Test Results of Quench-back Management Due to Fast Decaying Current-Induced AC Losses in SHMS Superconducting Magnets at Jefferson Lab

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ABSTRACT: The Super High Momentum Spectrometer (SHMS) of Hall C, part of the recent 12 GeV accelerator Upgrade at Jefferson Lab, was successfully commissioned in 2017. Fast current discharges of the SHMS Q2, Q3 quadrupoles and dipole superconducting magnets experienced some level of operational difficulty during commissioning and normal operation. Measurements and analyses demonstrate that the fast current discharge leads to substantial AC losses in the conductor and subsequently triggers a quench-back effect. The details of the measurements and analyses have been reported previously. This paper focuses on the test results of the magnets using a reduced value of the external protection dump resistor for each magnet to lower the current decay rate. The measurement setup is nearly identical to previous measurements but with higher sampling rates. The test results confirmed that the reduction to the dump resistances eliminated the quench-back effect for the SHMS Q2, Q3 and Dipole magnets, thus improving their cryogenic operability.

Fig. 1 HB, Q1, Q2, Q3, and Dipole magnets installed on the SHMS platform. Jefferson Lab's 11 GeV Super High Momentum Spectrometer (SHMS) has been successfully commissioned.

Outline of Quench-back Management

- Identified contributing factors to fast discharge induced quench-backs at high current.
- Computed AC loss (E_{st}) within superconducting strands, coupling AC loss (E_{cp}), hysteresis loss (E_{hy}), and penetration loss (E_p).
- Modeled eddy current in copper stabilizer using OPERA/ELECTRA.
- Compared computed starting time of quench-backs with measured ones to verify the computational method.
- Proposed reduced dump resistances to eliminate quench-backs.
- Tested reduced resistors by forced fast discharging.
- Confirmed that reduced resistances eliminated quench-back effects.

AC loss between superconducting strands (E_{st}) has two components: E_{tr} and E_{adj}

$$E_{st} = E_{tr} + E_{adj}$$

$$E_{tr} = \frac{1}{60}\frac{\dot{B}_{tr}^2}{r_c}p^2\frac{c^2}{b} = \frac{1}{120}\frac{\dot{B}_{tr}^2}{R_c}N(N-1)p\frac{c}{b}$$

$$R_c = \frac{N(N-1)r_c}{2pc}$$

$$E_{adj} = \frac{1}{12}\frac{\dot{B}_{tr}^2}{r_a}p^2\frac{c}{N\cos(\theta)} = \frac{1}{6}\frac{\dot{B}_{tr}^2}{R_a}p\frac{c}{b}$$

$$R_a = \frac{2Nr_a\cos(\theta)}{pb}$$

$$E_{cp} = \int_0^{t_0}\frac{2\dot{B}^2}{\mu_0}\tau_f V_{ct}\,dt$$

$$\tau_f = \frac{\mu_0}{2\rho_{et}}\left(\frac{L_t}{2\pi}\right)^2$$

$$\rho_{et} = \left(\frac{1}{\rho_t} + \frac{w}{a\rho_m} + \frac{aw}{\rho_m}\left\{\frac{2\pi}{L_t}\right\}^2\right)^{-1}$$

$$E_{hy} = \frac{8}{3\pi}aJ_{c0}B_0\ln\left\{\frac{B_2+B_0}{B_1+B_0}\right\}V_{NbTi}$$

$$E_p = \frac{1}{2}\frac{B_m^2}{2\mu_0}\frac{4\pi^2a^2}{L_t^2}$$

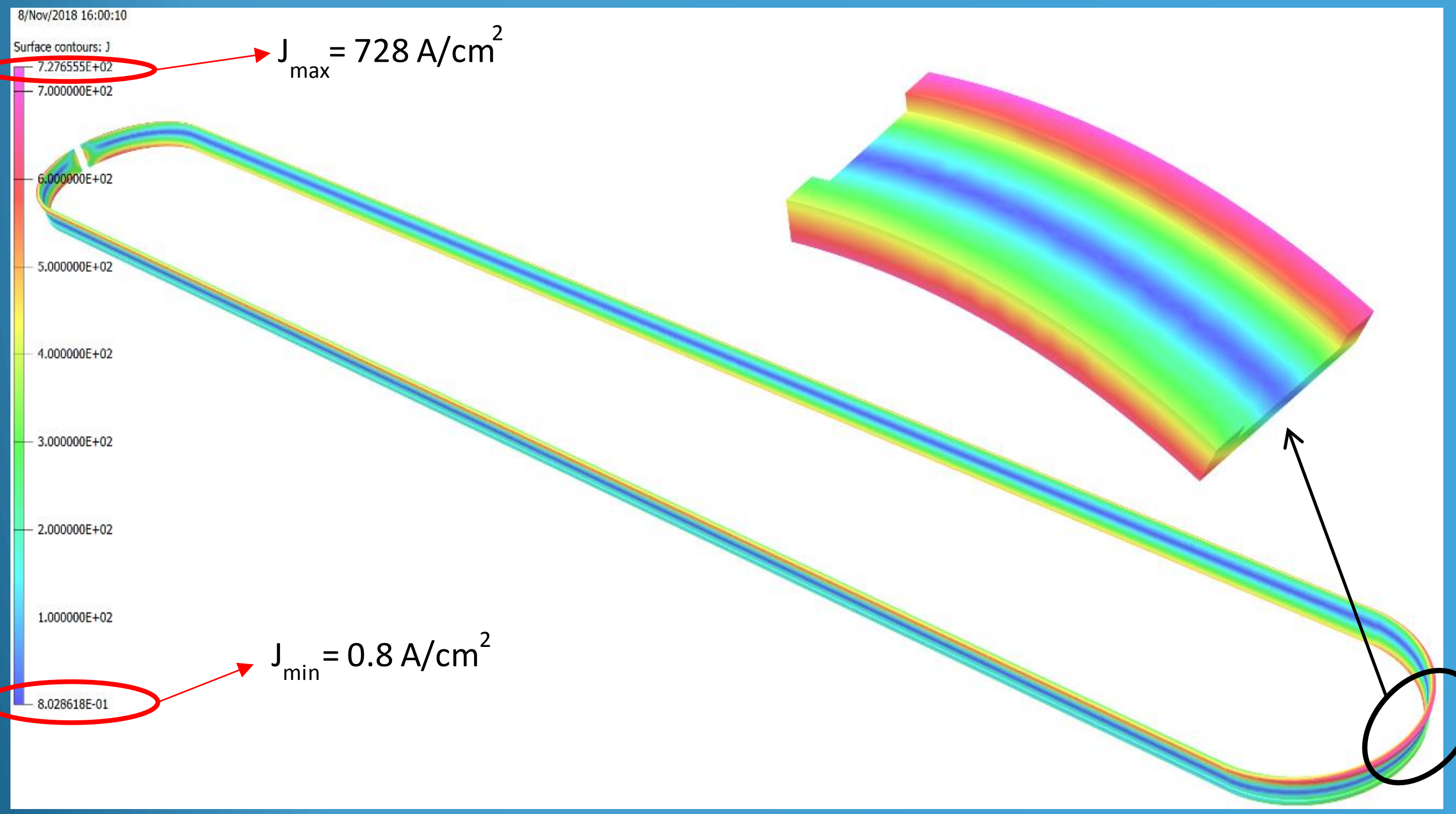

Fig. 2 Simulation model of current density in copper stabilizer for Q3 during fast discharge from 3500A for the first 2 seconds after the start of the discharge. The upper right image shows a zoomed-in section of the current density distribution across a section of the copper stabilizer.

AC Loss/Eddy Heating	Q2/Q3 (%)	Dipole (%)
E_{cp} (coupling loss)	2.66	2.68
E_{hy} (hysteresis loss)	0.93	2.22
E_p (penetration loss)	0.14	0.31
E_{tr} (crossover AC loss)	83.6	82.0
E_{adj} (adjacent AC loss)	1.32	1.33
E_{eddy} (eddy current)	11.0	11.5

Table 1 Percentage contribution of total heat (50 mm long conductor, within first 2 seconds, Rd = 0.075 Ω [design value])

Crossover AC loss plays a dominant role (>=82%). Eddy current heating also makes significant contribution (>=11%).

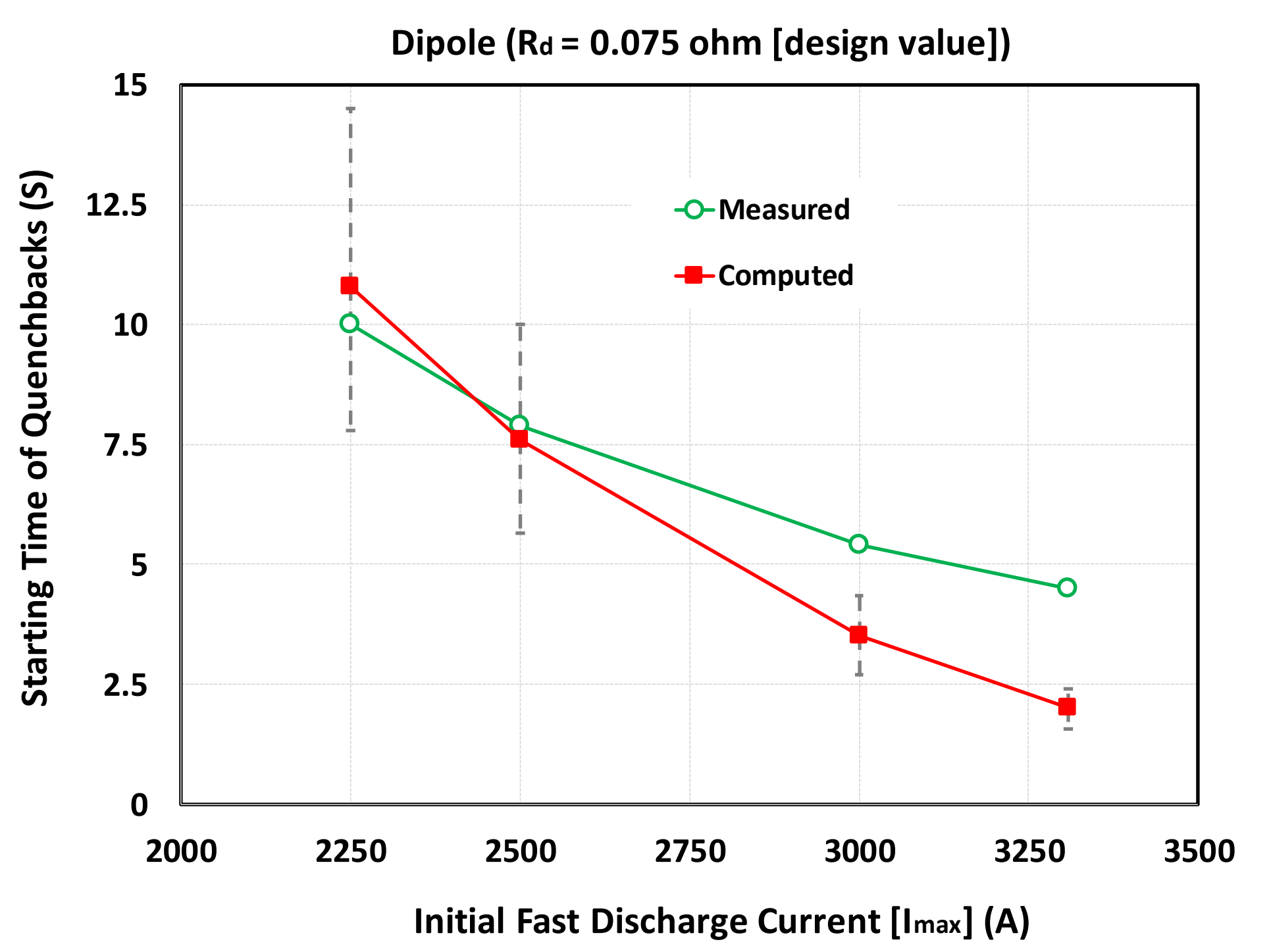

Fig. 3 Starting time of quench-backs versus fast discharge current. The computed starting time is based on RRR (stabilizer) = 120 and r_{sol_cu} = 45. The range of the long vertical dashed line represents the computed data points with r_{sol_cu} = 35 (lower) and 55 (upper).

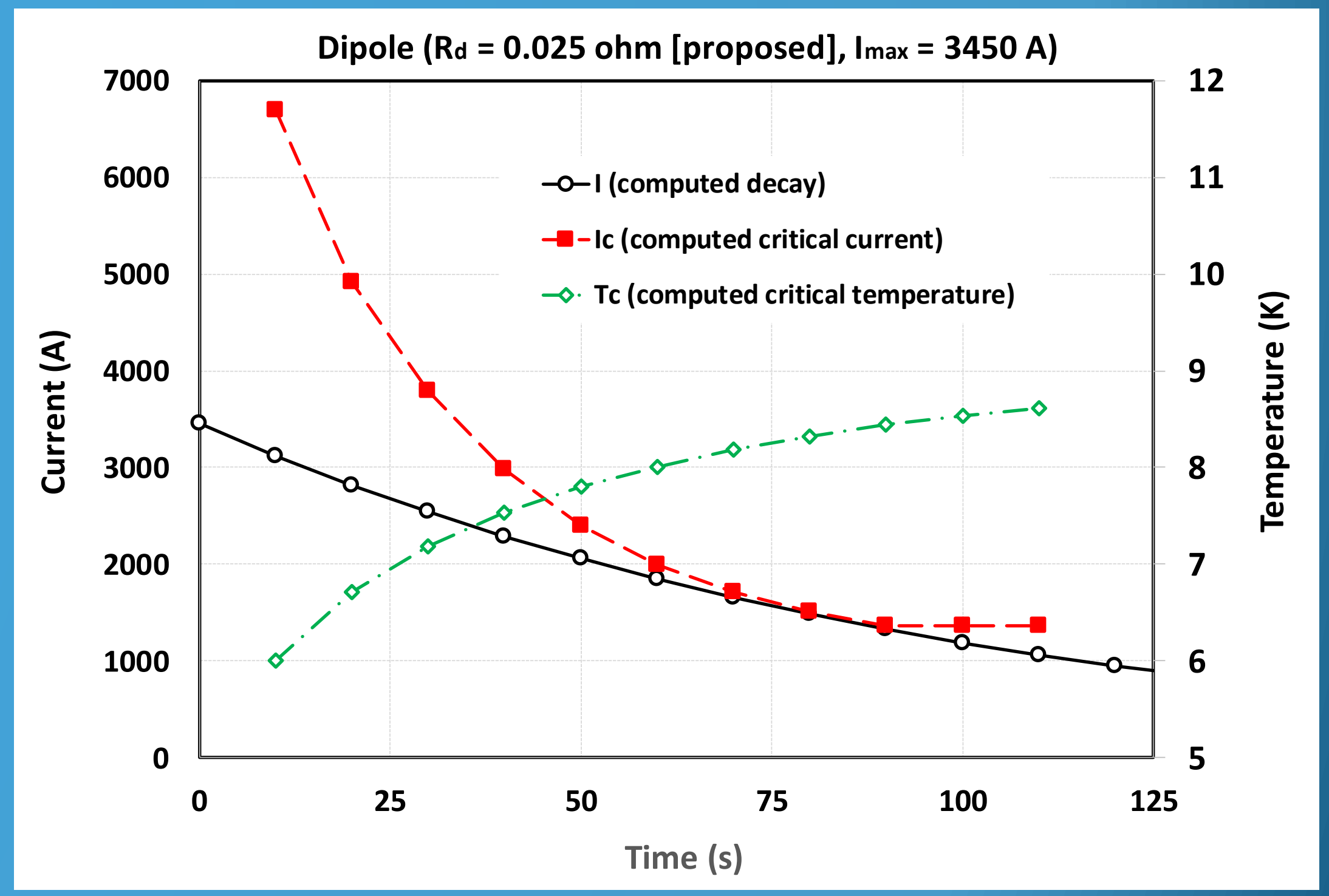

Fig. 4 Computed decay of Dipole and computed critical currents versus time. The solid line with open circles represents the natural current decay of Dipole when fast discharged from 3450 A with a 0.025 Ω dump resistor.

Measured Voltage Decay Curves Across Layers within One Coil for Q3 and Dipole Magnets

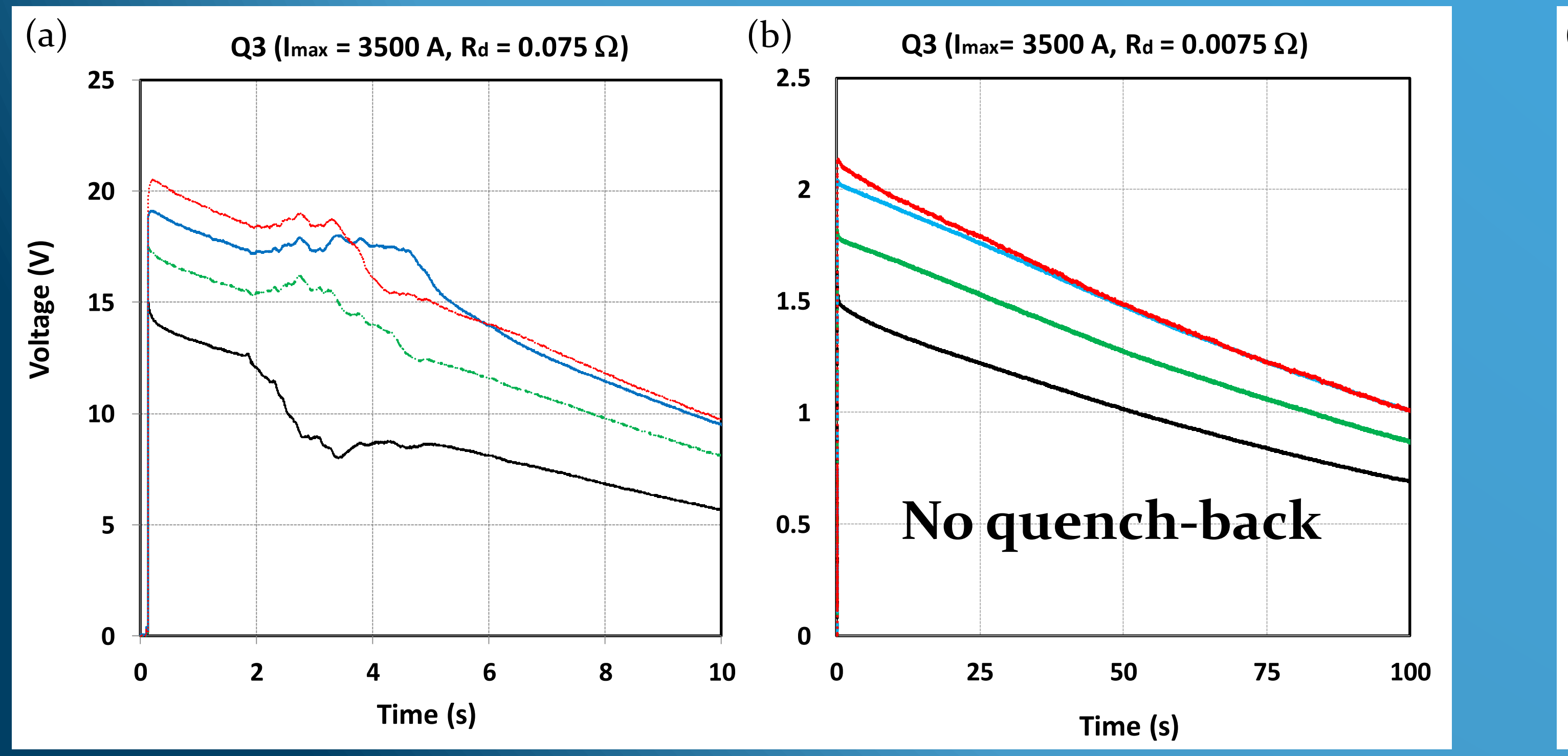

Fig 5 Current decay, voltage decay across the dump resistor as well as voltage decays across four layers in one coil of the Q3. (a) Discharge current = 3500 A, Rd = 0.075 Ω. Quench-back was detected. (b) Discharge current = 3500 A, Rd = 0.0075 Ω. No quench-back was observed.

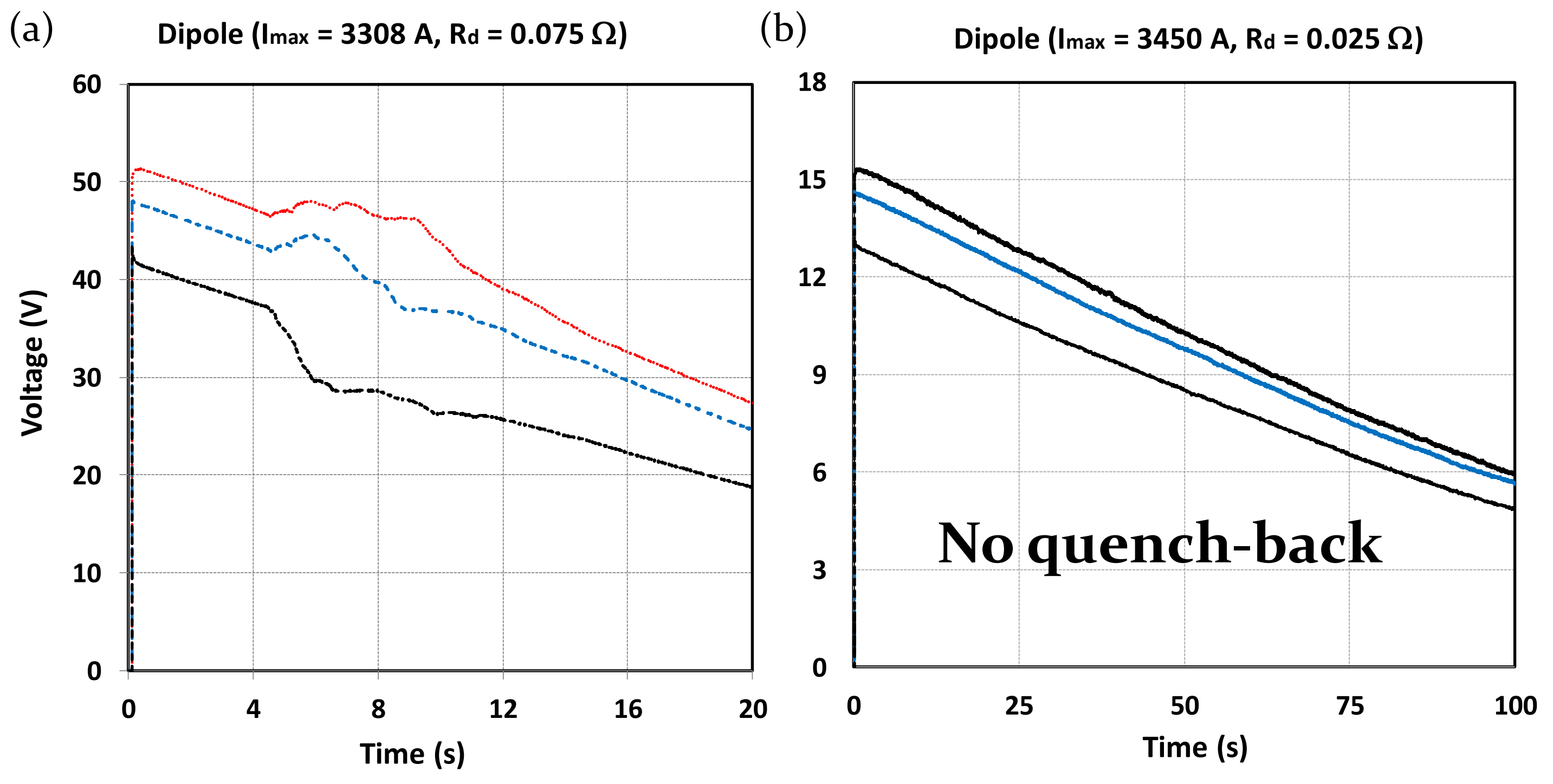

Fig. 6 Current decay, voltage decay across the dump resistor as well as voltage decays across three layers in one coil of the Dipole (a) Discharge current = 3308 A, Rd = 0.075 Ω. Quench-back was detected. (b) Discharge current = 3450 A, Rd = 0.025 Ω. No quench-back was observed.

Conclusion: The fast discharge tests of the Q3 and Dipole confirmed that the proposed dump resistors were able to eliminate the quench-back effect up to 3500 A for the Q3 magnet and 3450 A for the Dipole magnet. The operational performance of the SHMS's Q2, Q3, and Dipole magnets have improved significantly from a cryogenic perspective. Fast discharging from 3500 A (Q3) or 3450 A (Dipole) with the proposed dump resistances, both magnets had negligible coil temperature rise, helium pressure rise or helium liquid level drop. The effect of quench-back induced heating of the coils was evident with the original dump resistances; it was observed that all the helium boiled off from the magnets starting at currents as low as 3000 A for the Q3 or 2250 A for the Dipole.