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NATIONAL HIGH MAGNETIC FIELD LABORATORY

Superconducting Transformer for Superconducting Cable Testing up to 45 kA

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Abstract

A facility capable of testing superconducting cables with current of tens of kA is essential for the development of large superconducting magnets. A superconducting transformer (SCT) is a suitable choice as a high DC current source for testing superconducting cables. In this work, we will present our experimental results of a SCT that was originally developed by Lawrence Berkeley National Laboratory (LBNL) to reach a maximum output current of 45 kA. The SCT is characterized at 4.2 K in zero magnetic field. Its behaviors during a quench at different current levels are studied.

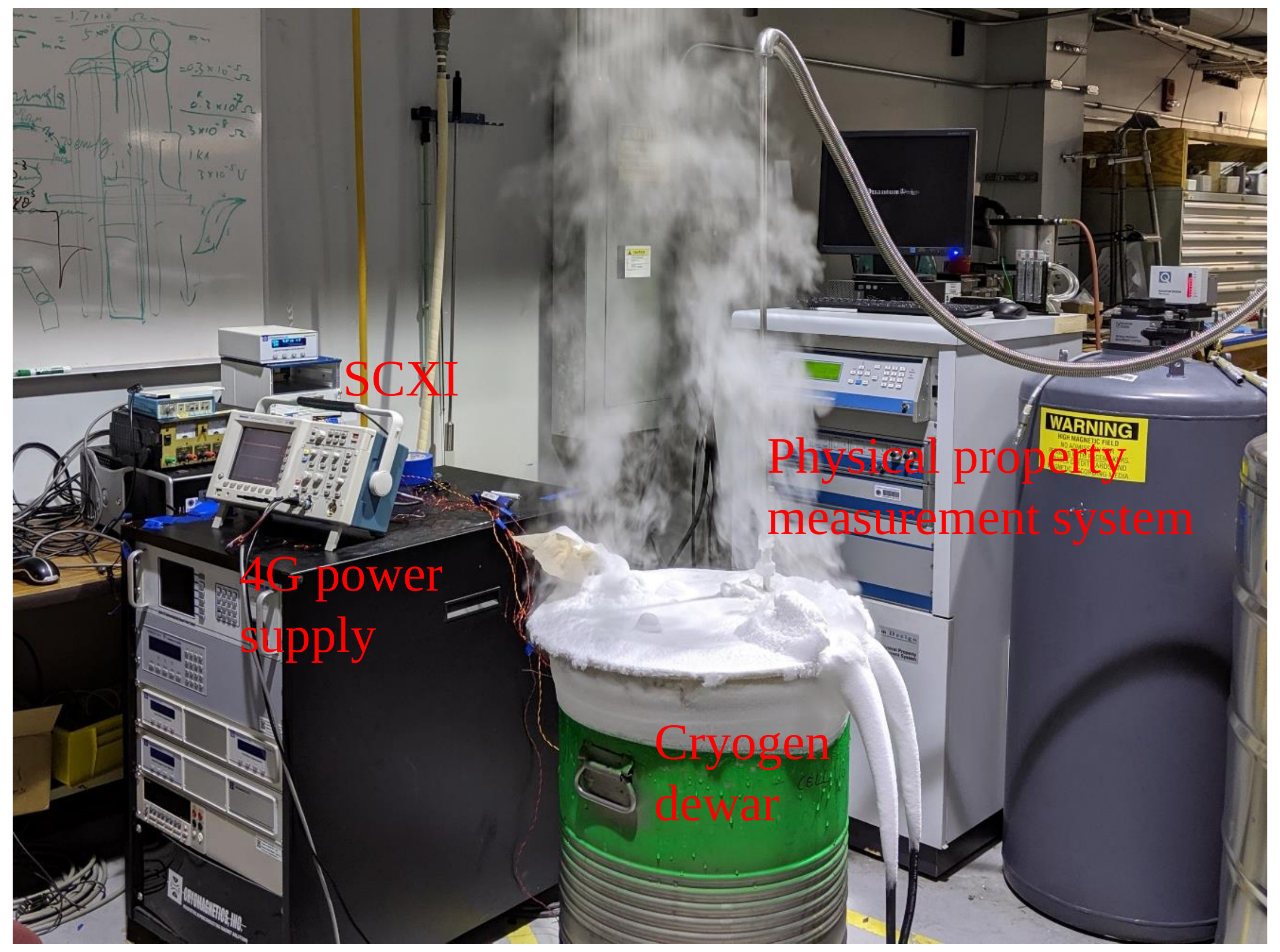
Introduction

- Large superconducting cables: required by large superconducting magnets systems.
- Tens of kA of electrical current: necessary for developing and characterizing large superconducting cables at or above its operating current.
- SCT: small current at its primary and large current output at its secondary; a very efficient way to provide large current to superconducting cable samples.
- A 50 kA SCT: developed by LBNL and tested up to 28 kA [1]; transferred to the NHMFL.
- This poster: our calibration of this SCT, the results of the maximum output current, its quench behavior, and the accuracy of the output current measurement.

Experimental Methods

- Primary: 10,464 turns of NbTi wire; Secondary: 6.5 turns of NbTi Rutherford cable [1].
- Two Rogowski coils: output current measurement; Two heaters: quench the SCT [1].
- Table listed its room temperature measured properties: in good agreement with designed values.
- SCXI: measure voltages; LabVIEW: digitally integrate the Rogowski coil voltage.
- Rogowski calibration: at both RT and 4.2 K, up to 80 A (equivalent of 4 kA output current).
- Hall sensors: absolute field measurement, calibrated in a physical property measurement system.
- 6 short pieces of superconducting cables: soldered to the output, TEVATRON 23 strands NbTi cable (critical current ~ 15 kA at 1 T [2]-[3]), soldered by Sn63Pb37.

Schematic diagram of the SCT

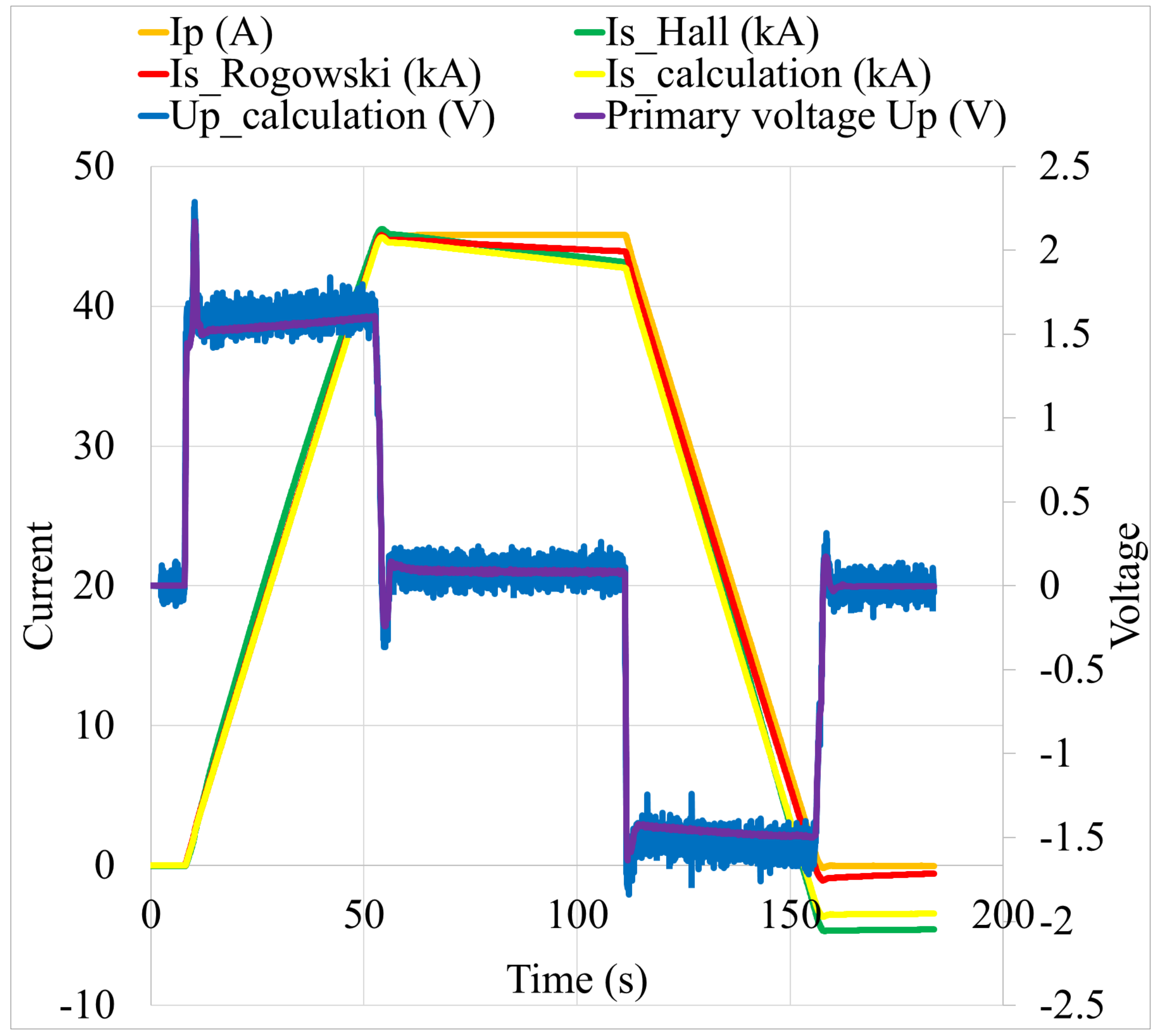


A photo of the test system

Room temperature properties	Measured (at 100 Hz)	Designed [1]
Current ratio	--	1000
Primary inductance, L_p (H)	4.158	4.5
Secondary inductance, L_s (H)	2.525E-6	2.27E-6
Mutual inductance between primary and secondary, M_{ps} (H)	2.75E-3	2.8E-3
Quench heater resistance (Ω)	10.2	--
Rogowski inductance (H)	8.257E-3	8.1E-3
Mutual inductance between secondary and Rogowski (H)	5.25E-6	5.3E-6
Calibration inductance (H)	2.253E-4	--
Mutual inductance between calibration and Rogowski (H)	2.665E-4	--
Primary resistance, R_p (Ω)	636	--

Results and Discussions

Maximum operating current

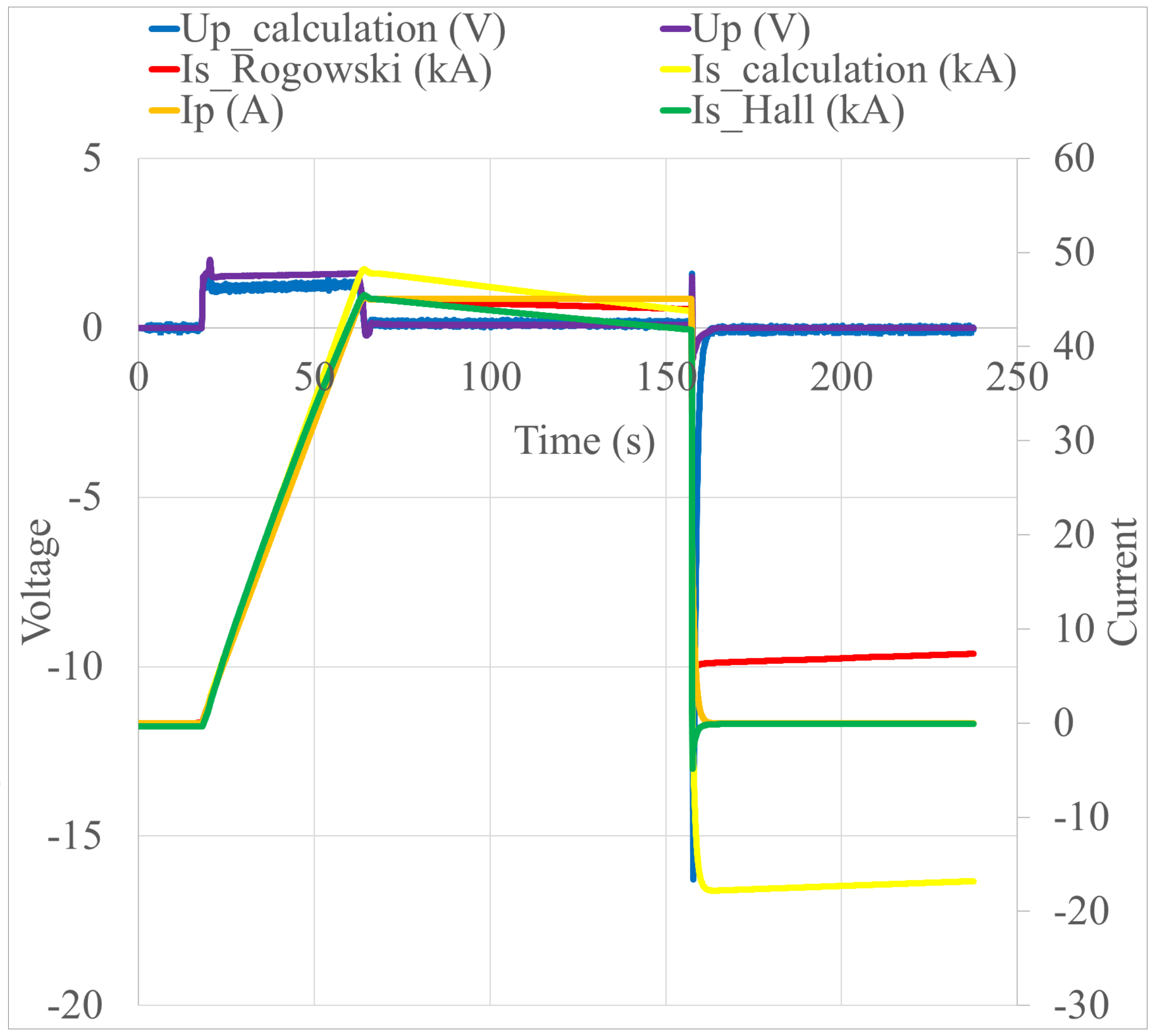


A typical ramp and hold cycle at 45 kA

- Ratio ~ 1000:1 as expected.
- Training behavior:
  1) First spontaneous quench: ~ 30 kA
  2) Quenches in 3 cooldowns steadily increased quench current above 45 kA.
- A typical ramp and hold cycle:
  1) Demonstrate the operating current could reach 45 kA;
  2) While the primary current Ip is kept constant: the secondary current I_s slowly decreases, consistent with predicable current decay due to the join resistance ~3E-9 Ω, decay time constant ~3000 s;
  3) When I_p ramped back to 0: I_s became negative, due to the current decay.

Quench

- Max stored energy in SCT: 45 kJ, latent heat of 2 L of LHe
- SCT differential equation: estimate inductive voltage
  1) Primary:
     $U_p = I_pR_p + L_p(dI_p / dt) - M_{ps}(dI_s / dt)$;
  2) Secondary:
     $0 = I_sR_s + L_s(dI_s / dt) - M_{ps}(dI_p / dt)$.
- An induced quench at 45 kA:
  1) I_s after quench cannot be measured correctly by Rogowski, because digital integration is difficult to handle an event of millisecond.
  2) Advantage of Hall sensors' measurement is evident.
  3) U_p during a quench is less than 2 V. The operation is quite safe.

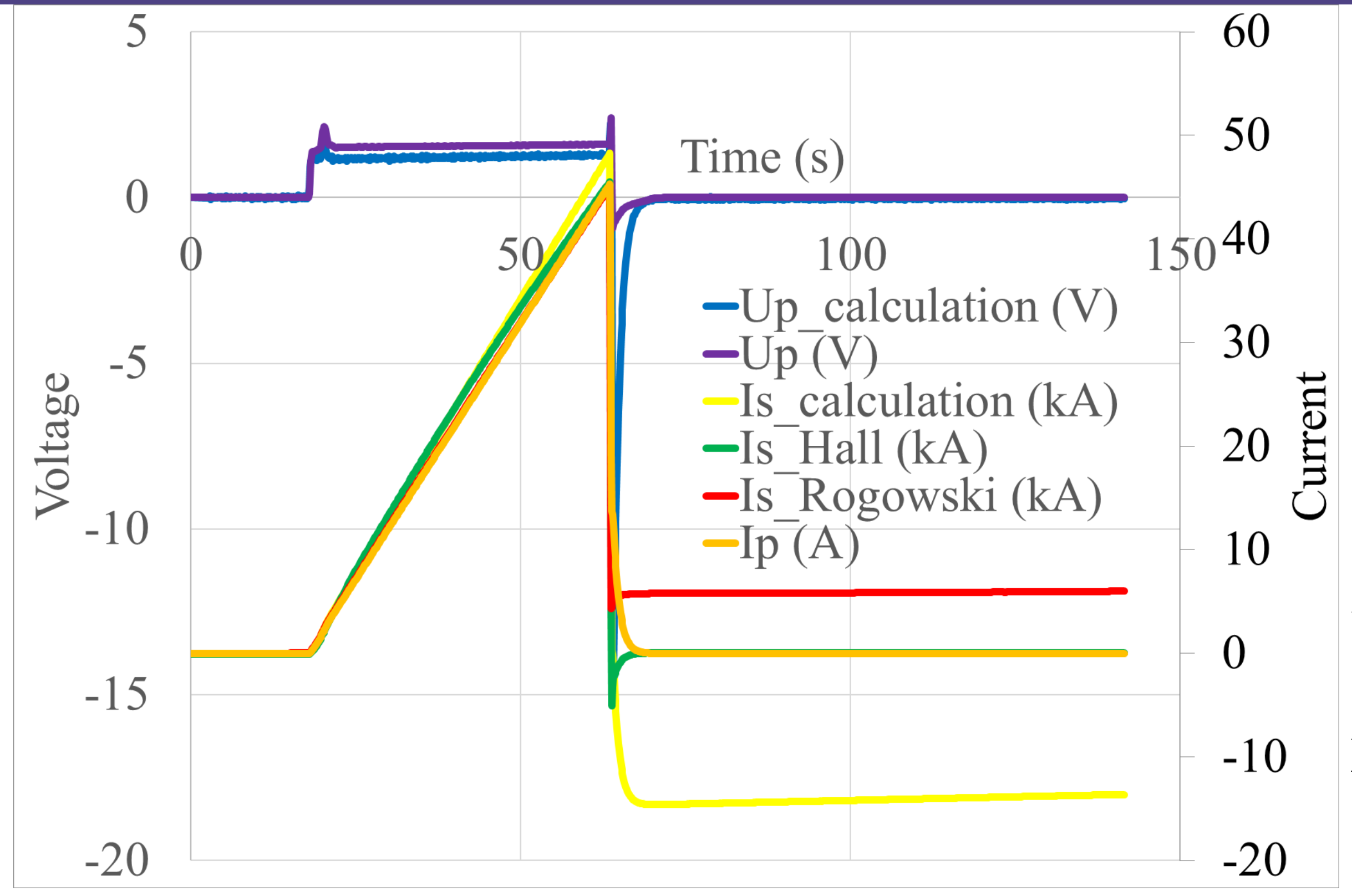


And induced quench at 45 kA

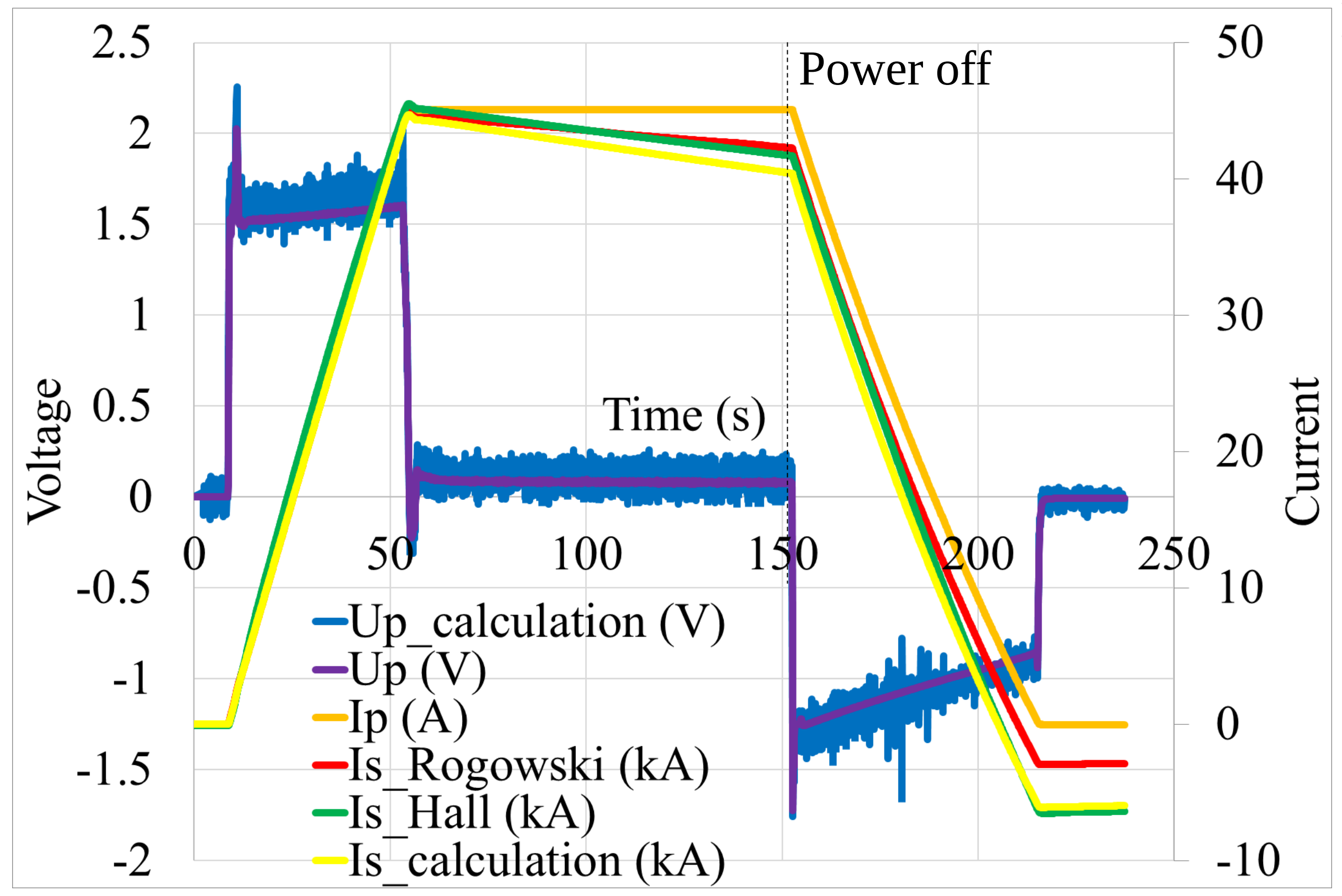
- Different minimum quench heater power at different current levels.

Nominal secondary current (kA)	Quench heater current (mA)	Minimal heater power (mW)
45	120	144
20	220	488
10	280	784

- Calculations assuming adiabatic heating.



Spontaneous quench at ~ 45.5 kA



Power supply shut down

- Spontaneous quench:
  1) Occurred at 45.5 kA when ramping to 50 kA.
  2) The quench seemed to be not caused by thermal run-away of the short cable.
  3) U_p during a quench is also less than 2 V, confirmed by a oscilloscope.
- Power supply shut down: Ramped to 45 kA then shut down the main switch of the power supply.
  1) I_p decayed to 0 at ~0.7A/s.
  2) U_p: ~-1.7 V at the shut down moment, increased almost linearly (suggesting a near exponential decay), then suddenly jumped to zero.
  3) I_s decayed to -2.9 kA.

Uncertainty in output current measurement

- Rogowski vs Hall sensor
  1) reasonably good agreement.
  2) some differences: we think the largest source of uncertainty comes from the I_s calculation by Hall voltage.
  3) Hall sensors are important when the initial current state is unkown

Conclusion

- The SCT developed at LBNL is fully characterized at 4.2 K at the NHMFL:

1) It was ramped and held up to 45 kA successfully.
2) Spontaneous quench occurred at about 45.5 kA.
3) Neither induced nor spontaneous quenches generated voltage higher than 5 volt in any circuit.
4) Integration of Rogowski coil and Hall sensors are both reliable ways of output current measurement.

- In near future, this SCT will be used to provide current for critical current measurement of a superconducting cable sample in magnetic field.

Acknowledgment

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Reference

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