Design, Construction and Operation of a 13 T 50 mm No-Insulation REBCO Insert for a 20 T All-Superconducting User Magnet

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Applied Superconductivity Center and Magnet Science and Technology

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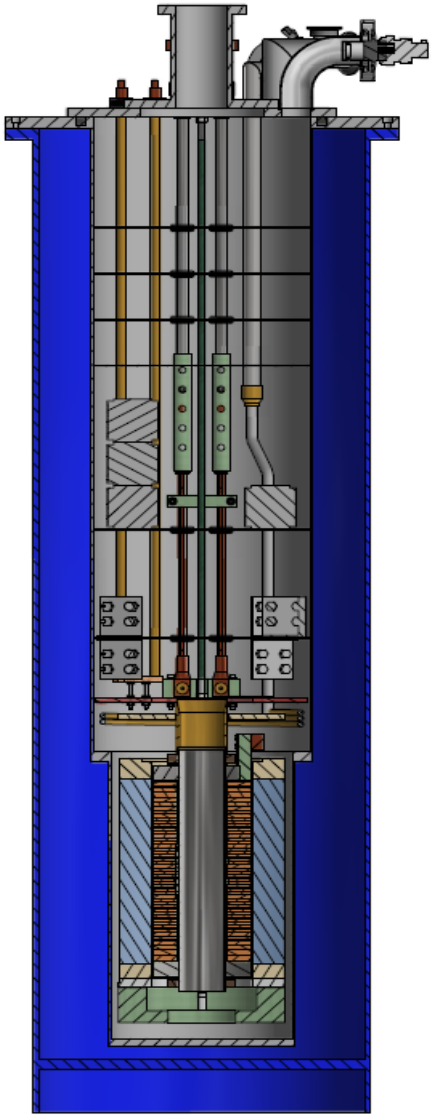
Outline

- Magnet system
- Feedback Control
  - 5 T, 13 T.
  - Ramp rates, LHe consumption, PS overcurrent.
- System Testing
  - Standalone
  - Insert + Outsert
- Characteristic Resistance
- Post quench
- Summary and Future plan

Magnet System

- 20 T User Magnet (52 mm bore)
  - Goal: build a magnet system containing a no-insulation coil with an LTS outsert that will function as a user instrument.
  - Multi-width and inside notch technic were applied to NI insert magnet.
  - Feedback control method for NI insert magnet charging was tested.
  - Outsert presents quench dynamic challenges.
  - Configuration: 13 T HTS coil nested inside of a 7 T NbTi coil.



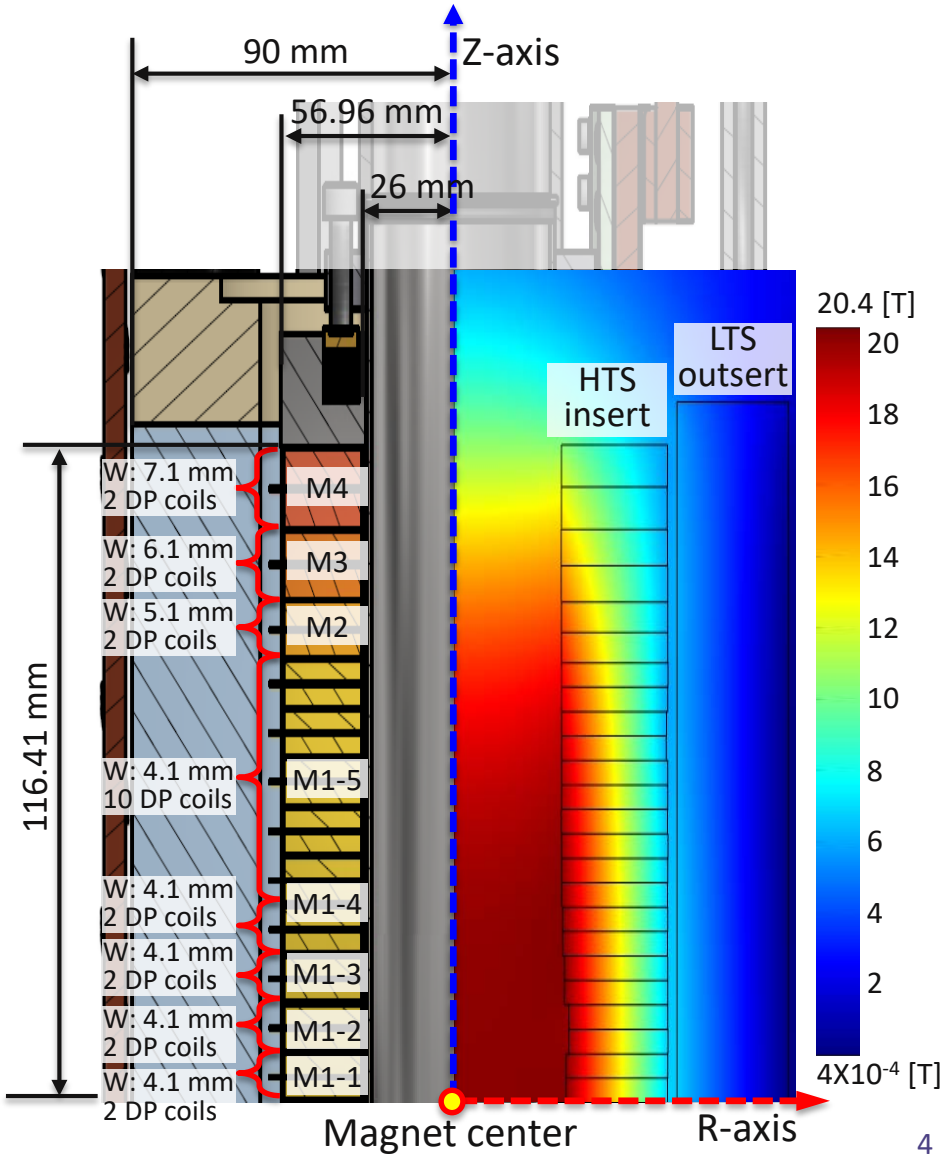
Whole structure drawing of 20 T user magnet

Key Parameters for 13 T NI Insert Magnet

Key Parameters

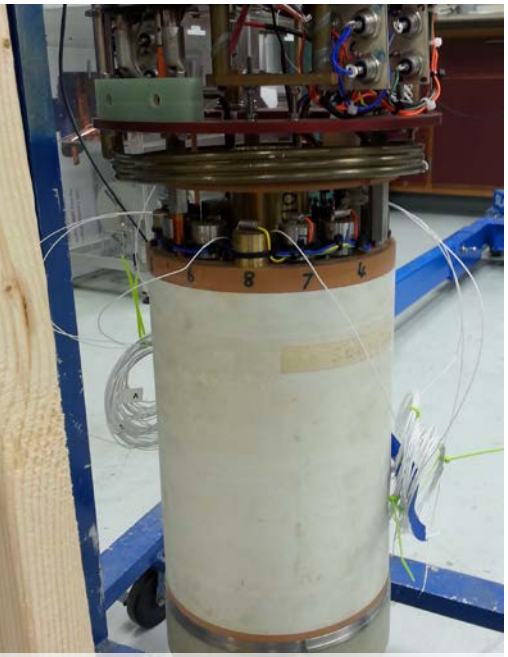
Parameters		Values
REBCO Tape		
Tape width	[mm]	4.1 to 7.1 (Multi width)
Tape thickness	[mm]	0.12 (0.126 ~ 0.117)
REBCO Insert		
Winding inner radius, a_1	[mm]	29.00 to 30.92 (Inner notch)
Winding outer radius, a_2	[mm]	56.96 (OD: 113.92 mm)
Overall height	[mm]	232.81
Number of DP coils		24
Turn per "single" pancake coil		217 to 233
Total REBCO tape	[km]	3.4 (4.1 mm equivalent)
Inductance, *L*	[H]	2.82
20 T Operation		
Center field	[T]	20.0 (13 T HTS + 7 T LTS)
Operating current I_{op}	[A]	213 (13 T HTS), 80.5 (7 T LTS)
Total inductance of magnet	[H]	36.87 (2.82 (HTS) + 23.37 (LTS) + (2*5.34 (Mutual)))
B1; B2 at 20 T		20.1; 6.4
Magnet constant of 13 T (HTS)	[mT/A]	61.03
Magnet constant of 7 T (LTS)	[mT/A]	86.96
Characteristic resistance, R_c (R_{ct} = 10 μΩ·cm²)	[mΩ]	9.15
Charging time constant (τ)	[sec]	308.20 (=2.82/0.00915)
Storage energy of insert/outsert/total system	[kJ]	64.0/75.7/231

½ Structure drawing

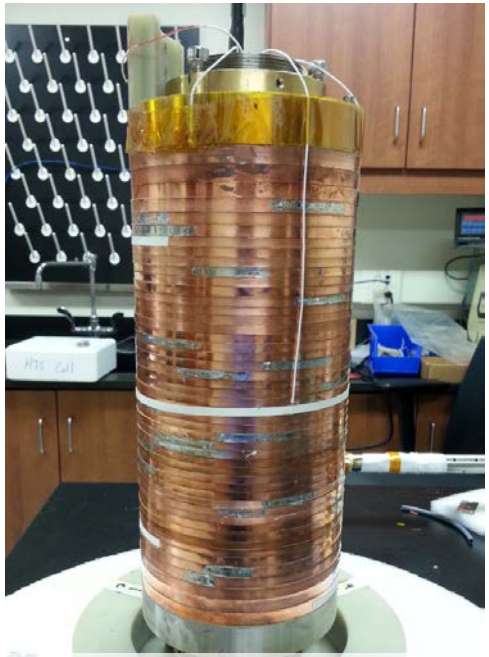


Construction

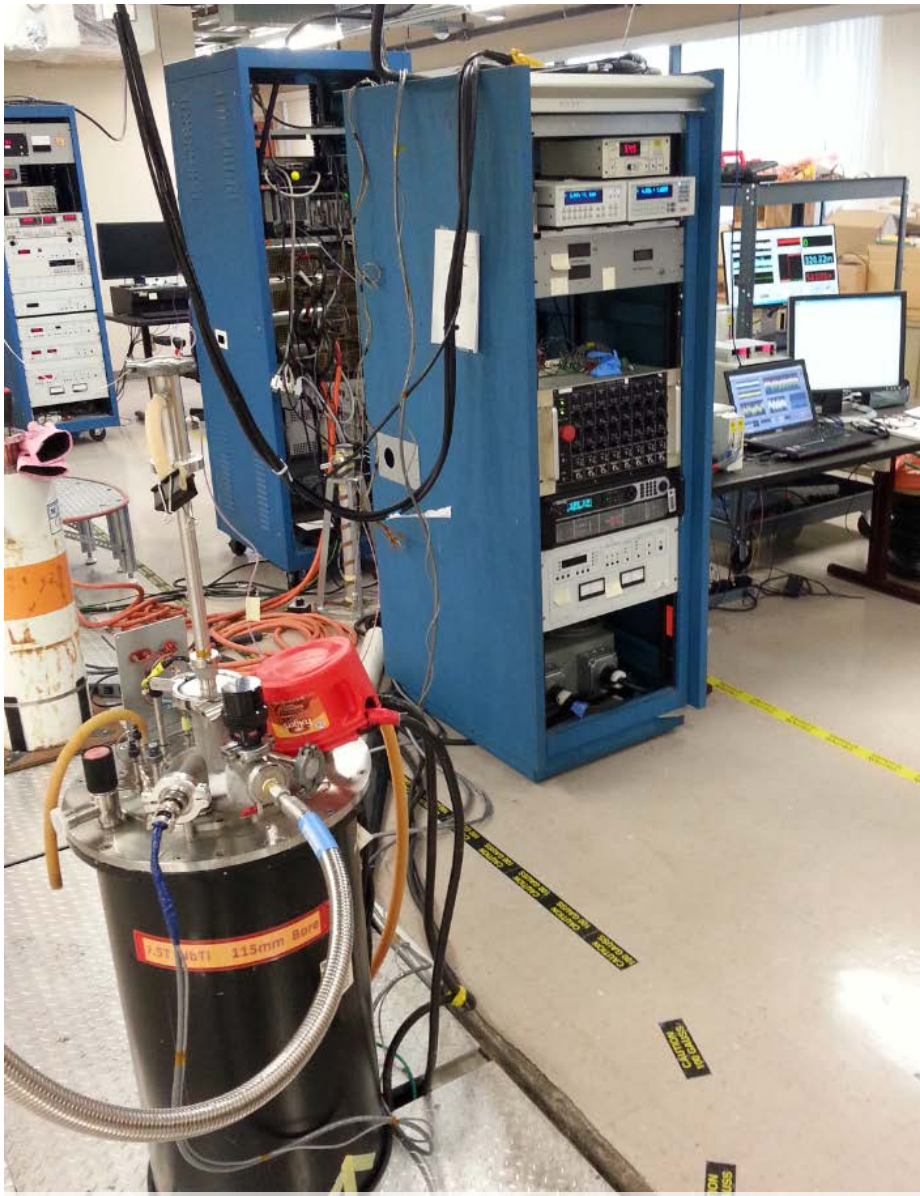
Winding and outer joint



7 T LTS outsert



13 T NI HTS insert

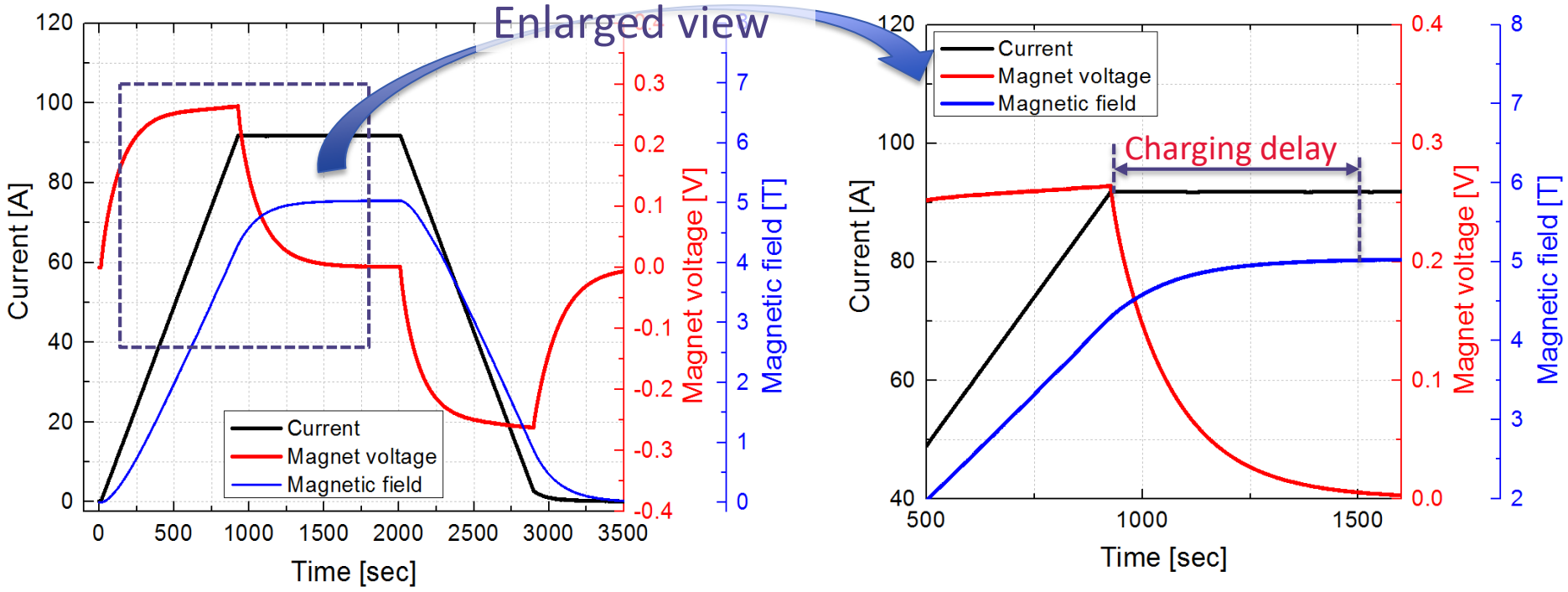


Magnet System

Feedback Control

Feedback Control: Uncontrolled ramp.

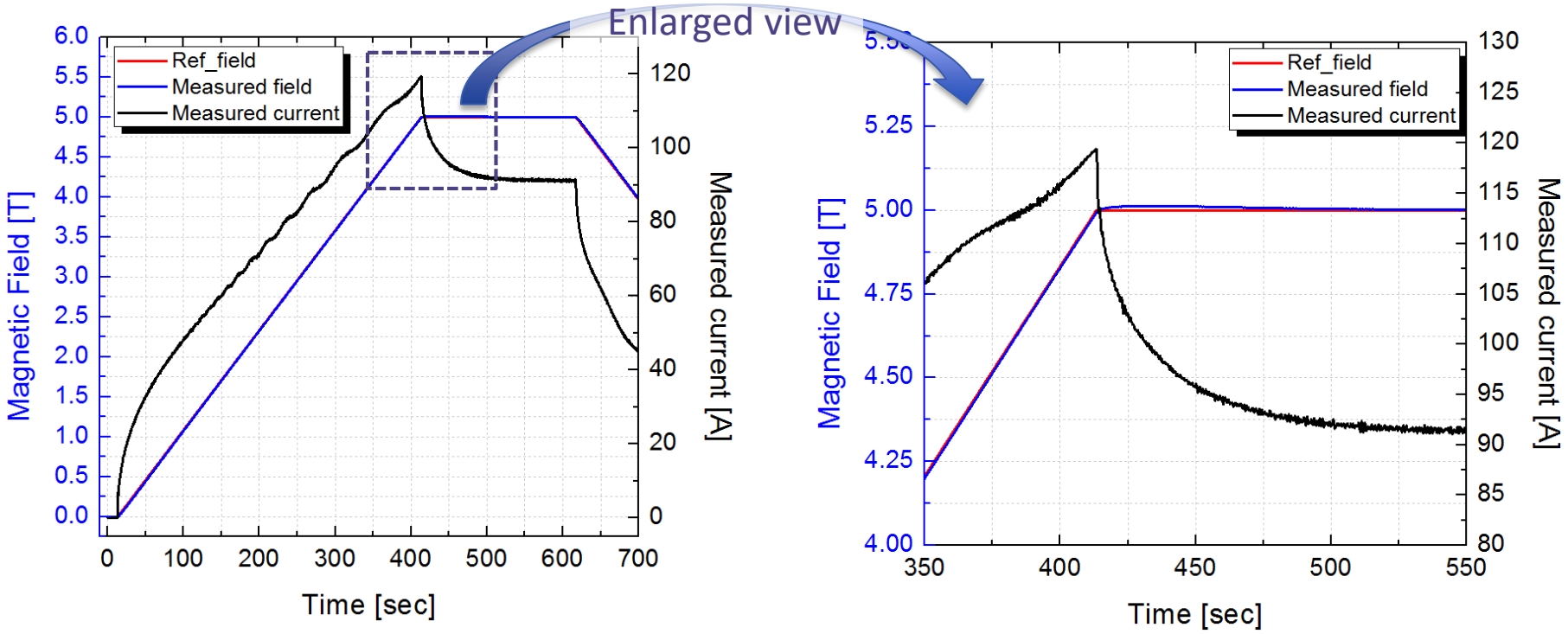
- Insert magnet without feedback control shows typical exponential decay response with characteristic L/R time constant.
- Over the range of characteristic resistances (contact resistance varied), time constant varied ~ 1 to 3 minutes.



Input current and generated magnetic field patterns of common NI magnet operation

Feedback Control: Initial controlled ramps to 5 T

- Insert magnet without feedback control shows typical exponential decay response with characteristic L/R time constant.
- Ramp rates were increased from typical uncontrolled ramp rate of 0.3 T/min to 0.75 T/min.
- **Field response is controlled very nicely!** Negligible field "bump" and delay.
- Penalty is increased liquid helium consumption and required overcurrent.



P/S current and magnetic field patterns of 13 T NI magnet under feedback control

Feedback Control: Liquid helium consumption

- Target Field: 5 T
- PI gain for feedback control: P-700, I-25
- Liquid helium consumption roughly doubles for twice as fast ramp rate.
- Helium boiloff was measured with LHe level detector and includes other conduction, convection and radiation heat losses.

	Ramping rate (T/min)	LHe level at charging start (liter)	LHe level at charging end (liter)	Δ (liter)
Normal Charging	0.32	72.6	68.5	4.1
Feed back control	0.30	82.3	76.8	5.5
	0.50	59.7	54	5.7
	0.60	73.6	67.2	6.4
	0.75	60.8	53.4	7.4

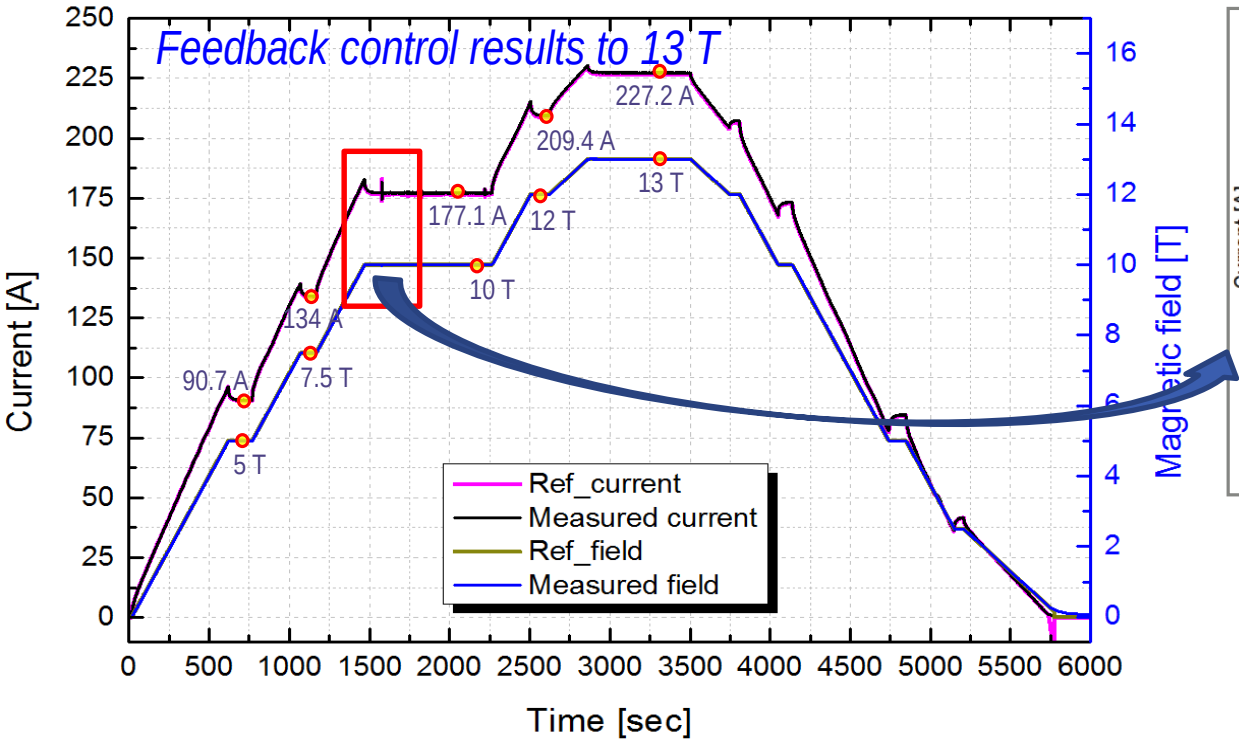
Feedback Control: Overcurrent

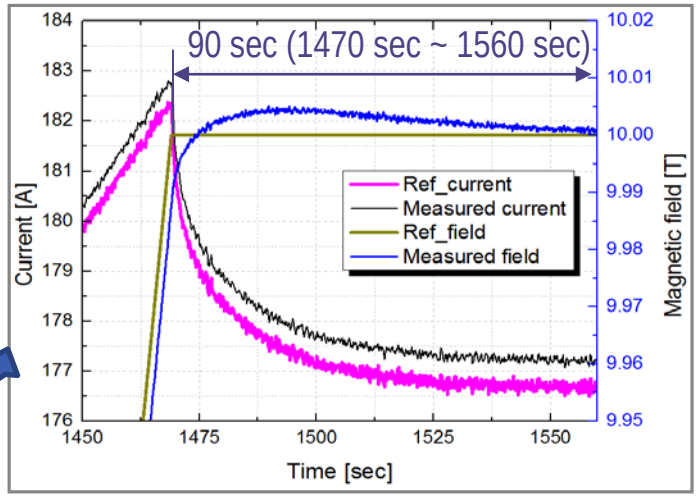
- Target Field: 5 T
- PI gain for feedback control: P-700, I-25
- Overcurrent required for twice as fast ramp rate = ~ 25 to 30%.
- Not desirable: increased stress/strain, reduced current margin, possible quench.

	Ramping rate (T/min)	Overcurrent (A)	Overcurrent (%)
Normal Charging	**0.32**	na	na
Feed back control	0.30	11.9	13.0
	0.50	19.2	20.9
	0.60	23.0	25.1
	0.75	28.4	30.9

Feedback Control: Final controlled ramp to 13 T

- Target Field: 13 T
- Charging procedure: 0 T → 5 T → 7.5 T → 10 T → 12 T → 13 T
- Ramp rate: 0.5 T/min (0 T → 12 T), 0.25 T/min (12 T → 13 T)
- PI gain for feedback control: P-250, I-10
- Over current values: 6 A(1.7%)@ 0.5 T/min, 3.2 A(1.4%)@ 0.25 T/min.
- Measured LHe consumption to 13 T was 11.4 liter



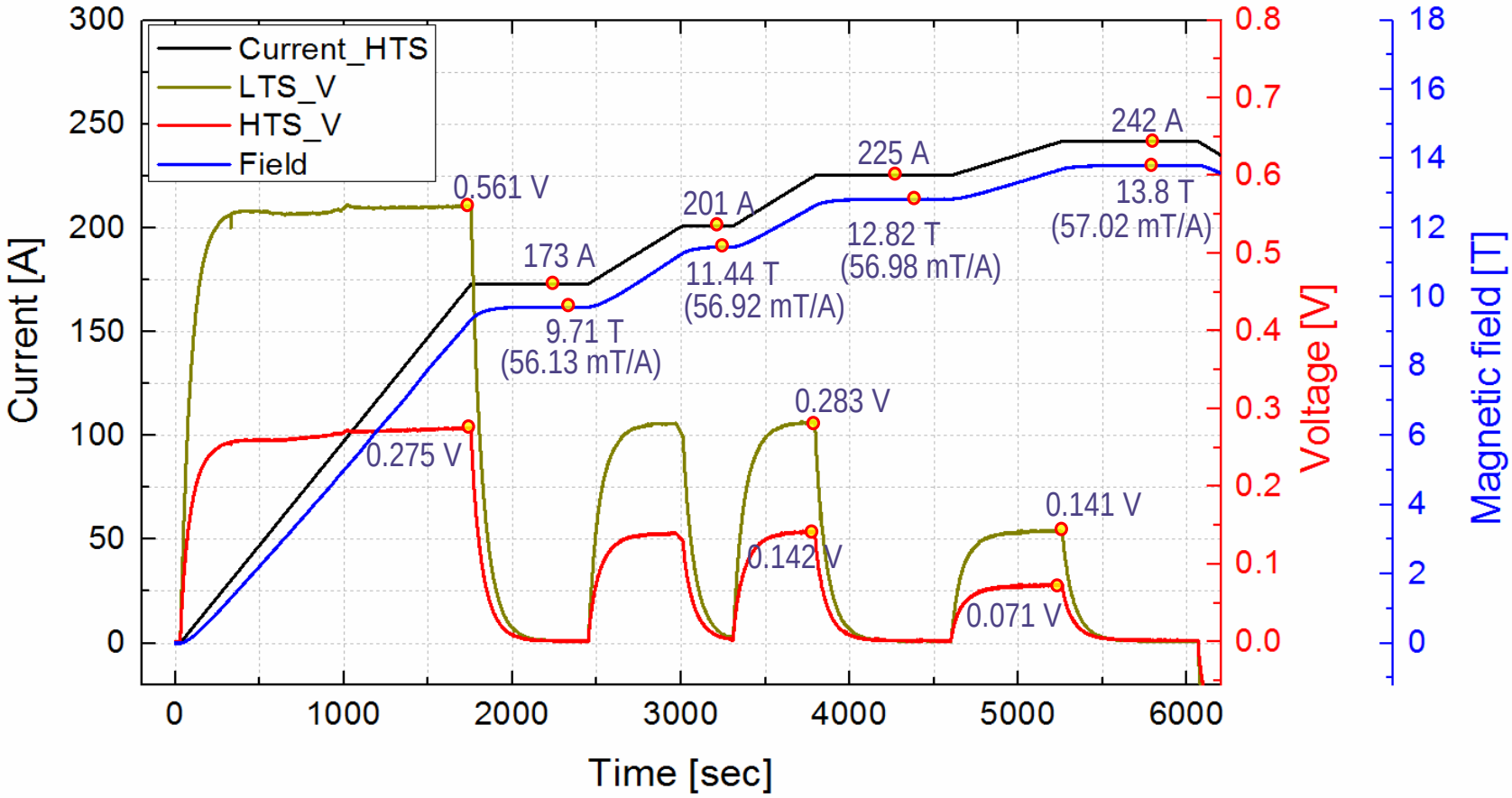


Over current and magnetic field control result (0.5 T/min)

System Testing

Standalone Insert Testing

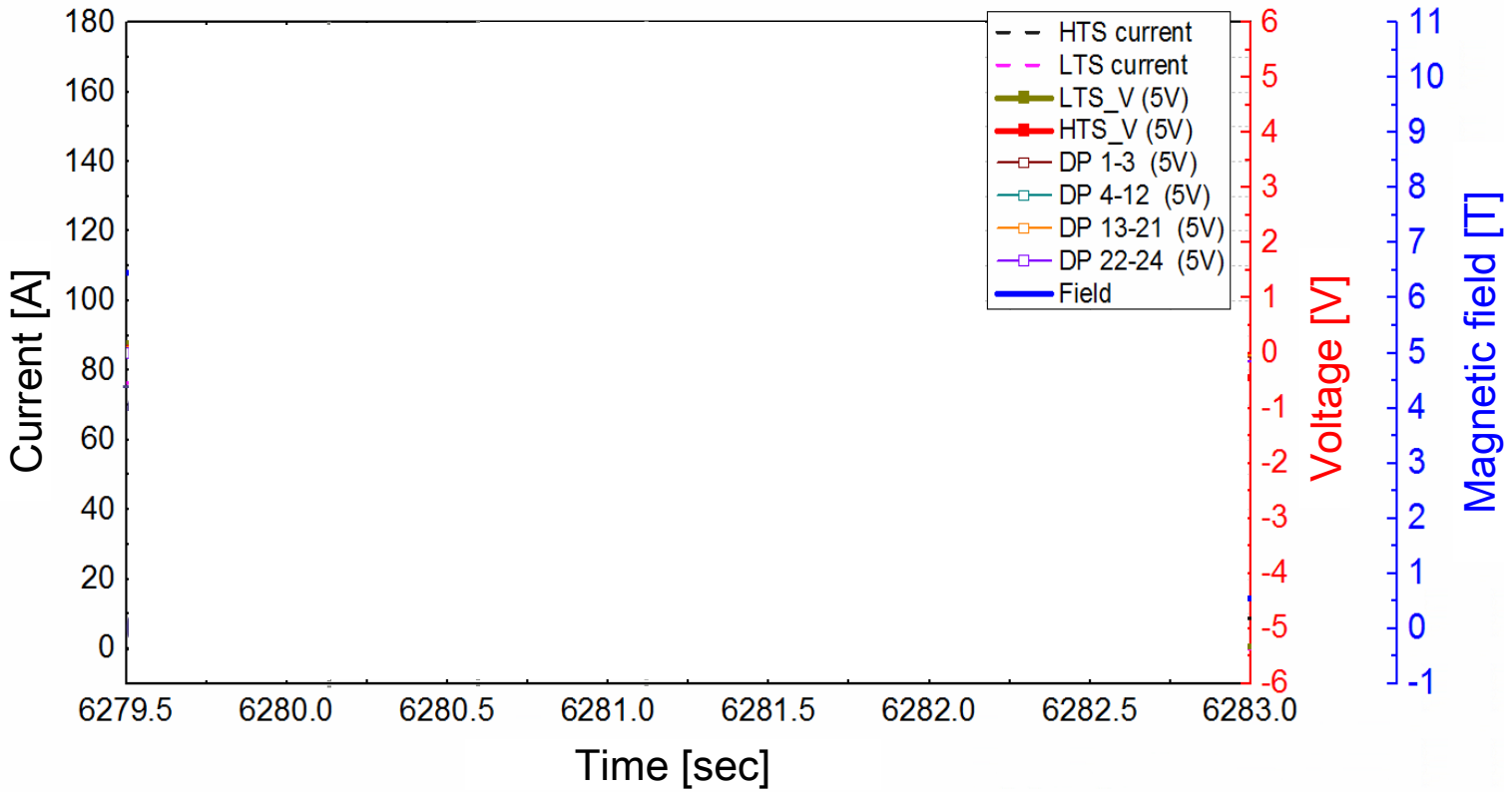
- Ramping rate of insert magnet
  - 0.34 T/min (0 A → 173 A), 0.17 T/min (173 A → 225 A), 0.08 T/min (225 A → 242 A)
- Insert was charged to 14 T with no quenches!



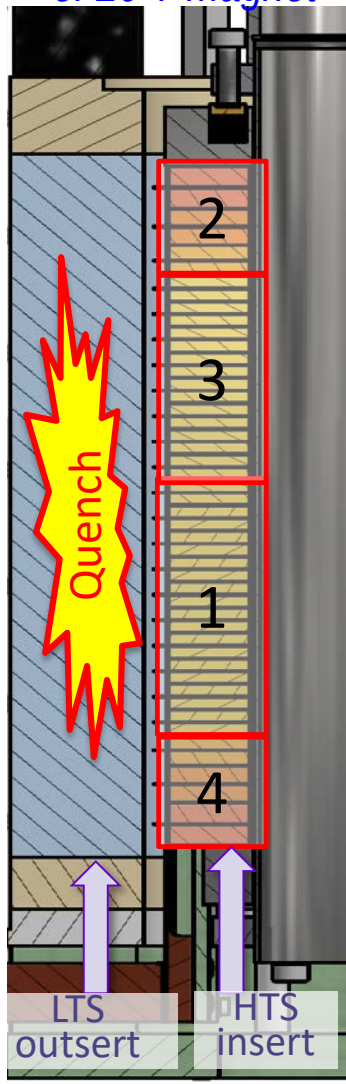
Whole charging procedure of 13 T NI HTS insert magnet

Standalone Outsert Quench

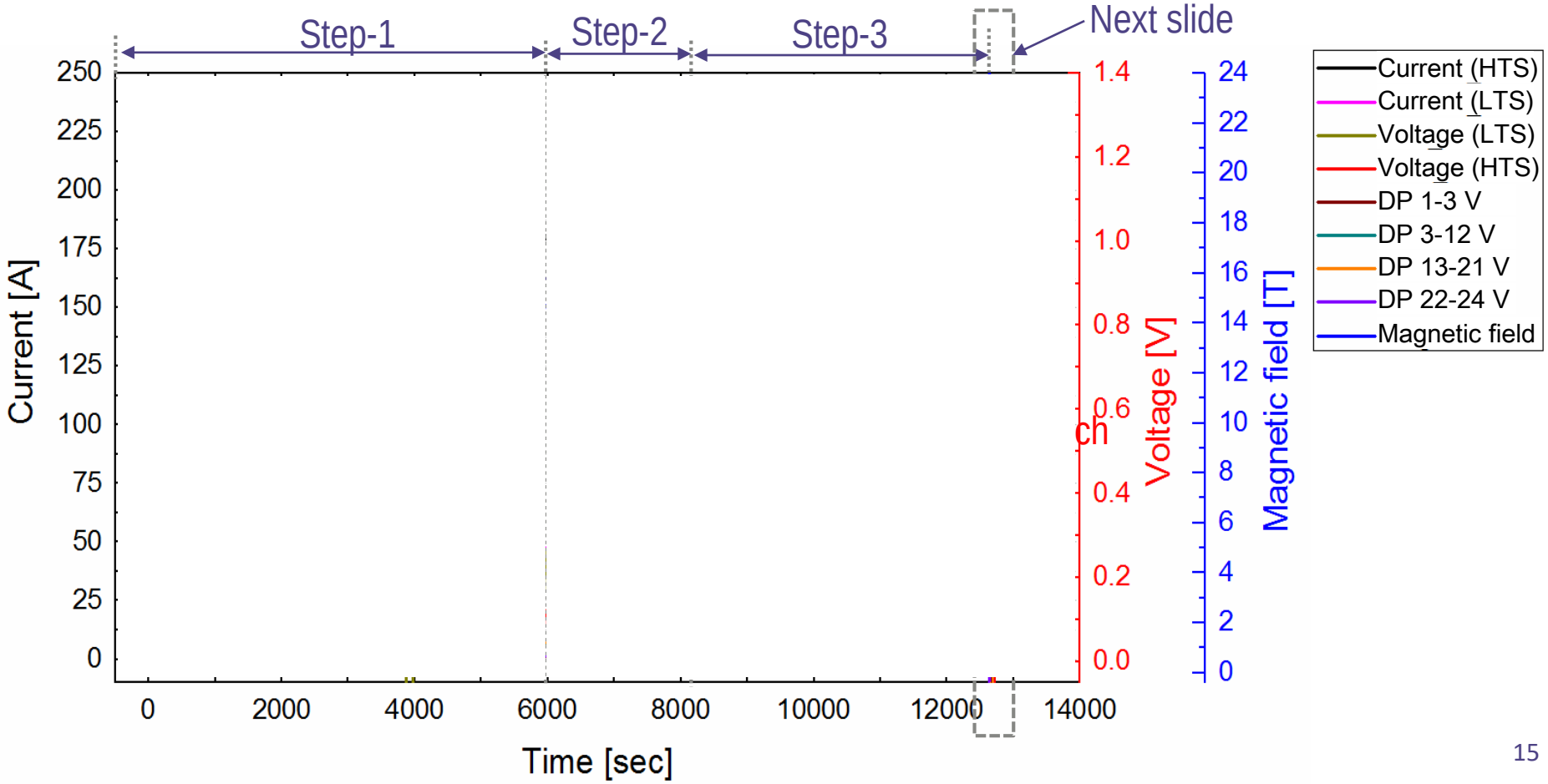
- Outsert quenched three random times at 6.9, 6.5 and 6.0 T.
- High resolution quench data obtained.
- Insert "quenched" asymmetrically: First lower middle section → upper outer section → upper middle section → lower outer section.
- Insert quench sequence was consistent (at zero current initially) during outsert quench.



Half drawing of 20 T magnet

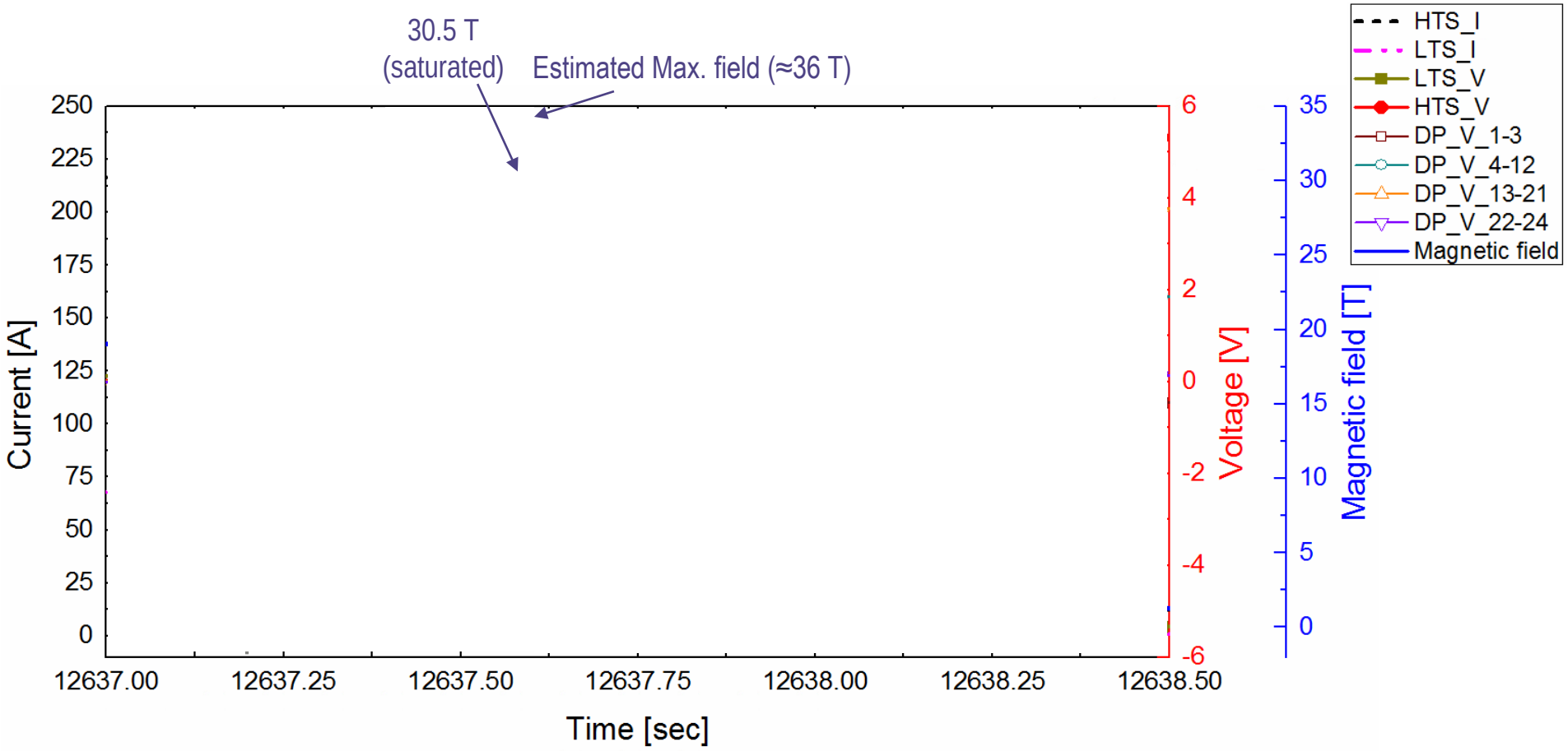


Dual Operation Testing to 20 T



Dual Operation Outsert Quench at 19 T

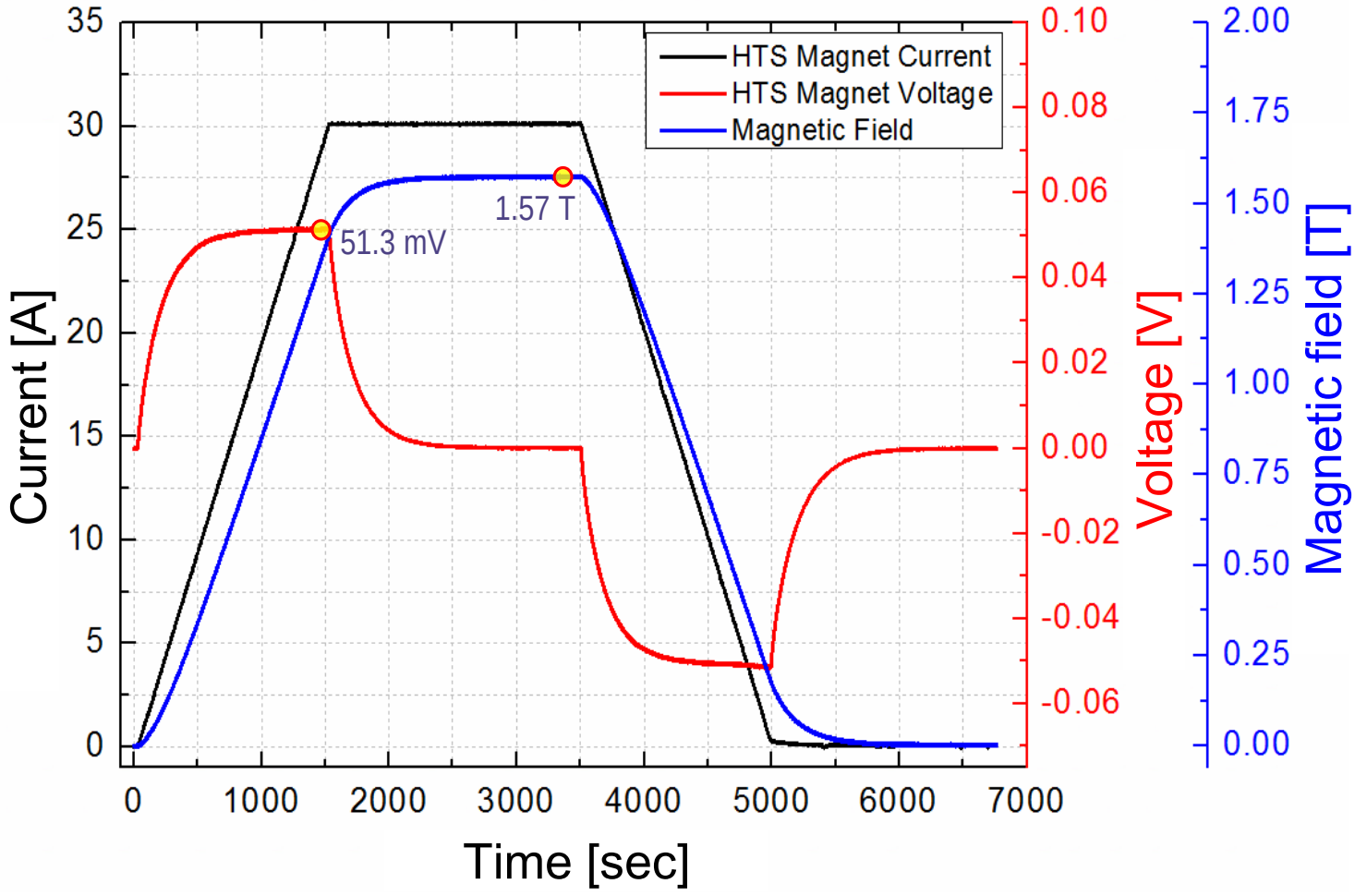
- Quench sequence of insert sections is not completely consistent with zero current insert response of outsert quench. (timing sequence of middle portions are switched)
- Relevant point is that asymmetric quench generates magnetic centering forces. Last section to quench was lower pancakes.



Characteristic Resistance (R_c) Variation

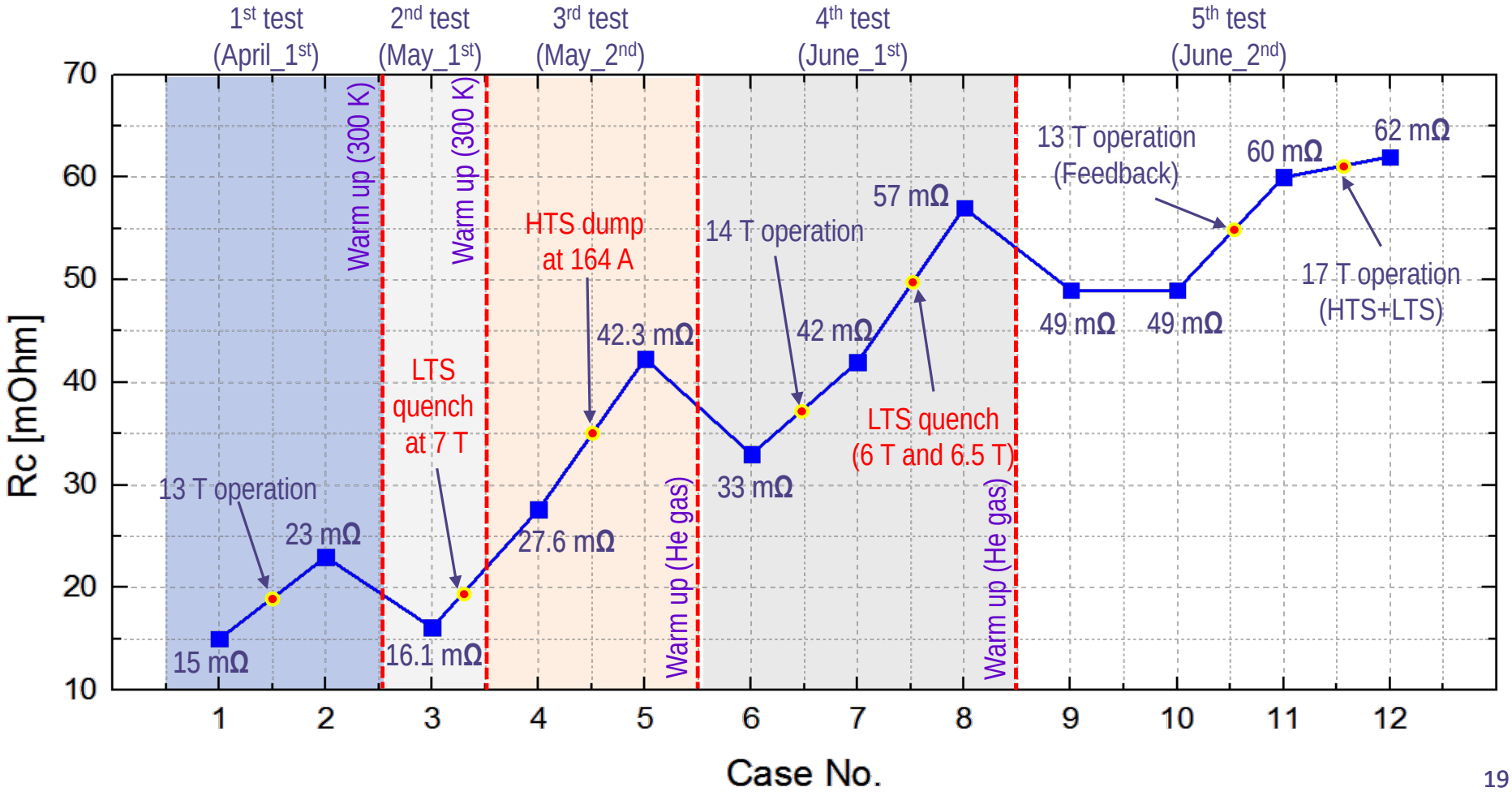
Characteristic Resistance (R_c) Measurement

- Typical characteristic resistance (R_c) measurement at 30 A.
- Performed before and after significant test events.



R_c Measurement Timeline at Low current:15-30 A

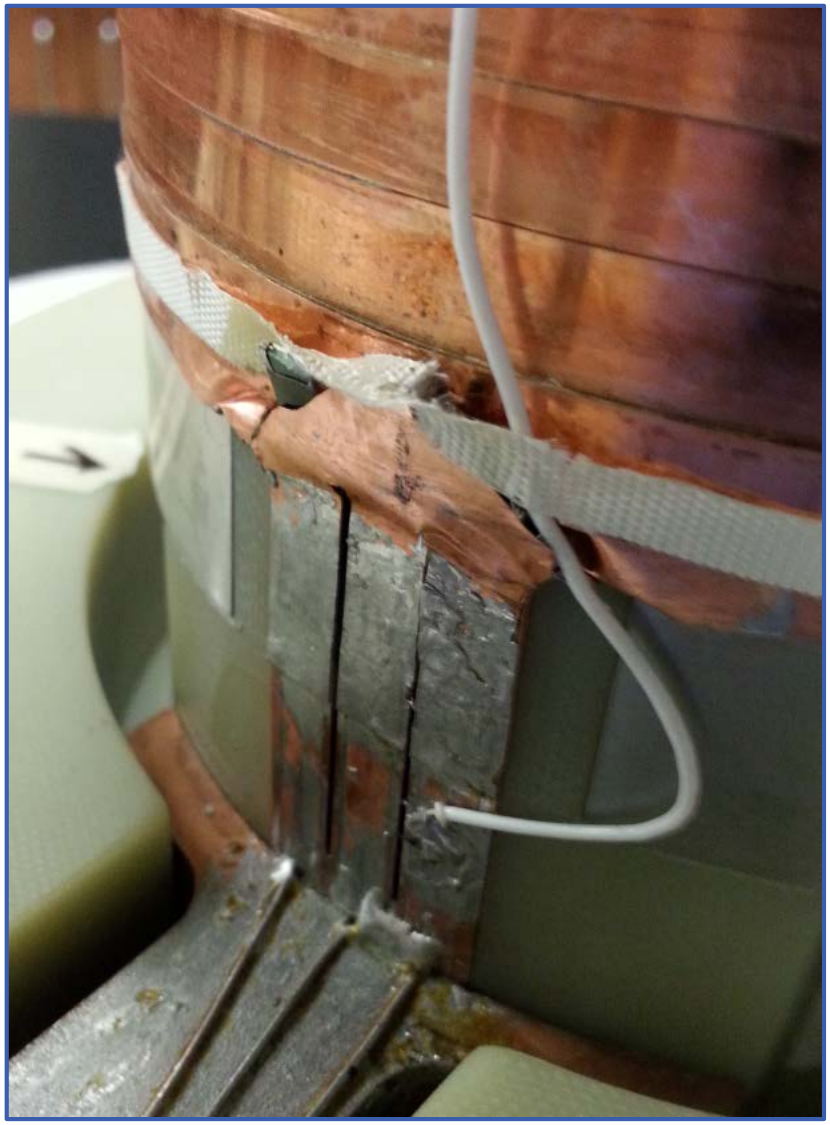
- History of measured characteristic resistance.
- Consistent increase in resistance with cycling except for 3 of 4 warm up events.



Post Quench

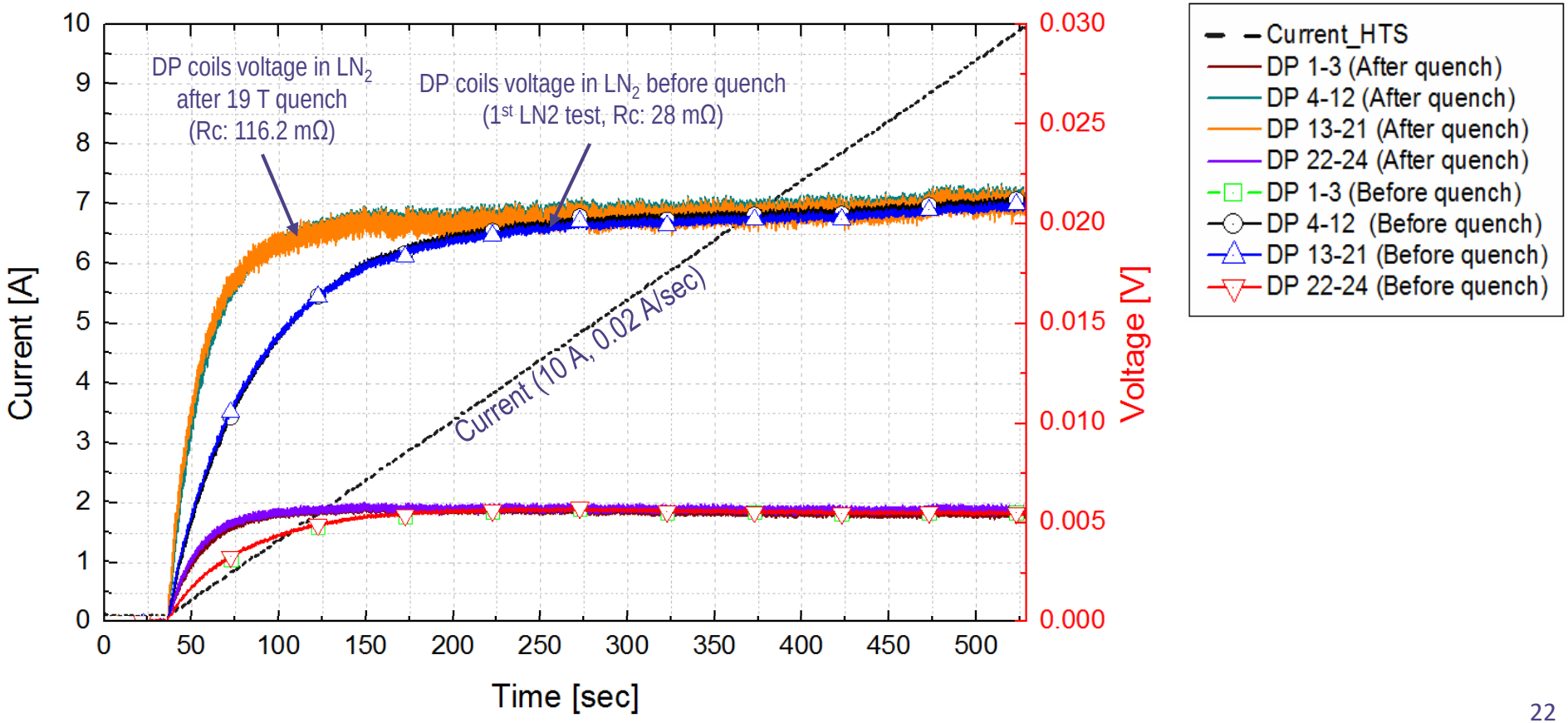
Post Quench

- Coil bottom lead was damaged.
- Remainder of coil seems intact.
- Damage likely due to unbalanced centering forces from asymmetric quench.
- Further inspection, repair underway.



Comparison of Measured DP Coils Voltage at LN_2

- After 19 T quench, the DP coils voltage was measured in LN_2 and compared with the previous LN_2 test result.
- Measured Rc was increased, but each peak voltage seems to be similar.



Summary and Future Plan

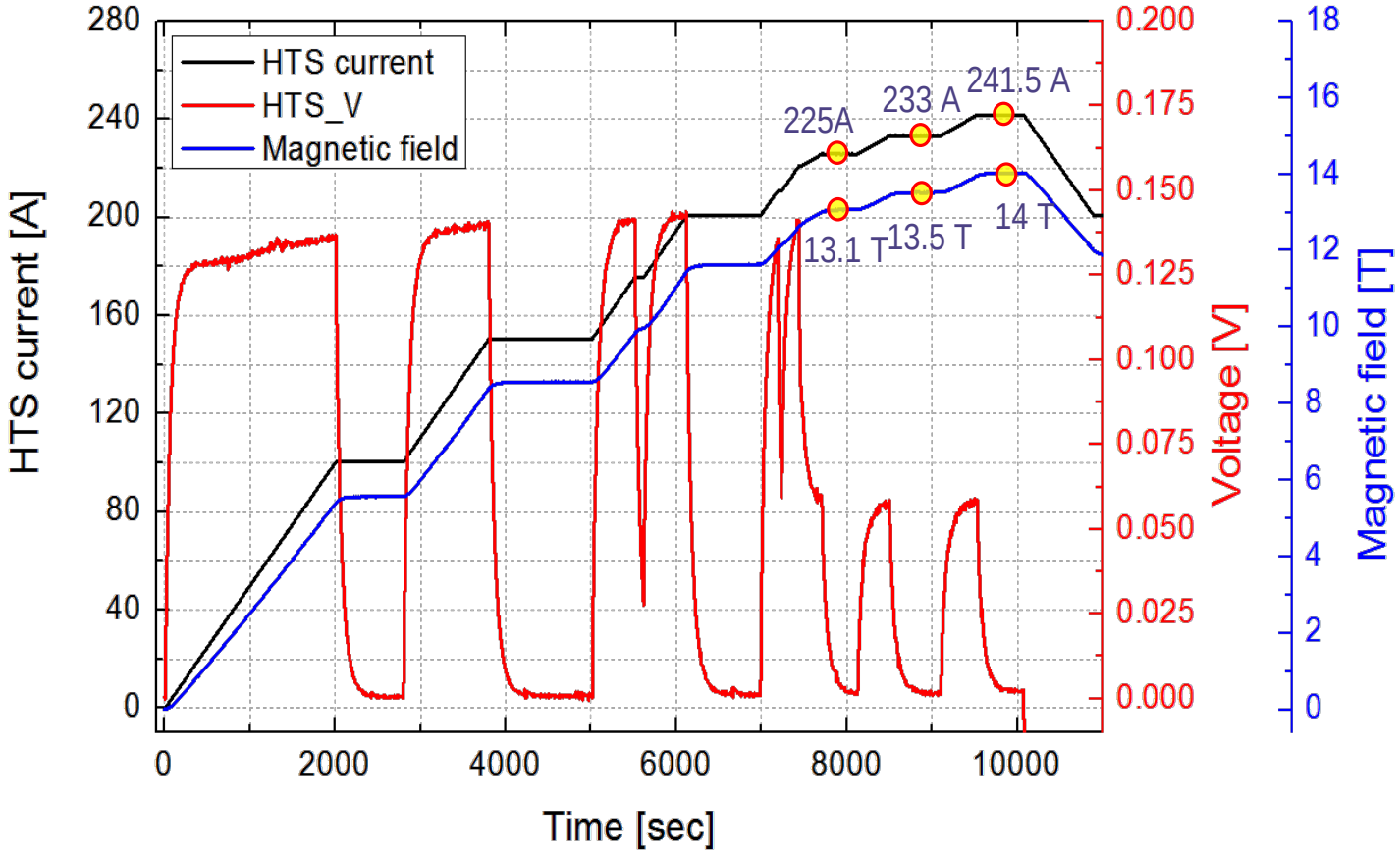
Summary and Future Plan

- Feedback control works very nicely to produce proportional field to current response. Penalty is increased helium liquid consumption at higher ramp rates. Excessive power supply over-currents can be controlled with proper control parameters.
- NbTi outsert coil was unstable. Quenches at 6 to 7 T make user system impractical with this outsert.
- NI REBCO insert magnet performed well, no quenches even to 14 T in standalone test.
- Characteristic resistances grew consistently with operational cycles and with some decrease with warmup cycles (3 of 4 times).
- Insert coil lead out was damaged during quench likely due to asymmetric quench and resultant centering forces (investigation ongoing).
- Quench dynamics of multi-coil systems using NI coils are complicated and will require extensive analytic tools and verification thereof prior to implementing reliable user magnets employing multiple coils.
- Future work: Replace outsert NbTi coil with more stable replacement and continue characterization of NI coil as part of 20 T user magnet.

Extra Slide

14 T Operation result of HTS Insert Magnet

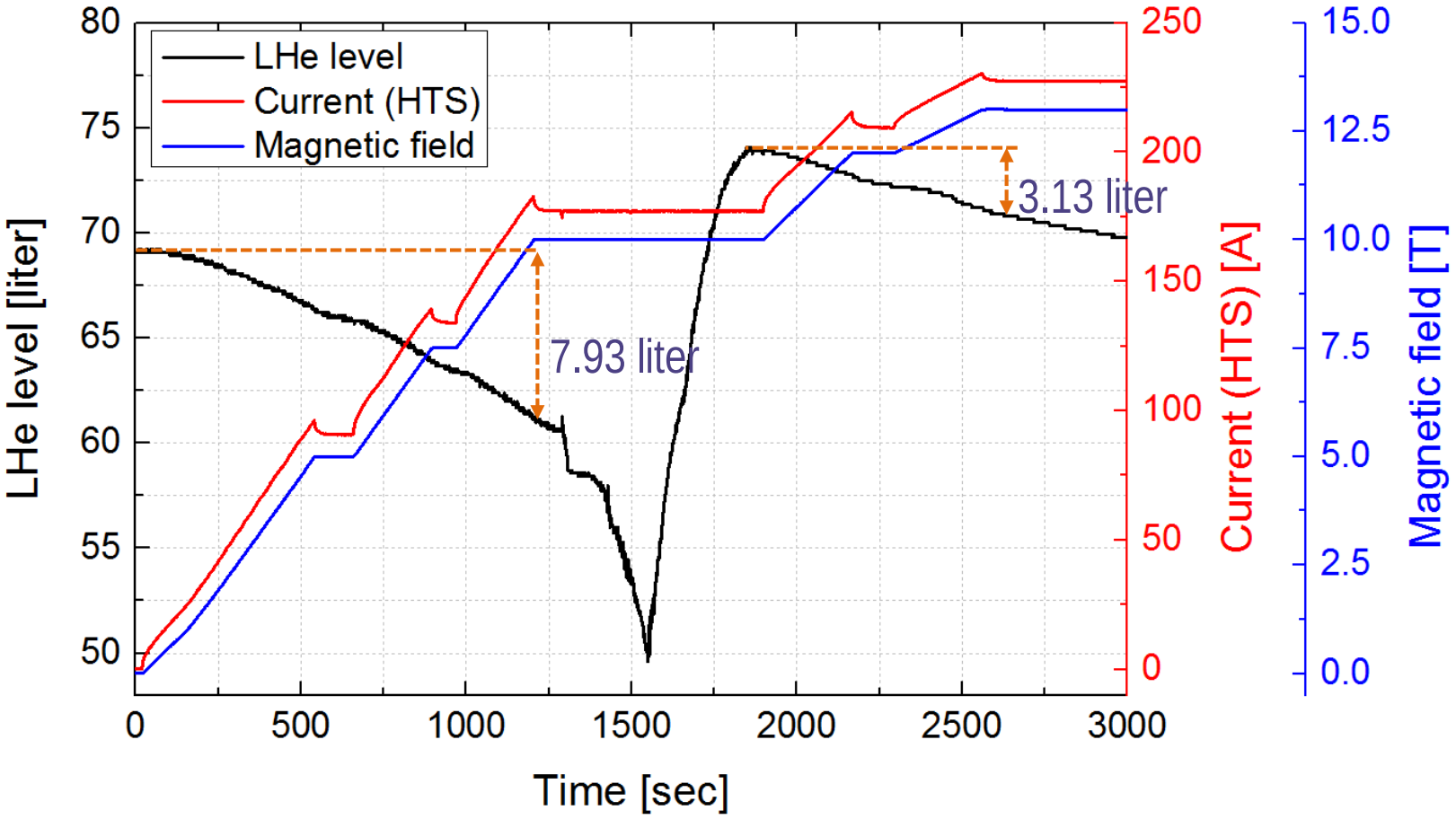
- Ramping rate of insert magnet
  - 0.5 A/sec (0 A → 220 A), 0.2 A/sec (220 A → 241.5 A)
- Measured magnetic field and current
  - 13.1 T (225 A), 13.5 T (@ 233 A), 14 T (@ 241.5 A)



Current [A]	Magnet Constant [mT/A]
100	55.7
150	57.13
200	58.2
225	58.16
233	58.03
241.5	58.1

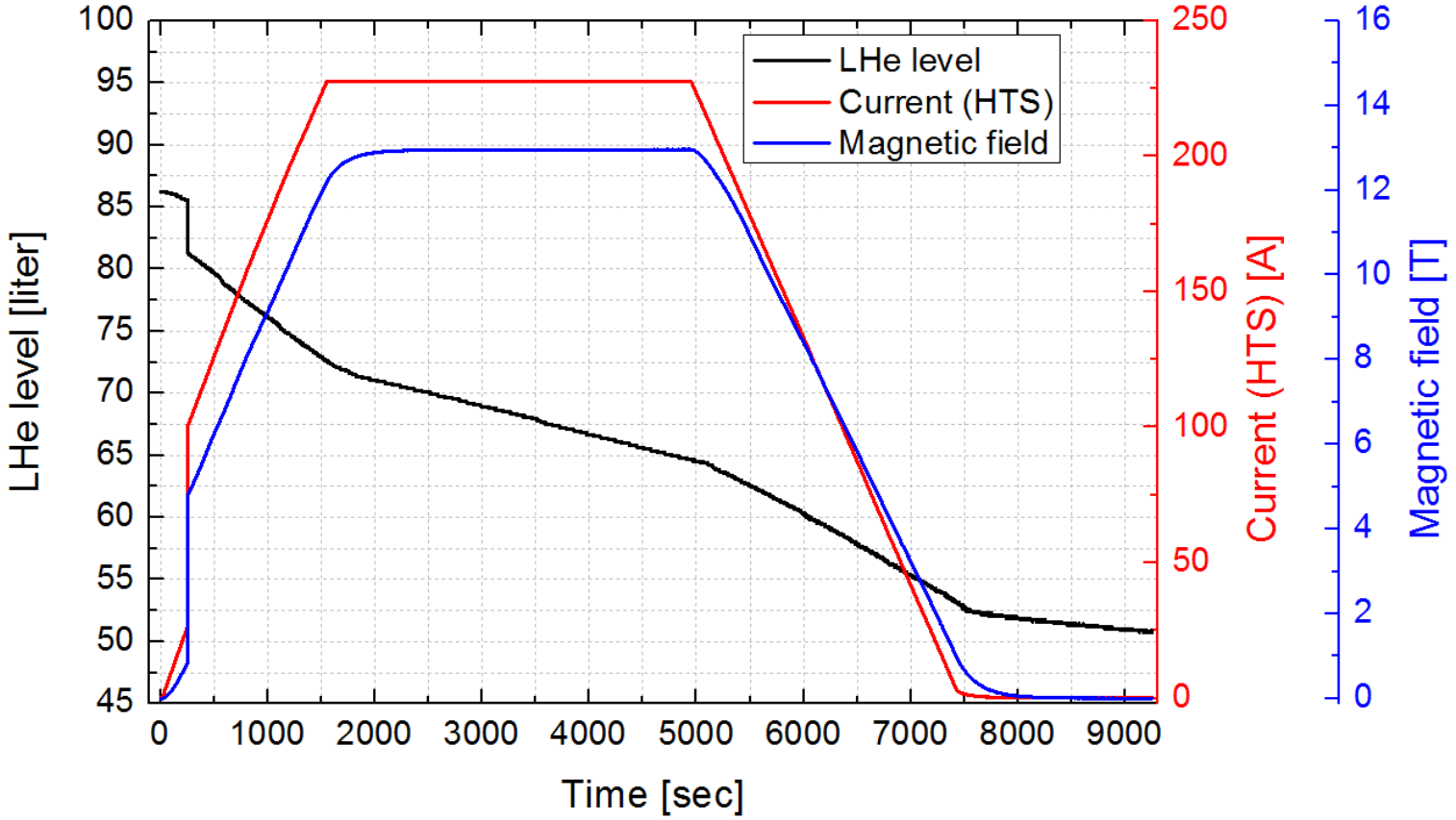
LHe Comsumption of HTS Insert to 13 T through Feedback Control

- Total LHe consumption to 13 T: 11.06 liter
  - (0 T → 10 T: 7.93 liter, 10 T → 13 T: 3.13 liter)



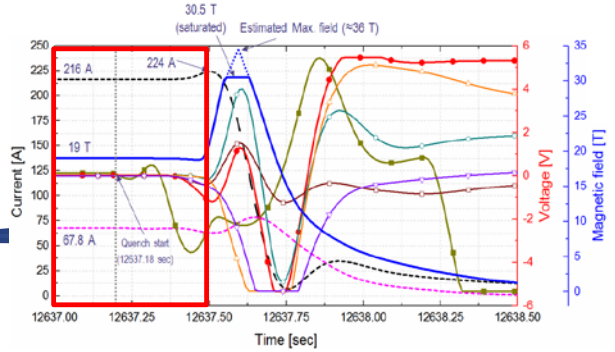
Insert Magnet Charging to 13 T

- Ramping rate of insert magnet: 0.1 A/sec
- Power supply current: 227.7 A
- Measured magnetic field: 13.1 T
- LHe consumption
  - Charging (to 227 A): 13.64 liter
  - Steady state: 1.33 liter (per 10 min)

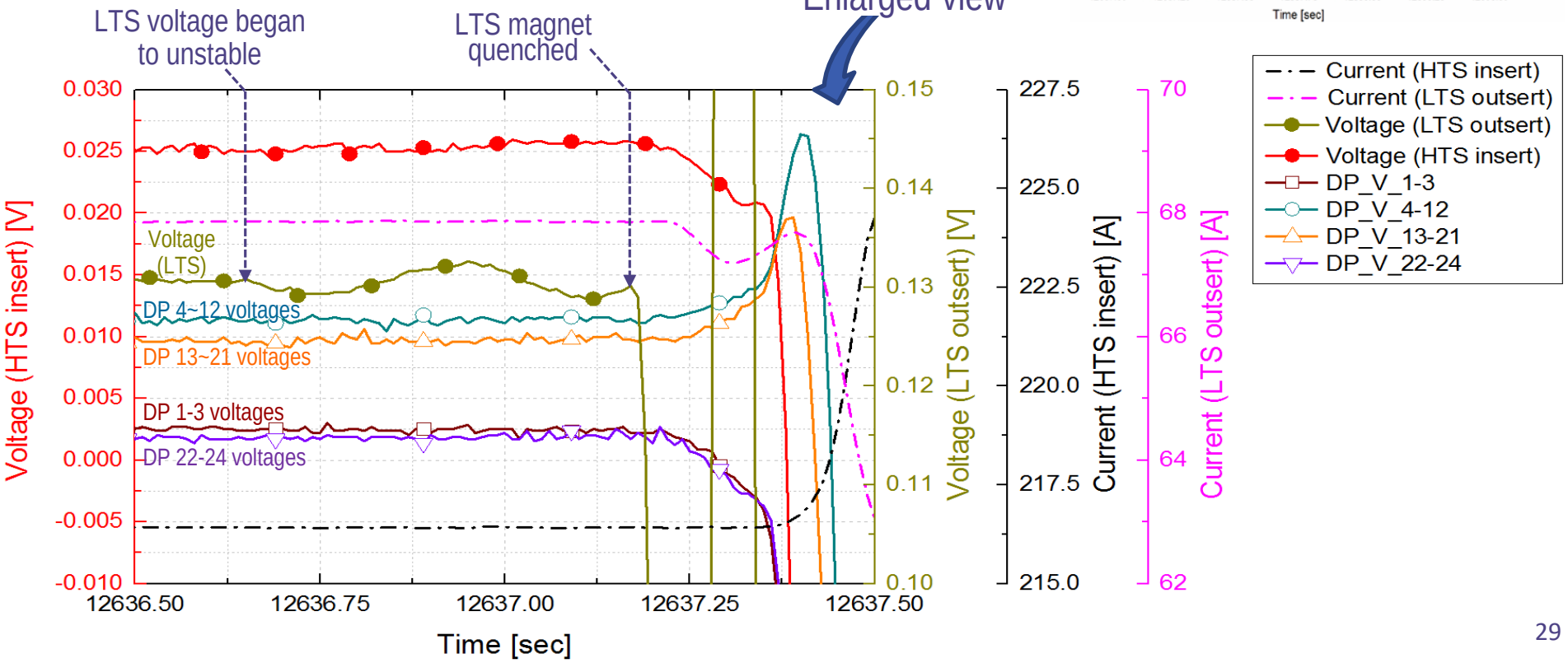


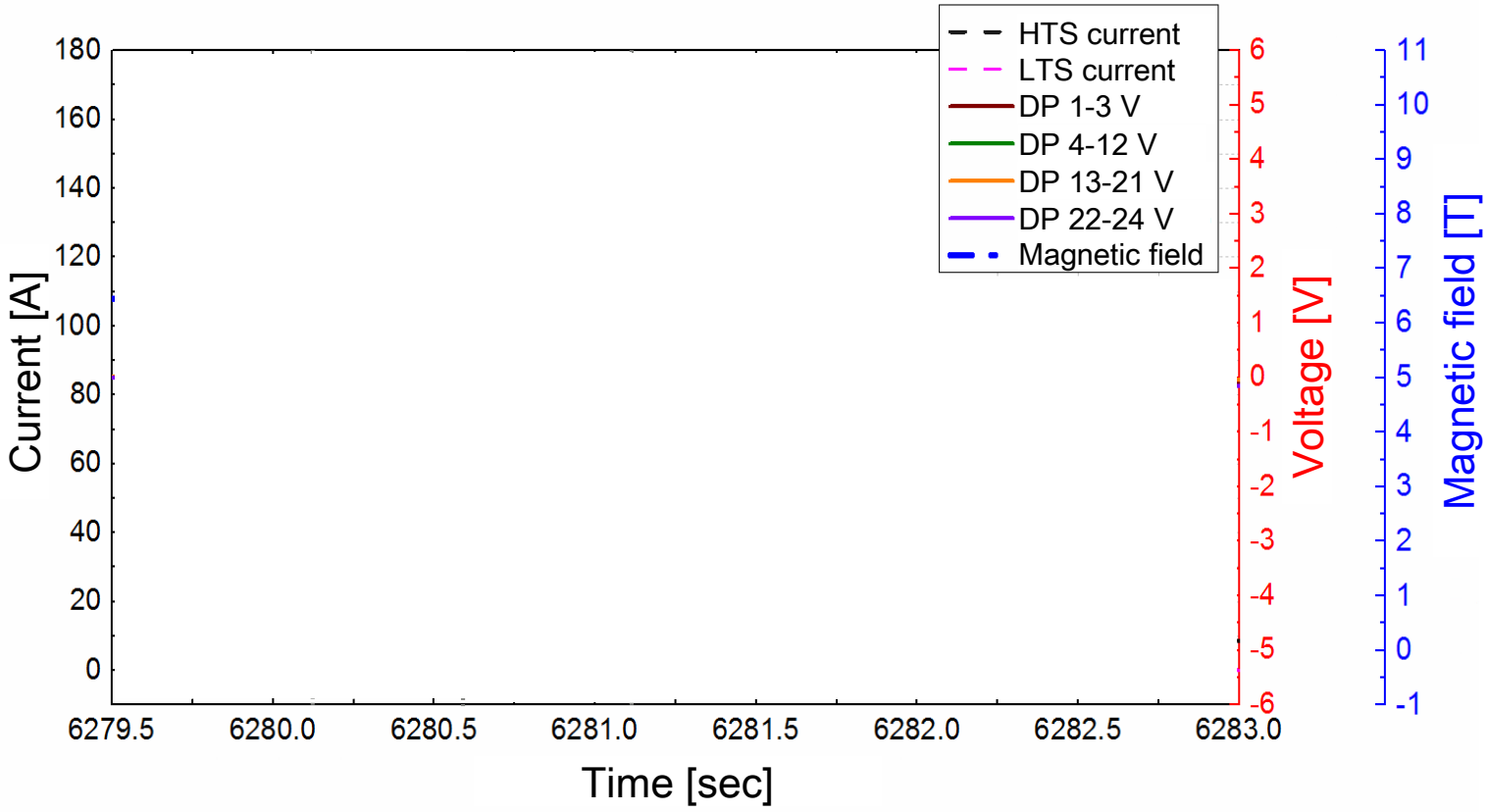
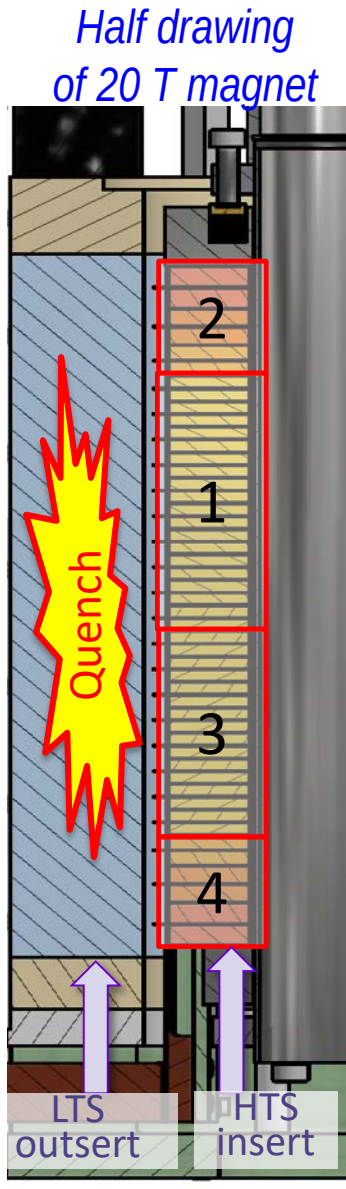
Dual Operation Outsert Quench at 19 T

- LTS magnet voltage began to unstable from 12636.65 sec and quenched after ≈5 sec.
- The voltage of DP-coils were symmetrically changed at the initial quench stage by LTS magnet quench.
- Whole magnet quench was estimated that occurred from LTS magnet quench.



Enlarged view



Standalone Outsert Quench

- Outsert quenched three random times at 6.9, 6.5 and 6.0 T.
- High resolution quench data obtained.
- Insert "quenched" asymmetrically: First upper middle section → upper outer section → lower middle section → lower outer section.
- Insert quench sequence was consistent (at zero current initially) during outsert quench.