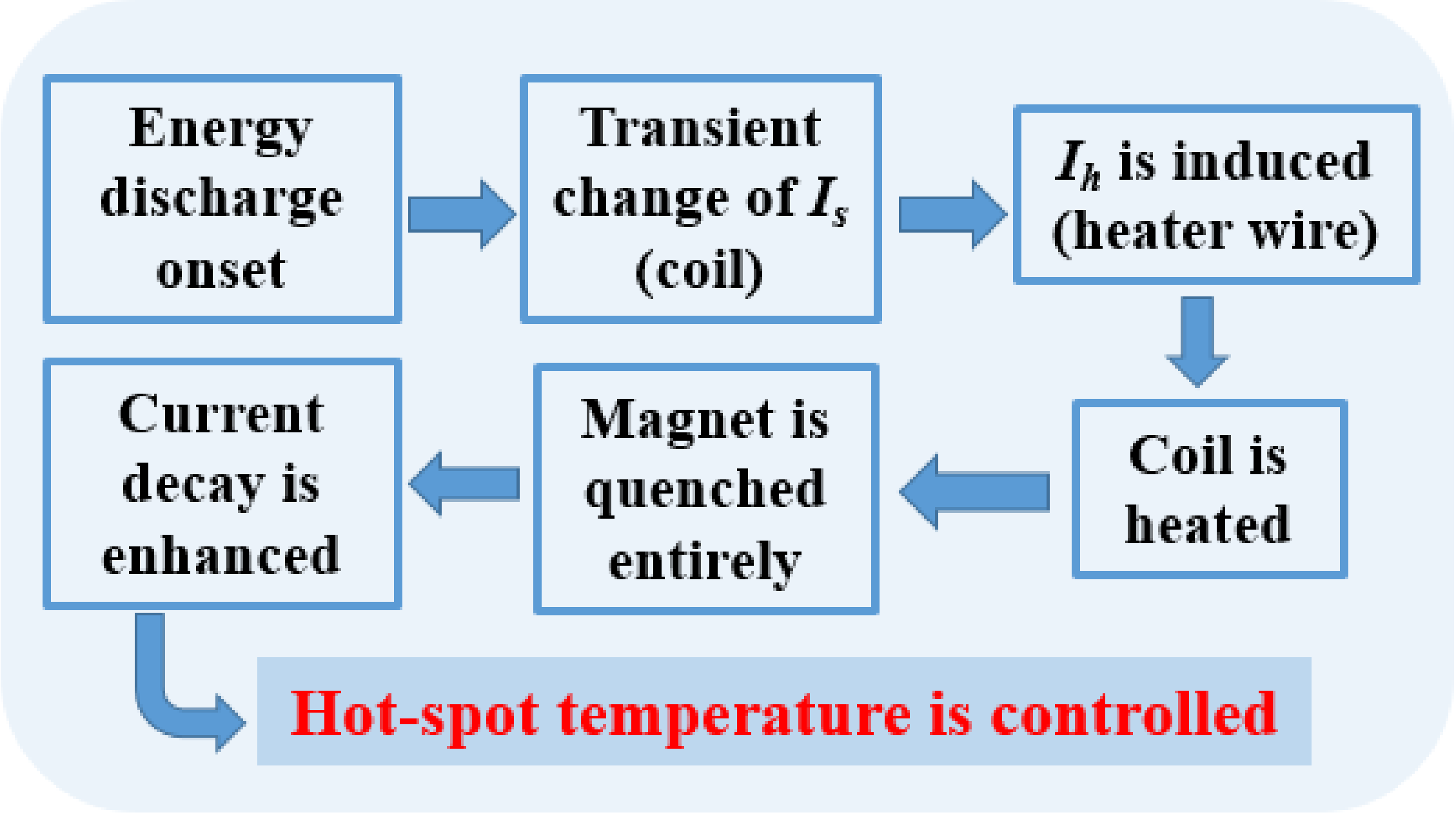
Circuit model

$$L_s\frac{dI_s}{dt} + M\frac{dI_h}{dt} + [R_d + R_s(T)]I_s = 0$$

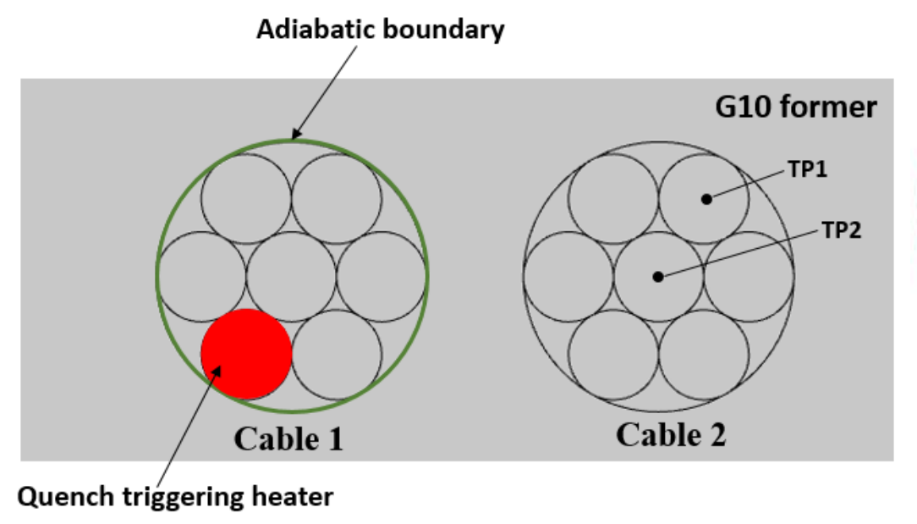
$$L_h\frac{dI_h}{dt} + M\frac{dI_s}{dt} + [(R_a + R_h(T)]I_h = 0$$

$$M = k_0\sqrt{L_sL_h}$$

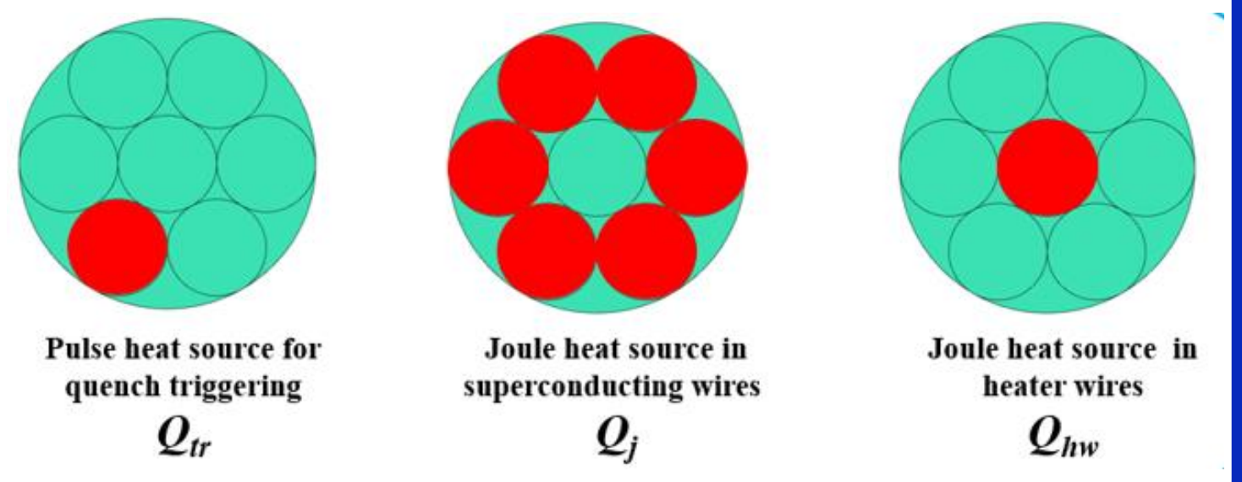
Quench protection scheme

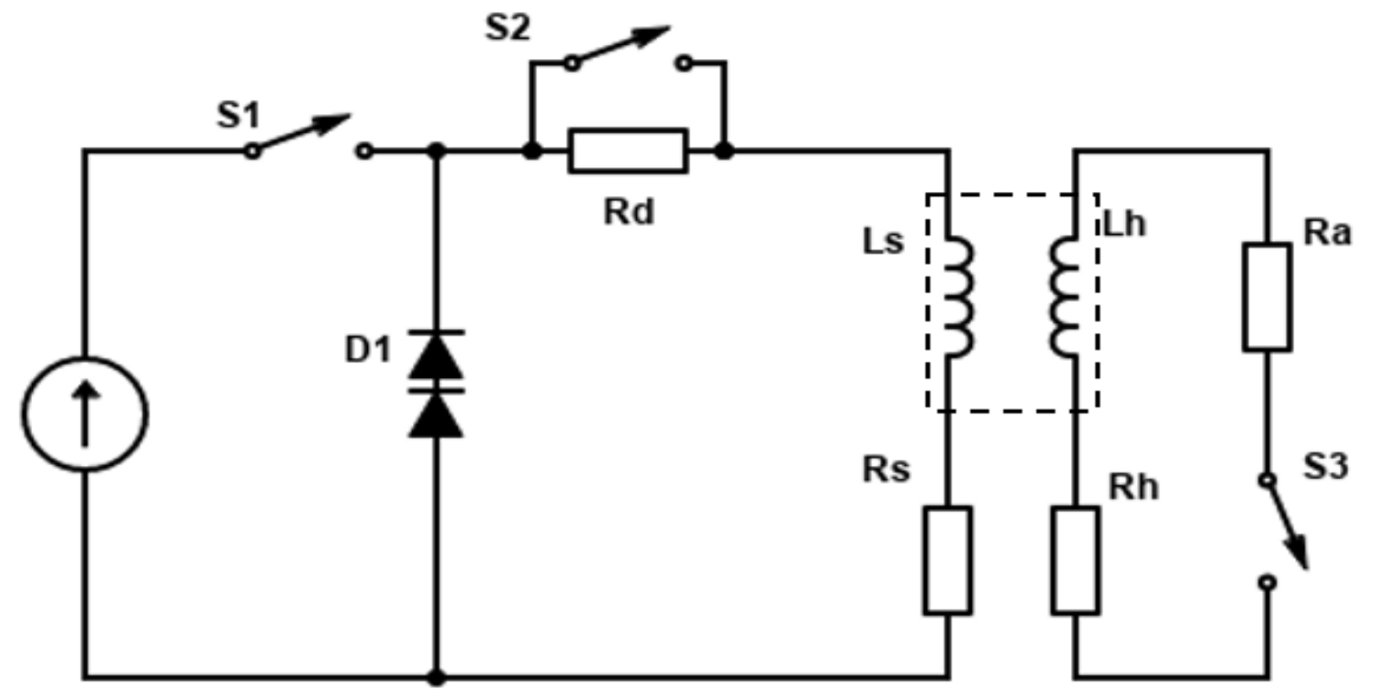

Energy discharge onset → **Transient change of I_s (coil)** → **I_h is induced (heater wire)** → **Coil is heated** → **Magnet is quenched entirely** → **Current decay is enhanced** → **Hot-spot temperature is controlled**

Two cables model



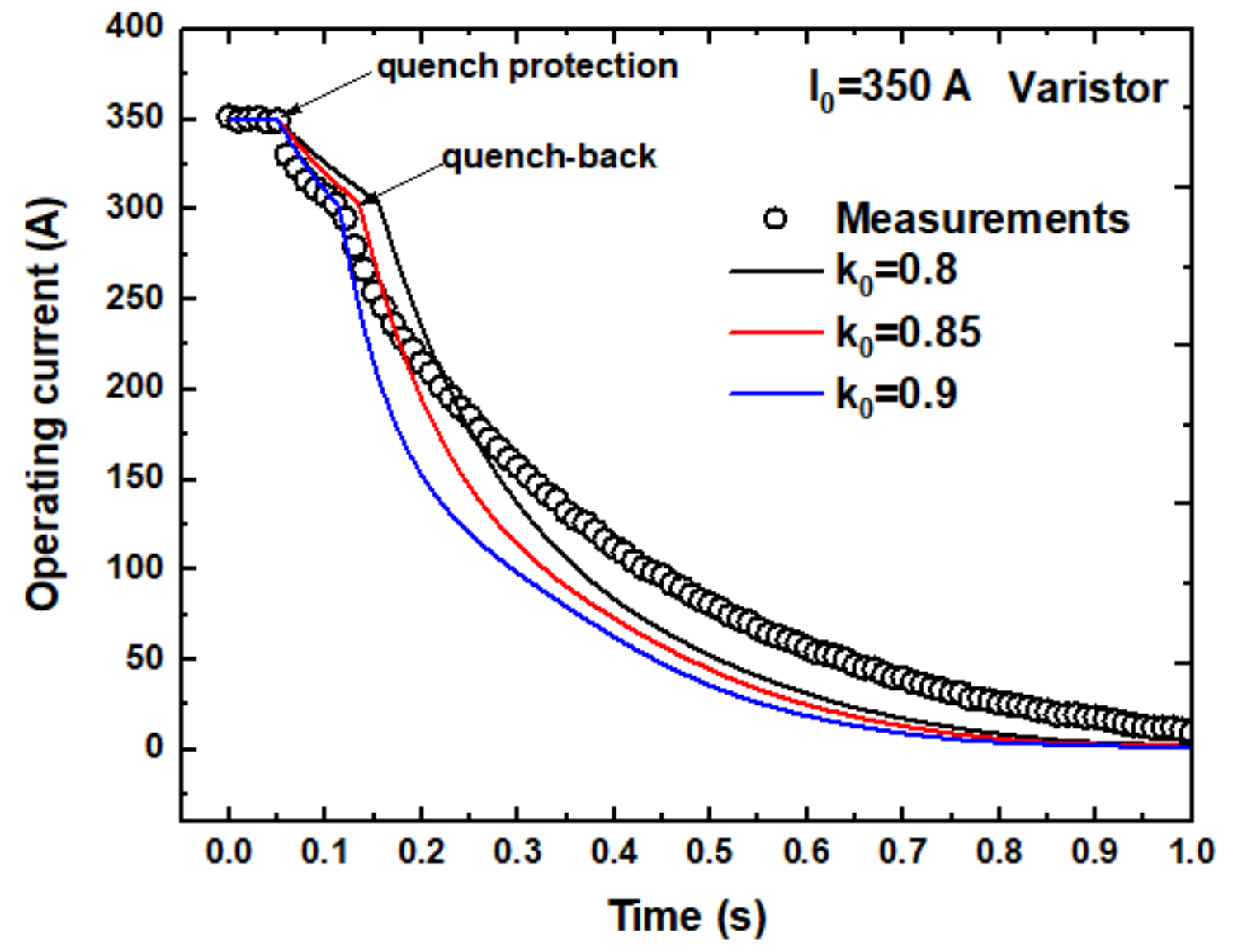
Heater source distribution





Quench protection circuit

Current decay curve (simulations vs measurements)

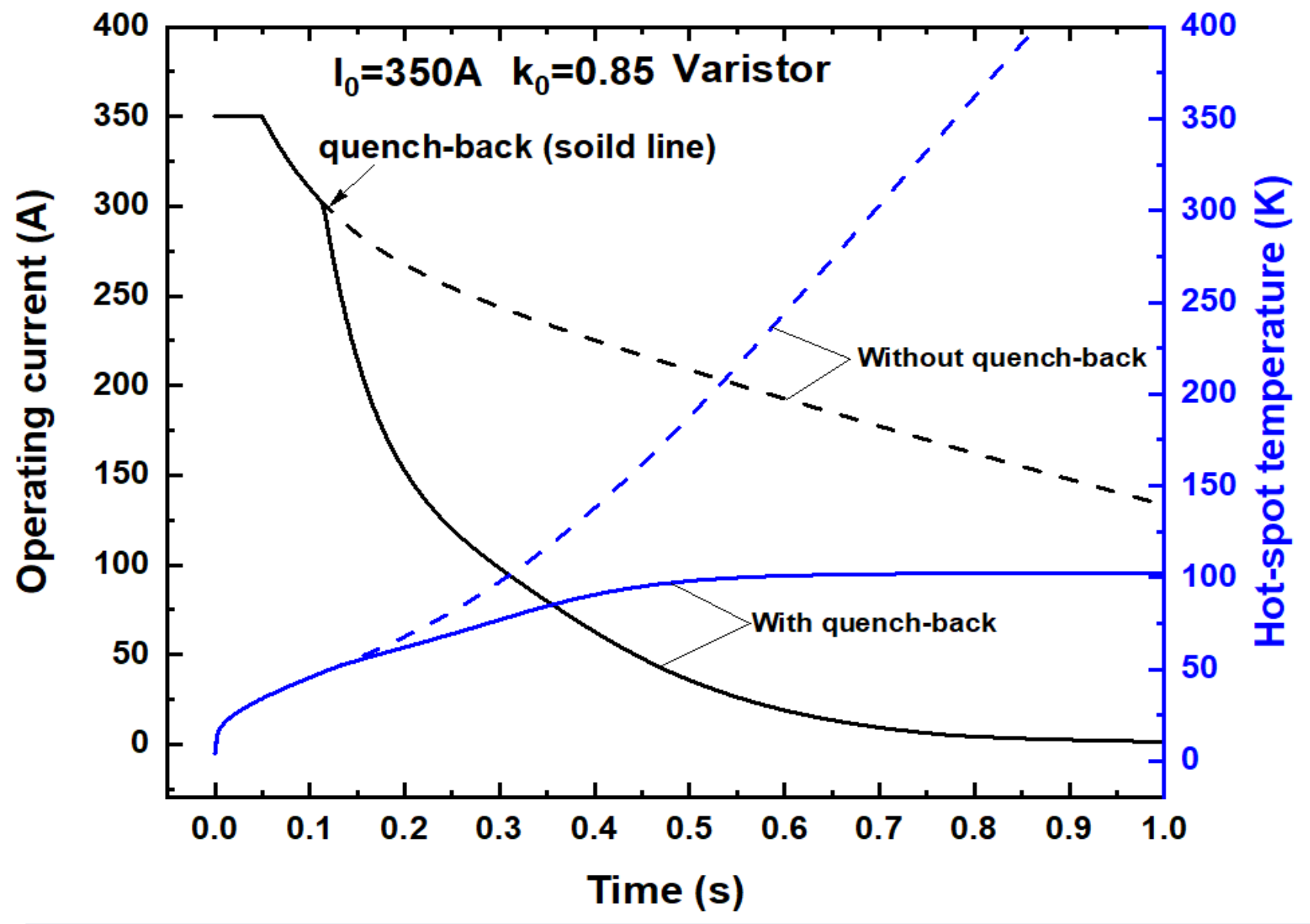


The model is validated by comparing with experimental results

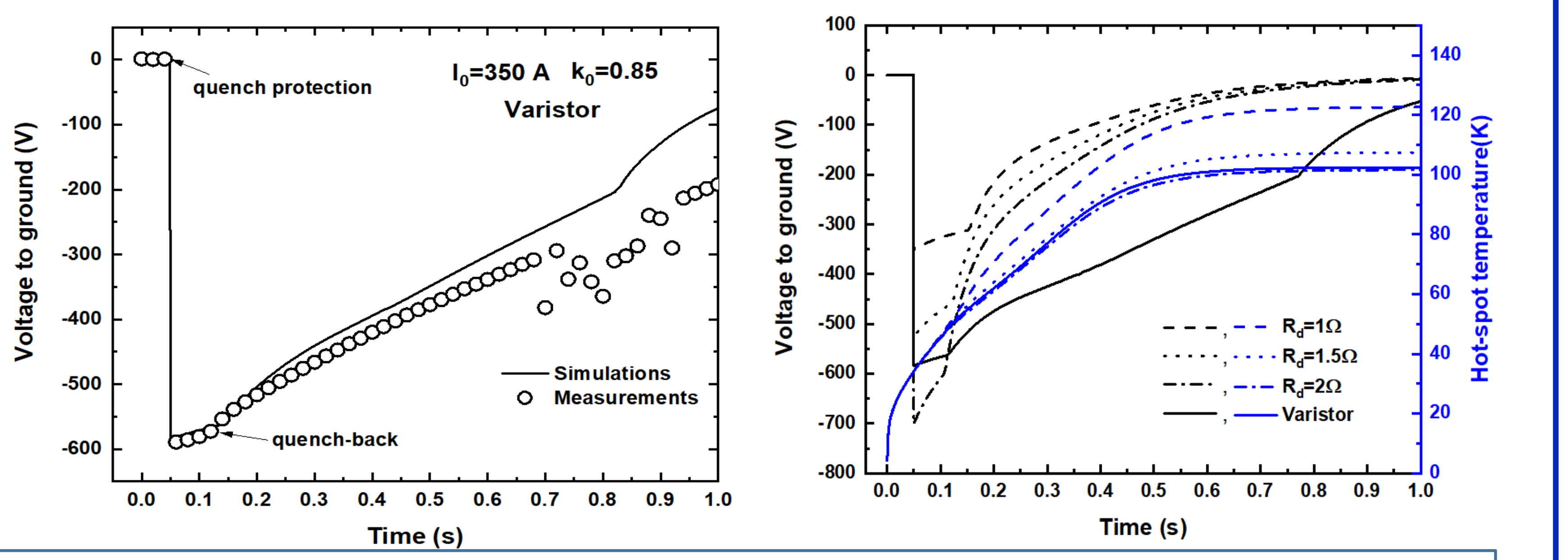
■ Results and discussion

➢ Analyses of quench-back behavior

Current and hot-spot temperature



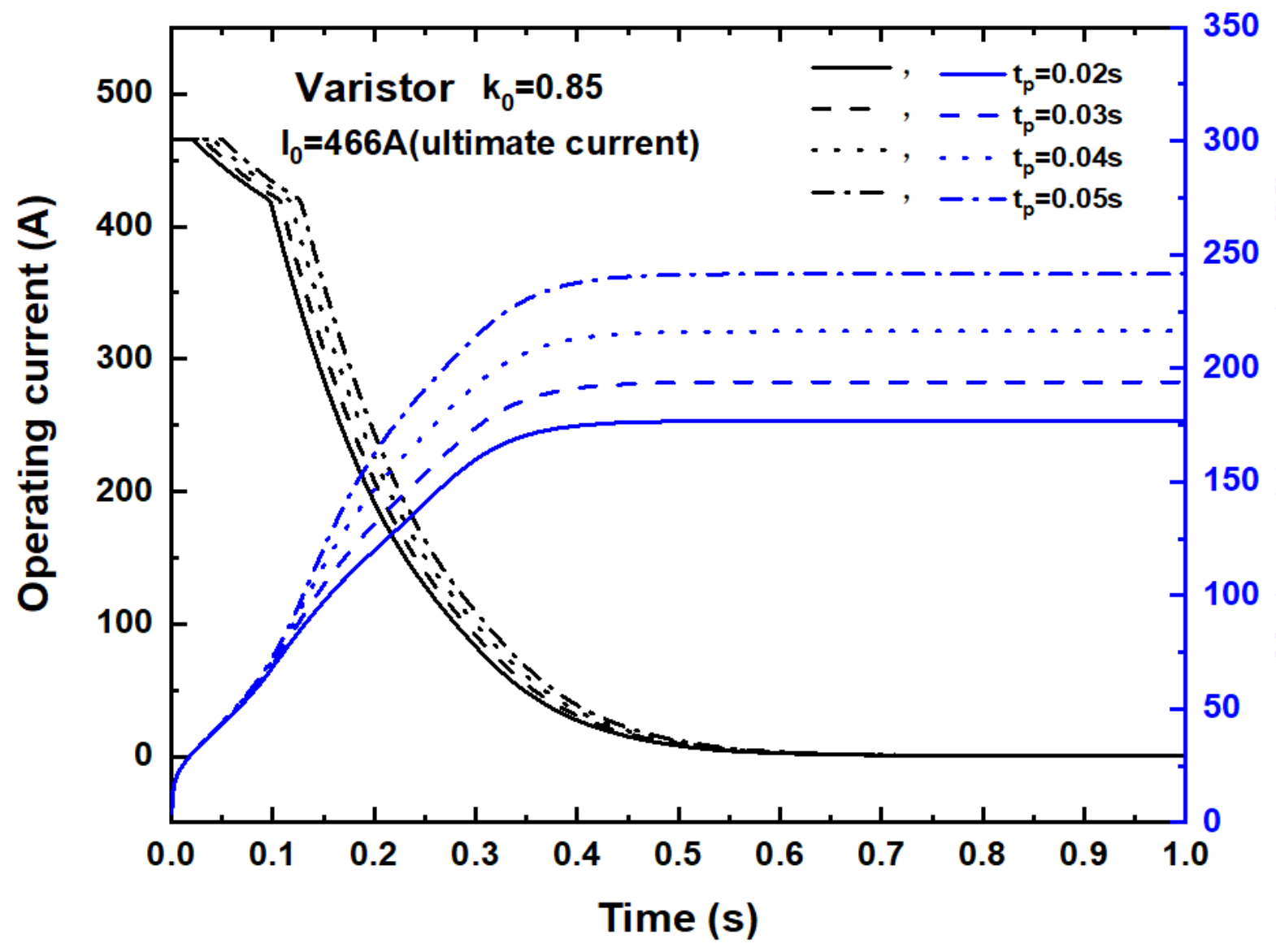
Evolutions of Voltage-to-ground



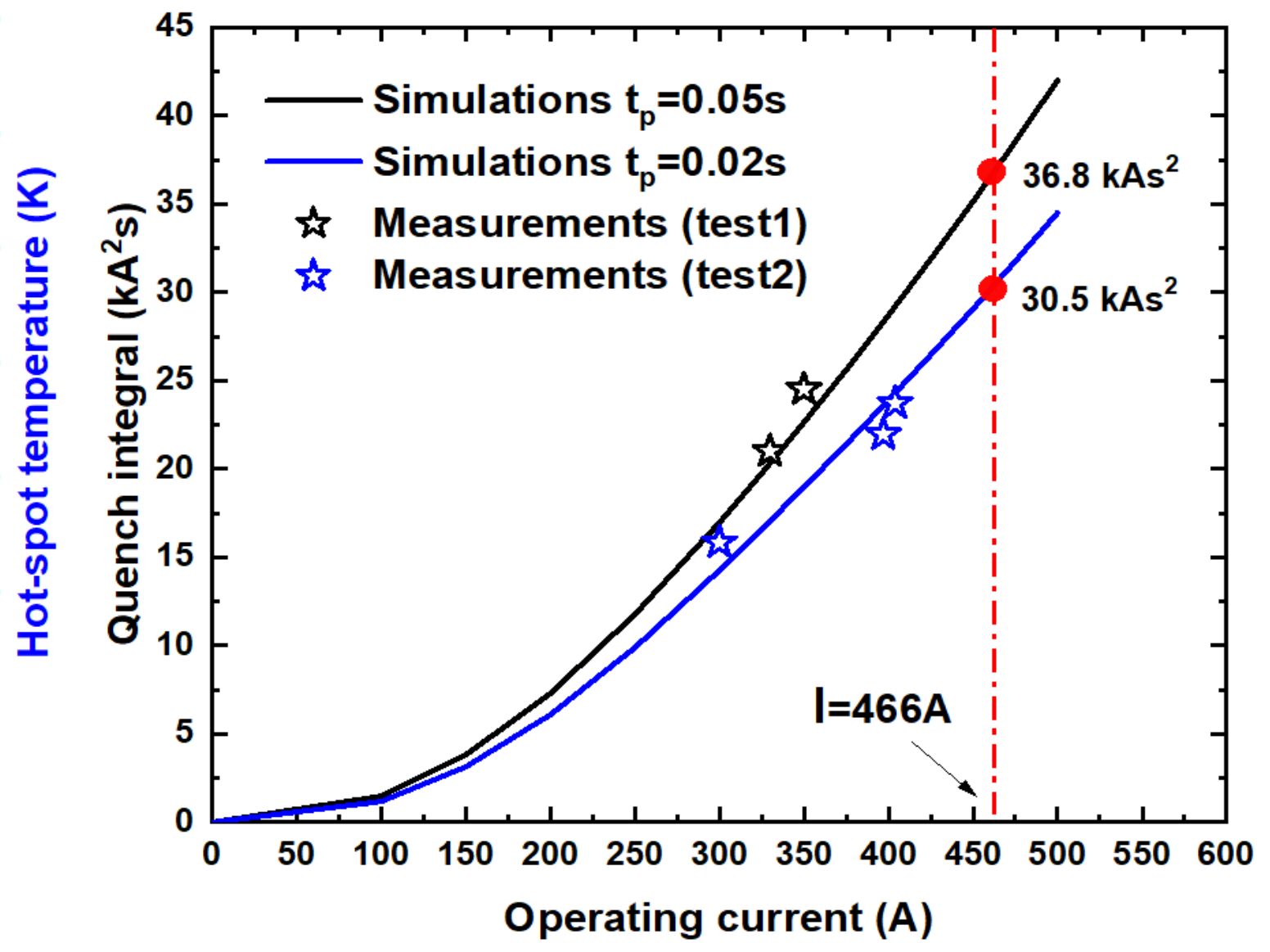
- ✓ **Obvious quench-back effect can be observed on both current and voltage curve during a energy discharge, and the hot-spot temperature is controlled blow 150 K by protection with a quench-back.**
- ✓ **Compared to a fixed resistor, a quench-back can be triggered more effectively by a varistor in consideration of the voltage limit for a magnet.**

➢ Quench protection baseline of the prototype magnet

Hot-spot temperature



Predictions of quench integral



- ✓ **At ultimate current 466A, the simulated hot-spot temperature and voltage-to-ground are below 250K and 650V respectively, ensuring the safety of magnet operation.**
- ✓ **The simulations of QI are in good agreement with the measurements, and the QI baseline is predicted at different protection delay time.**

■ Conclusion

- **An electro-thermal coupling quench model is developed and validated, which can describe the quench-back behaviors during the quench protection of DCT&CCT magnets.**
- **The electro-thermal mechanisms of a quench-back are revealed by analyzing transient evolutions of current, voltage and hot-spot temperature, comparing with measurements.**
- **The quench protection baselines of hot-spot temperature, voltage and QI are predicted for the prototype magnet at ultimate current, ensuring further tests.**

■ References

[1] M. A. Green . Cryogenics, 1984, 24(12):659-668.
[2] X. L. Guo , M. A. Green , L. Wang , et al. IEEE Transactions on Applied Superconductivity, 2010, 20(3):2035-2038.
[3] M. Mentink , J. van Nugtere , F. Mangiarotti , et al.. IEEE Transactions on Applied Superconductivity, 2018, 28(3):4004806.
[4] M. Mentink , M. Duda , F. Mangiarotti , et al.. IEEE Transactions on Applied Superconductivity, 2020, 30(4):4701306.
[5] W. Wu, Y. Liang, L. Zhou, et al.. Journal of Physics: Conference Series, HIAT-2018, 2020, 1401:012015

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