Simulation of Quench Behavior in CS LTS Magnets for Next-Generation Compact Fusion Devices with Alternating Operation

ID: 3009

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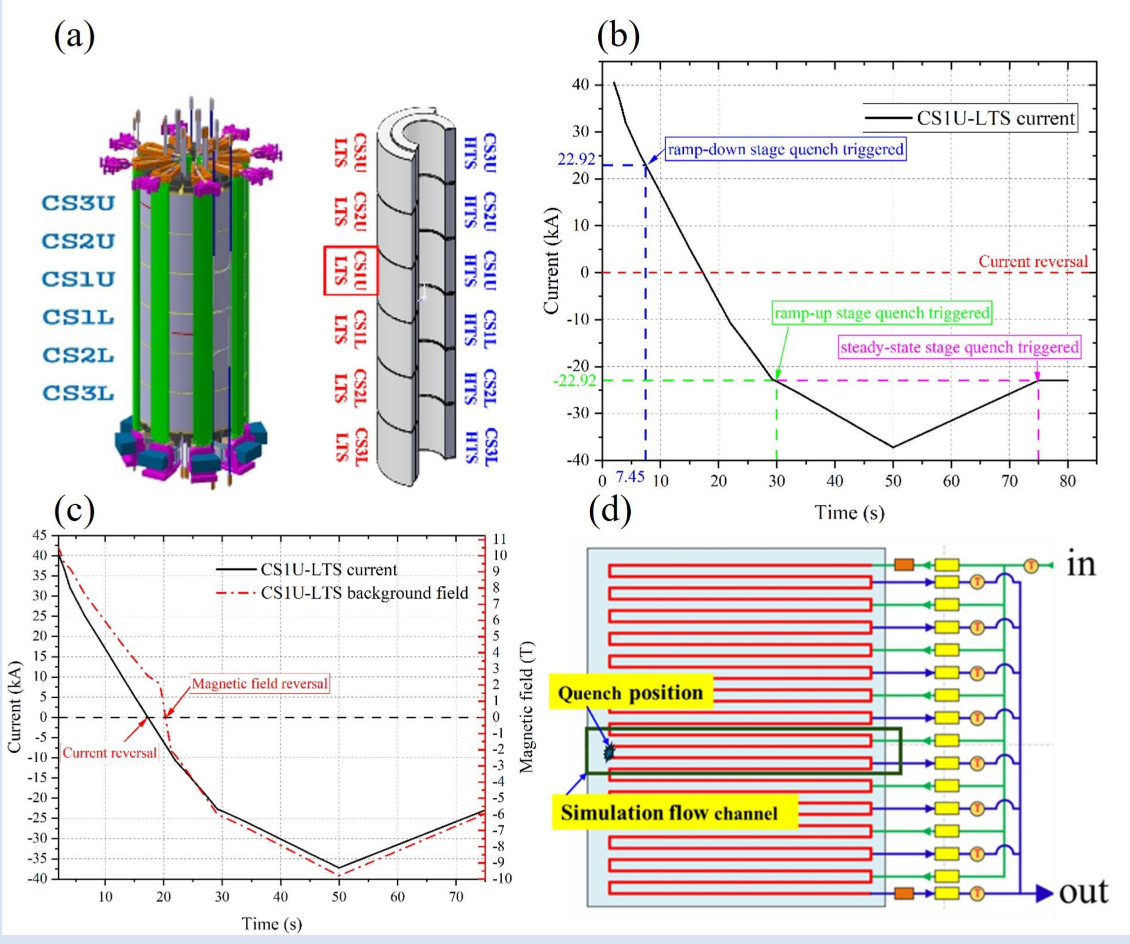
ABSTRACT

- Constructed a three-dimensional model of the superconducting magnet system for a compact fusion energy experimental device, providing the geometric basis for subsequent simulations.
- Analyzed the three-dimensional alternating magnetic field distribution under pulsed current conditions in COMSOL, offering a realistic background field for quench studies.
- Applied the THEA program to assess the quench performance of the CS coil, including minimum quench energy and propagation velocity, to guide safe operation and protection system design.

BACKGROUND

- The central solenoid (CS) magnet system is essential for plasma initiation, shaping, and current control in next-generation compact fusion devices. It consists of six coils, with high-field YBCO HTS and low-field Nb_3Sn LTS submodules. The CS must operate with large alternating currents and ramp rates up to 7 T/s, posing stability challenges due to shielding currents, thermal accumulation, and potential defects that may trigger premature quench.
- Previous studies on ITER and CFETR CS coils mainly assumed steady currents and constant background fields. In contrast, future devices require the CS to operate under strongly time-varying fields with alternating currents.
- In this work, the CS1U-LTS module, where current and field variations are largest, is selected for detailed analysis. Electromagnetic simulations provide realistic transient fields, which are then applied in extended THEA-based quench simulations to assess quench behavior during ramp-down, ramp-up, and steady-state stages.



(a) CS coil structure; the CS1U-LTS coil is the subject of this study.
(b) Current waveform and trigger quench position at each stage.
(c) Waveforms of current and magnetic field.
(d) CS1U-LTS cooling circuit and quench position.

METHODS I: Magnetic Simulation

Magnetic Field Analysis

The TF coils vary slowly, so their effect on the CS coil is negligible and excluded. The system includes CS, PF, and CC coils, with configurations shown in Fig. (e) and currents in Fig. (f). Finite element simulations indicate that the CS1U-LTS magnetic field, though coupled with other coils, mainly follows its own current. The maximum field reaches ~10.5 T near the current peak and decreases during ramp-down. This dynamic field profile is used as input for quench simulations.

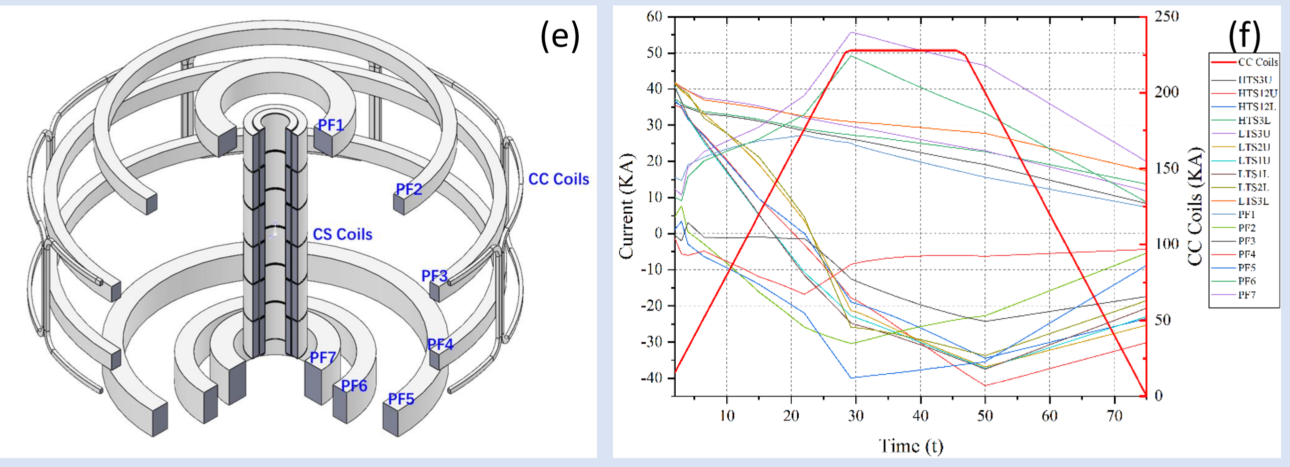


Fig. (e) and Fig. (f): Next generation compact fusion energy device magnet system and its Current (excluding TF coil).

METHODS II: Quench Simulation

A. Numerics

A coupled electromagnetic–thermal model of the CS1U-LTS coil was developed. Quench simulations across ramp-up, ramp-down, and steady-state stages reveal propagation mechanisms, guiding safe magnet design and protection in compact fusion devices.

B. Quench Detection and Current

Quench simulations at 22.9 kA cover ramp-up, ramp-down, and steady-state. Current decays exponentially (τ=0.814) after detection, enabling analysis of propagation and protection performance.

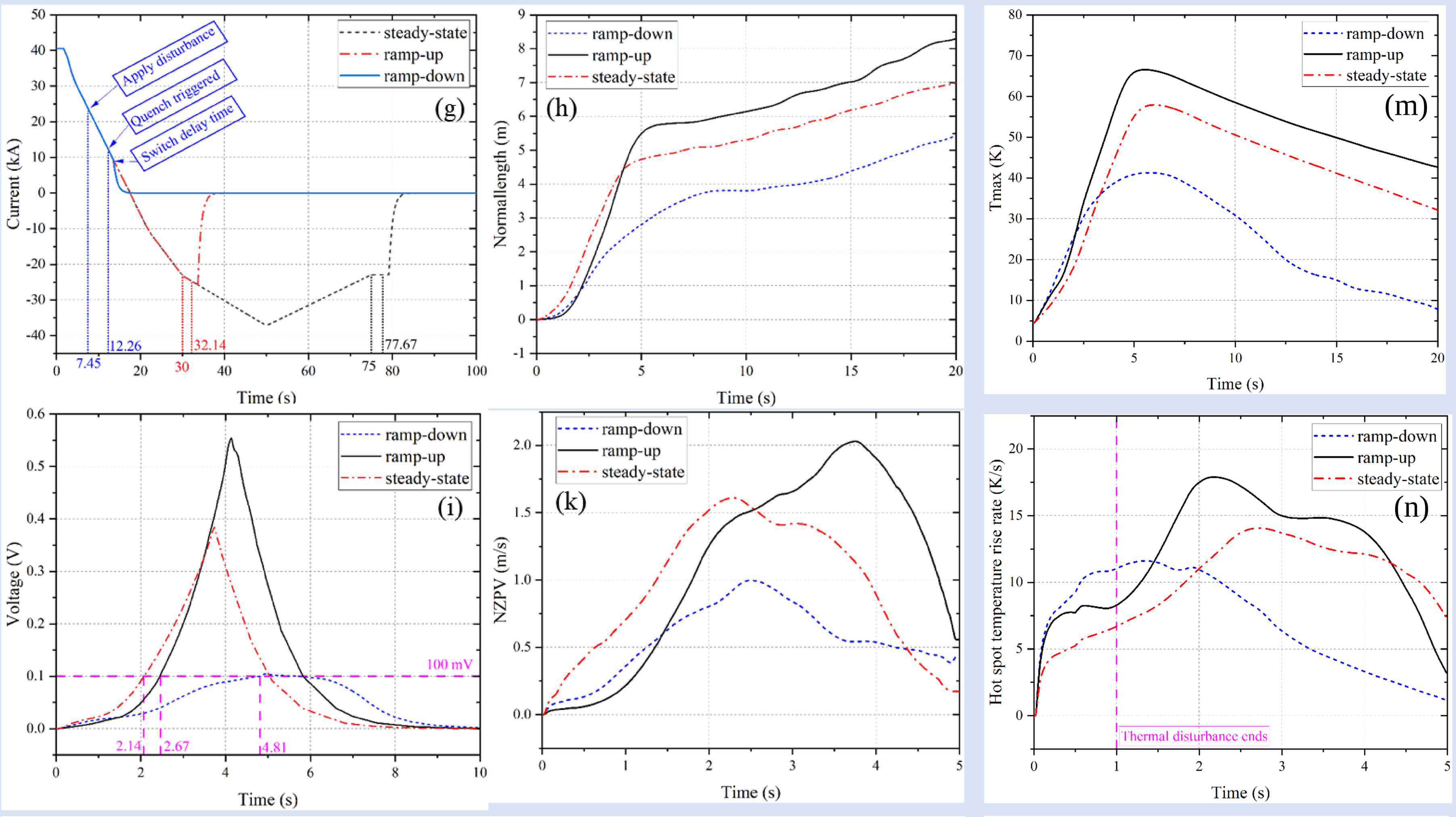
$$I = I_{op} e^{-t/\tau} \quad (1)$$

C. Thermal Disturbance

Quench simulations are initiated by applying a local 1 cm, 1 s thermal disturbance pulse at the channel center. Disturbance power is gradually increased to determine MQE, calculated by Eq. (2). Inductive heating effects are evaluated using Eq. (3), with parameters consistent across reference and transient conditions.

$$Q_{MQE} = \frac{Q\cdot\Delta L\cdot\Delta t}{(A_{sc}+A_{Cu})\Delta L\times 10000} \quad (2)$$

$$\begin{cases} I_{ind}(t) = \dfrac{A\cdot\frac{dB}{dt}}{R_{eff}} \\ P_{ind}(t) = R_{eff} I_{ind}^2(t) \\ Q_{ind}(t) = \int_0^t P_{ind}(s)ds = R_{eff}\int_0^t I_{ind}^2(s)ds \end{cases} \quad (3)$$



(g) Current discharge curve, the switch delay time is 1.5s.
(h) Normal zone propagation curves at each stage.
(i) Voltage propagation curves at each stage.
(k) Time evolution of the normal zone propagation velocity (NZPV).

(m) Maximum temperature (Tmax) rise curve at each stage (hot spot).
(n) Temperature rise rate of each stage changes with time.

CONCLUSION

- The time from disturbance to quench varies: shortest in ramp-up, moderate in steady-state, and longest in ramp-down. Detection thresholds should be adjusted accordingly.
- Voltage rise and NZPV accelerate during ramp-up, are moderate in steady-state, and slowest in ramp-down, showing strong correlation with current variation rates.
- Hot spot temperature rises in ramp-up (+14.9%) and drops in ramp-down (-28.7%) compared to steady-state, all below 150 K..
- Temperature rise rates: ramp-up highest on average, ramp-down fastest initially, steady-state overtakes ramp-up after 4.2 s.

ACKNOWLEDGEMENTS

- We thank the staff members of the Experimental Advanced Superconducting Tokamak (https://cstr.cn/31130.02.EAST), for providing technical support and assistance in data collection and analysis.