Quench protection system for superconducting solenoids

Quench test of ESR1

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- ✓ Schematic of superconducting solenoids
- ✓ Quench simulations
- ✓ Quench protection system
- ✓ Quench tests

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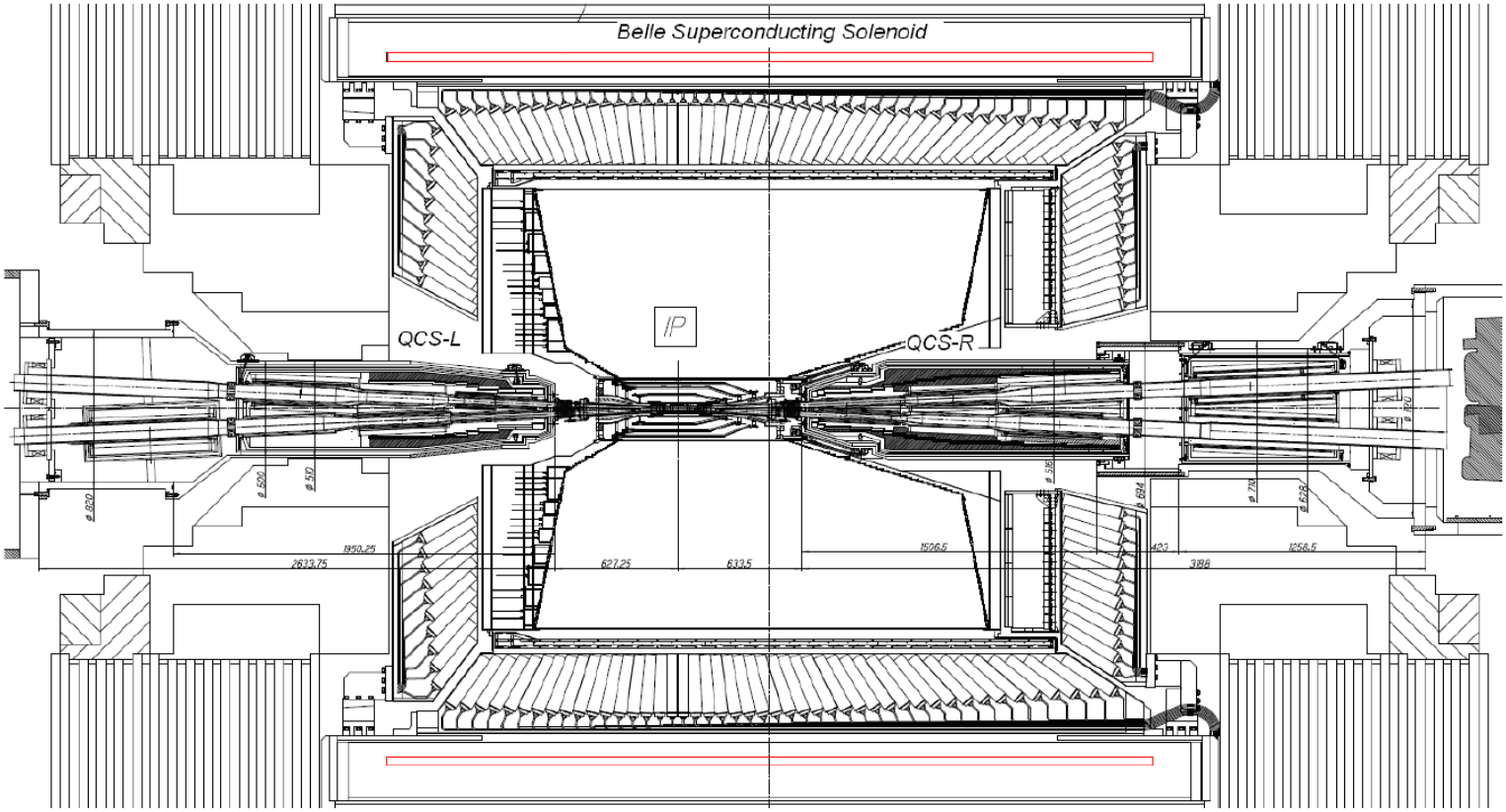
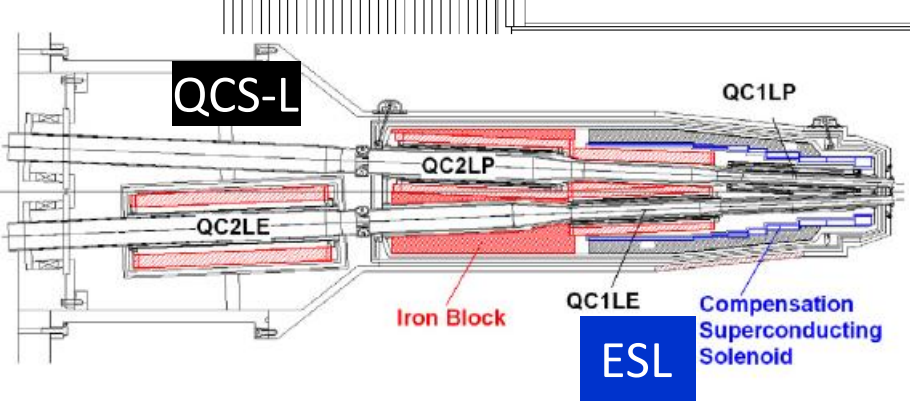
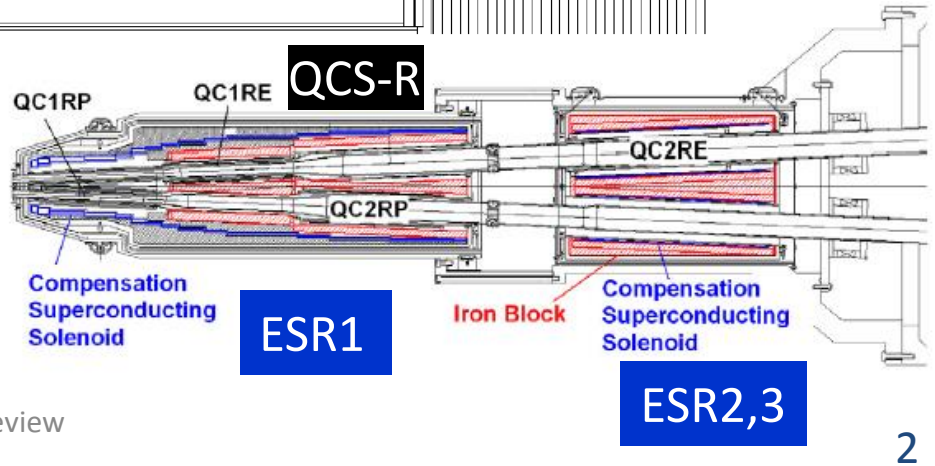
KEKB QCS Group

Superconducting solenoids





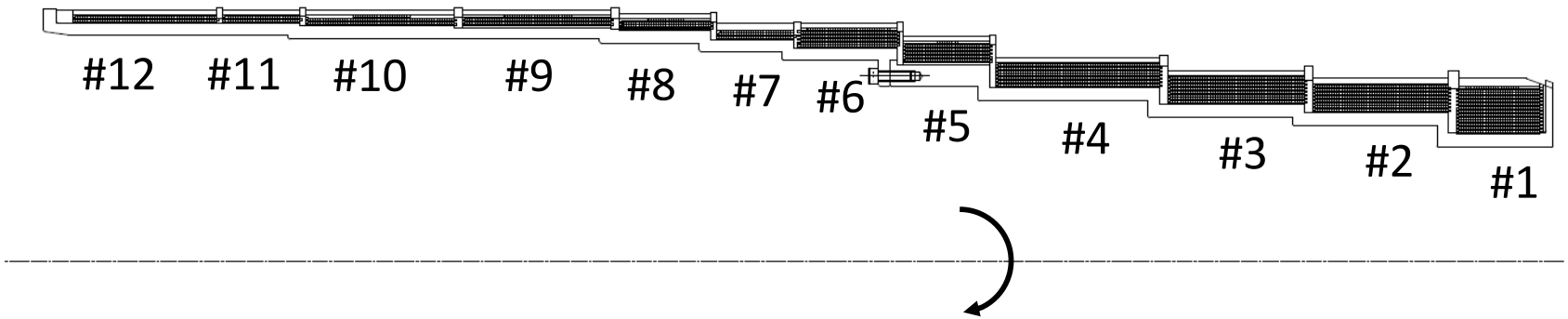


Specifications of superconducting solenoids

	ESL	ESR1	ESR2, 3
Number of coil blocks	12	15	1
Nominal operating current	404 A	450 A	151 A
Stored energy	118 kJ	244 kJ	1.6 kJ
Inductance	2.53 H	8.81 H	0.14 H
Maximum field in the coil	3.53 T	3.19 T	0.48 T
Load line ratio	0.53	0.51	0.11

From the perspective of quench protection, higher stored energy means higher quench temperature.

ESL



Preliminary design of quench protection system

Design condition

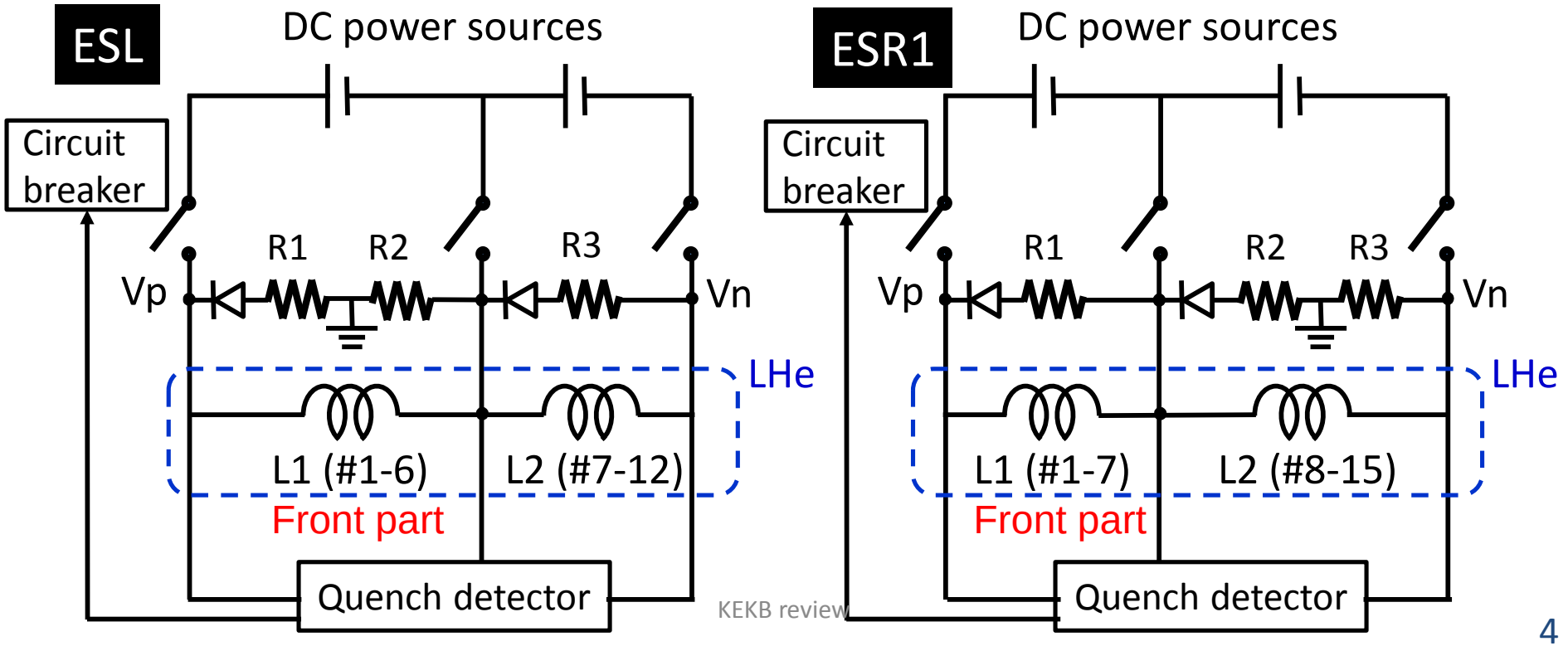
✓ To enable adjusting the field of front part (IP side) of ESL and ESR1

⇒Separate each solenoid into two circuits

✓ Withstand voltage < 200 V

⇒Set the upper limit of dump resistor

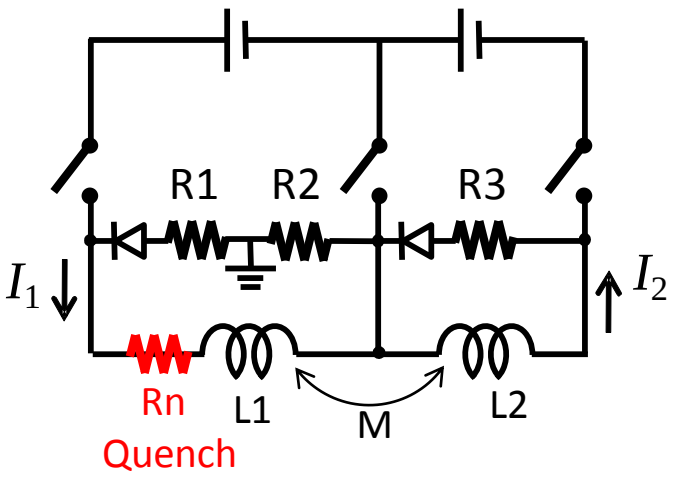
	Total	R1(Ω)	R2(Ω)	R3(Ω)
ESL	0.93	0.465	0.345	0.12
ESR1	0.828	0.34	0.074	0.414



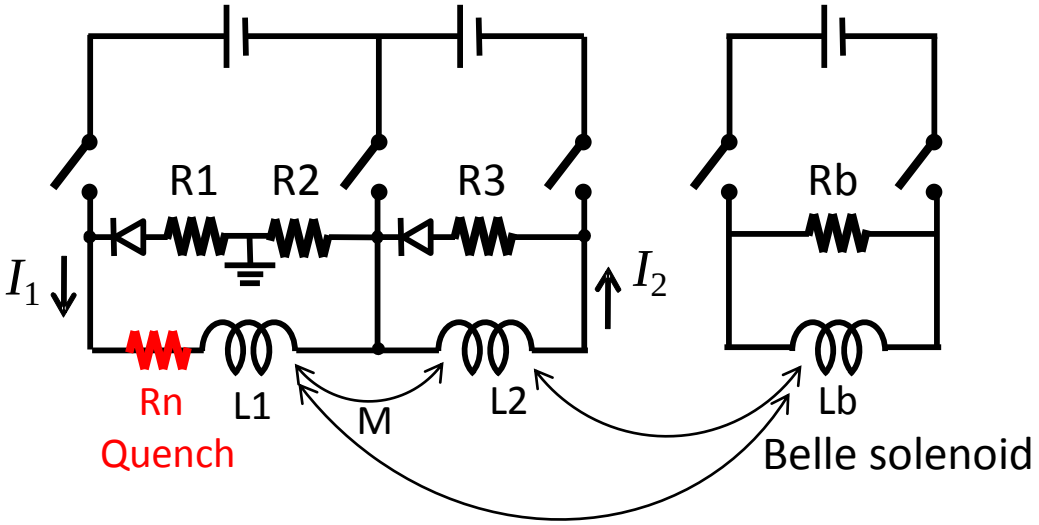
Quench simulation model

Quench pattern of superconducting solenoids

✓ Solo



✓ Coupled with Belle solenoid



Non-linear transient analysis

Dump circuit model

$$[\mathbf{M}]\frac{d}{dt}\{\mathbf{I}\}+[\mathbf{R}]\{\mathbf{I}\}=0$$

Adiabatic thermal model

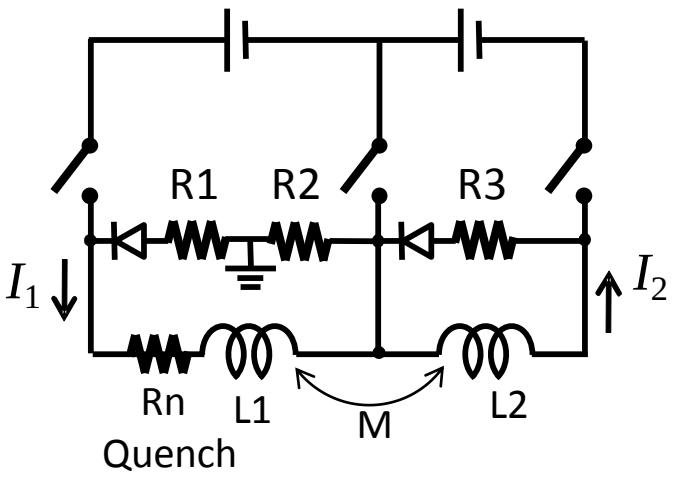
$$C(T)\frac{\partial T}{\partial t}=\rho_n(T)J^2$$

- ✓ Quench analysis is adiabatically performed on each coil block to conservatively evaluate the quench properties.
- ✓ Dump circuit model considers the time delay of the detection and circuit breaker.
- ✓ Inductances have non-linear properties because of the saturation of iron yoke.
- ✓ Thermal conduction is neglected because of the excellent propagation velocity of the NbTi wire.

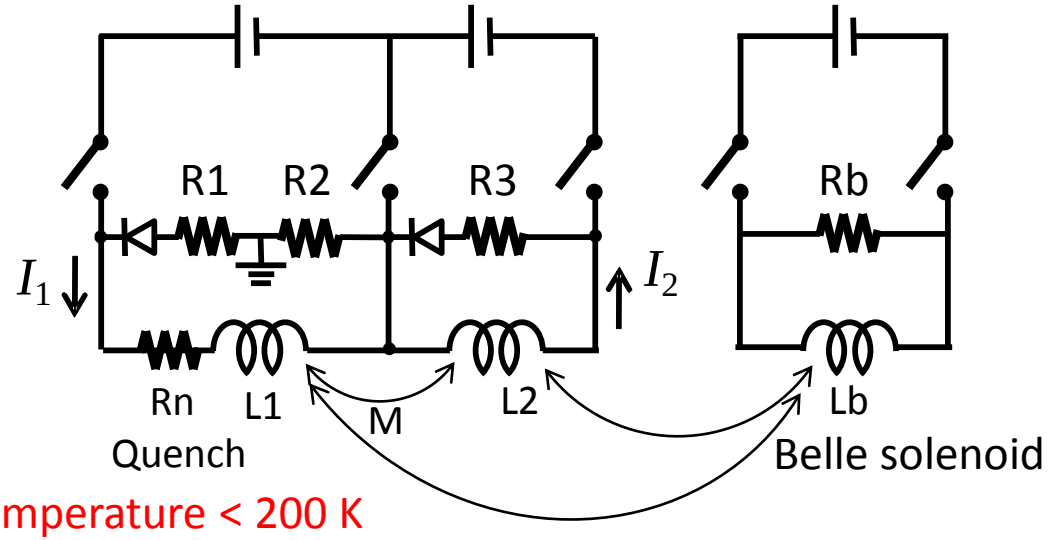
Quench simulation results

Quench pattern of superconducting solenoids

✓ Solo



✓ Coupled with Belle



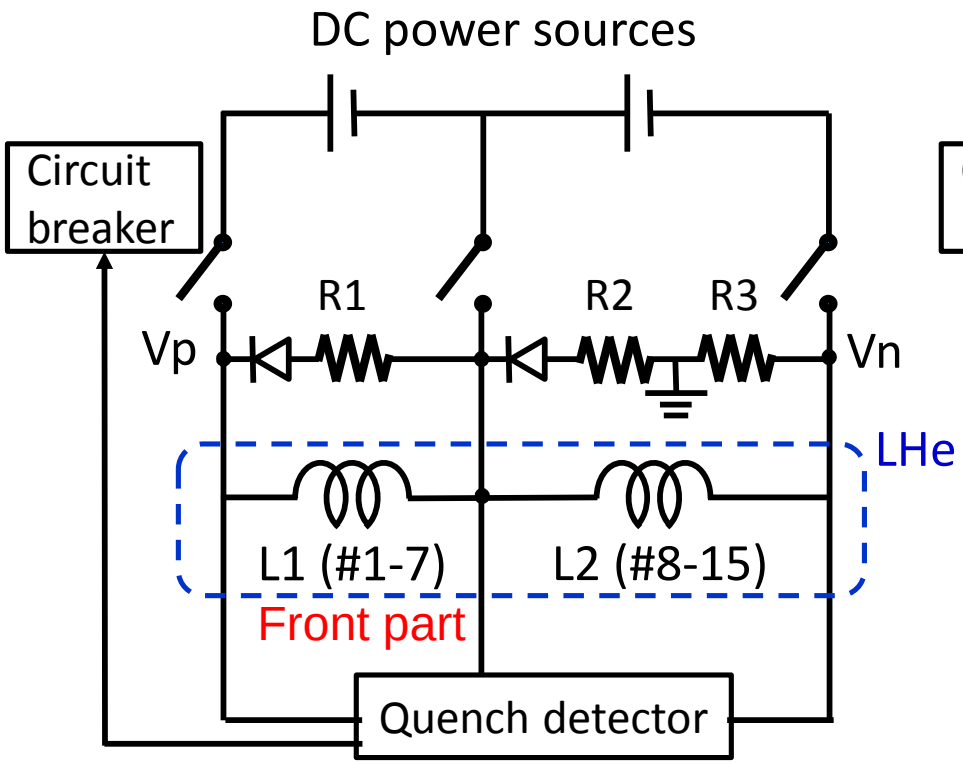
Design condition : Maximum quench temperature < 200 K

Maximum temperature (K)		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
ESL	Solo	81	79	78	76	90	89	105	95	76	77	98	87	-	-	-
	Coupled with Belle	81	79	78	76	90	89	105	95	76	77	98	87	-	-	-
ESR1	Solo	154	121	87	96	129	129	155	399	294	306	152	223	159	148	270

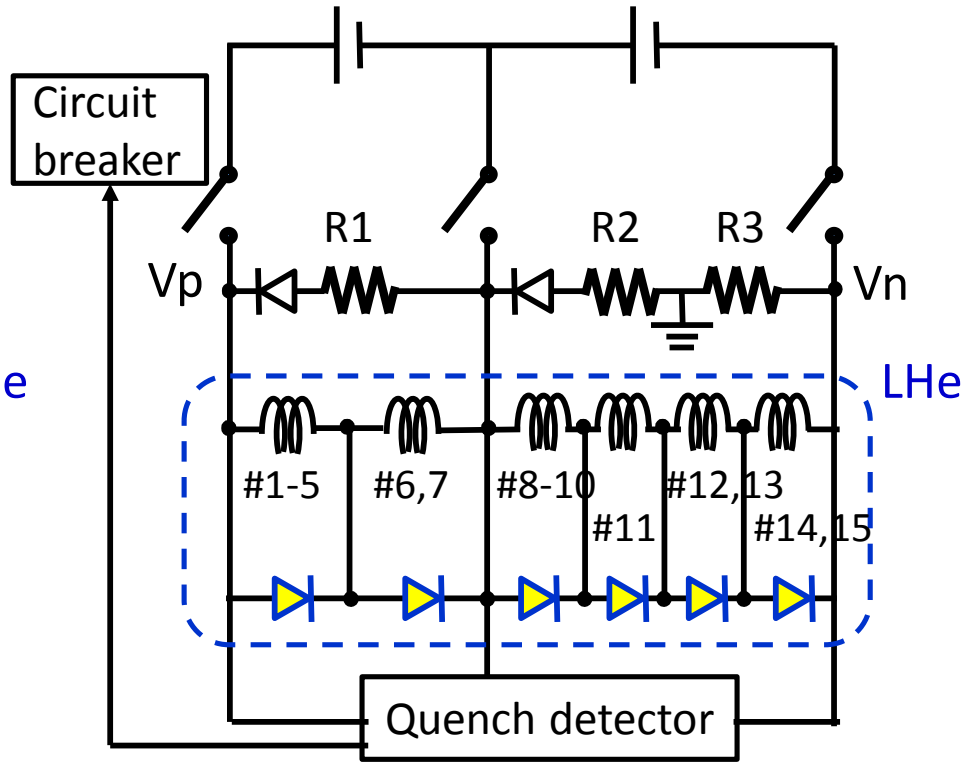
Maximum temperature of ESL is satisfied with the preliminary protection design.
But, the temperature of ESR1 is higher than the design condition.

Redesign ESR1 protection system

Preliminary design

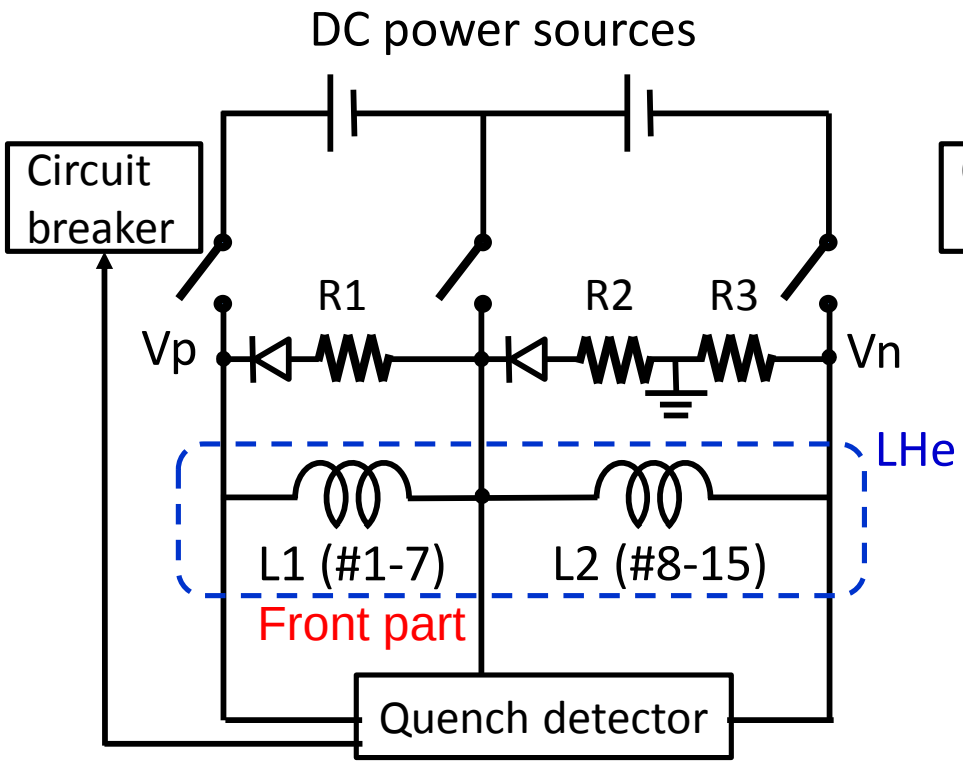


Cold diode protection (Turn on voltage : 10 V)



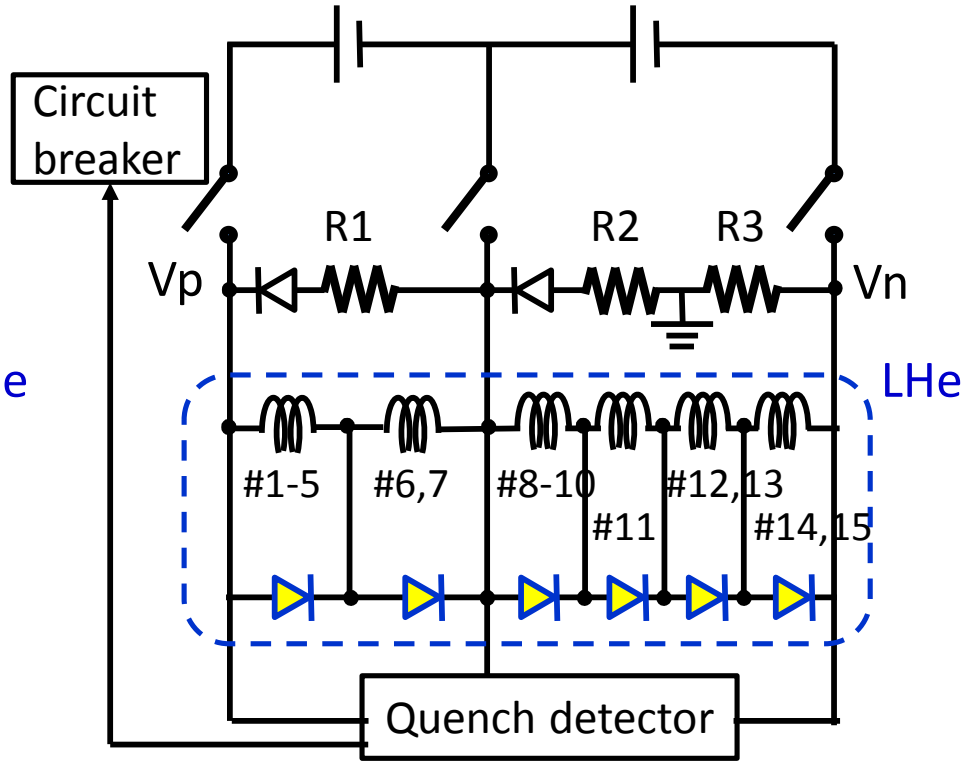
Redesign ESR1 protection system

Preliminary design



Maximum quench temperature < 200 K

Cold diode protection (Turn on voltage : 10 V)

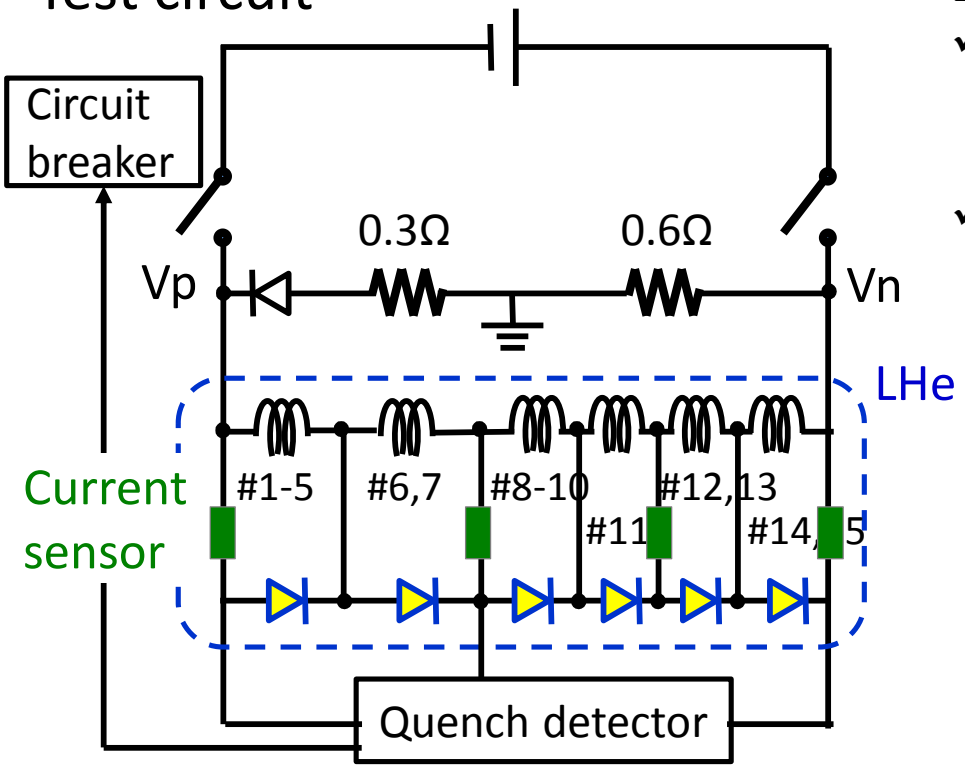


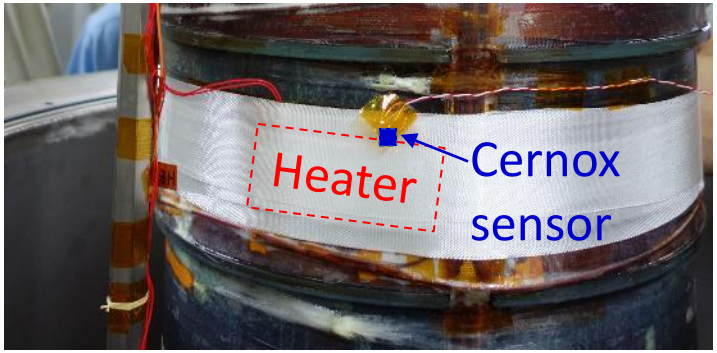
Maximum temperature (K)		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15
ESR1	Solo	39	39	39	39	39	67	75	136	109	112	84	121	108	91	144
	Coupled with Belle	39	39	39	39	39	66	75	128	105	108	82	110	94	88	132

Maximum temperature of ESR1 is satisfied with the cold diode protection.

Quench test of ESR1 with cold diode protection

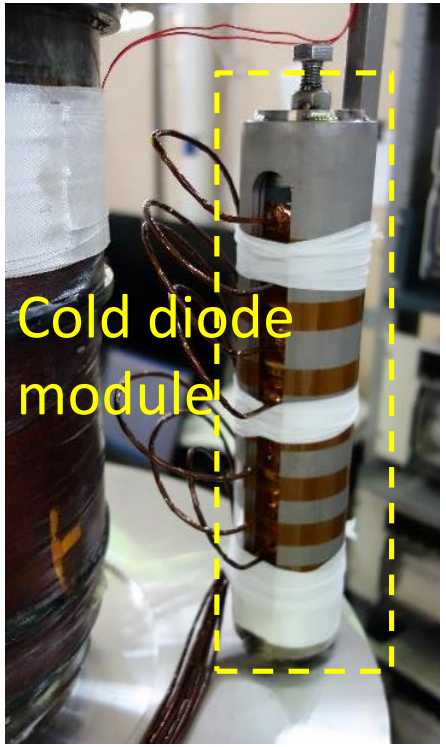
Test circuit





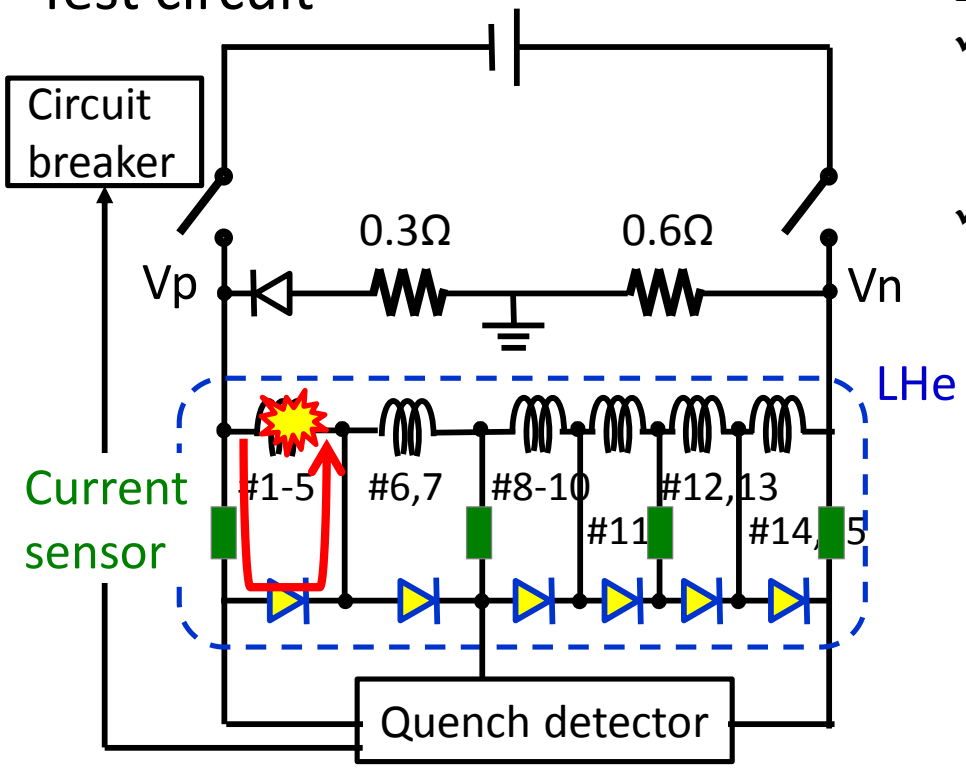
Experimental setup

- ✓ 6 heaters are attached on coil #4, #7, #8, #11, #12, and #14 to demonstrate heat-induced quench for each cold diode circuit.
- ✓ Temperature, coil voltage, and bypass current are measured to check the cold diode protection properties.



Quench test of ESR1 with cold diode protection

Test circuit



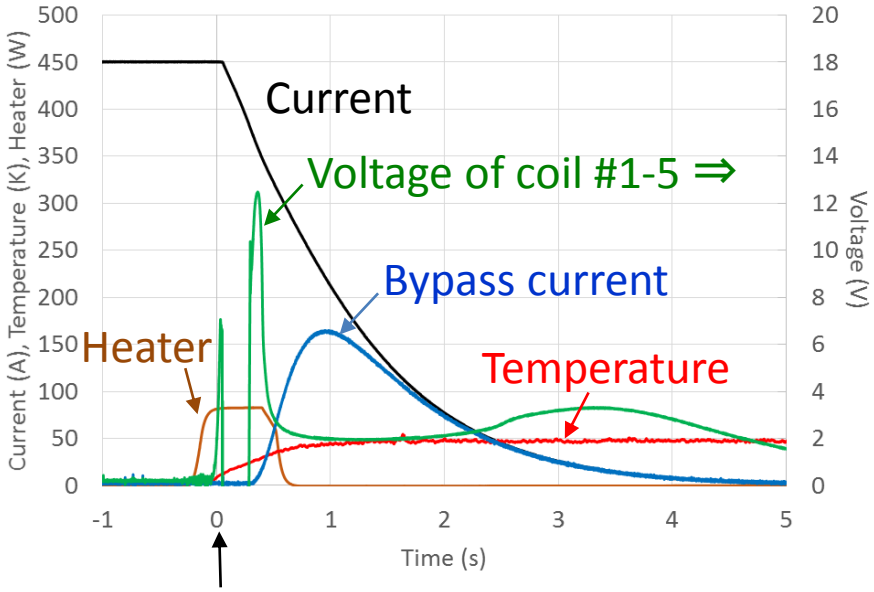
Test results

- ✓ Cold diode protection system works properly.
- ✓ Temperature of hot spot is much lower than the design condition.

Experimental setup

- ✓ 6 heaters are attached on coil #4, #7, #8, #11, #12, and #14 to demonstrate heat-induced quench for each cold diode circuit.
- ✓ Temperature, coil voltage, and bypass current are measured to check the cold diode protection properties.

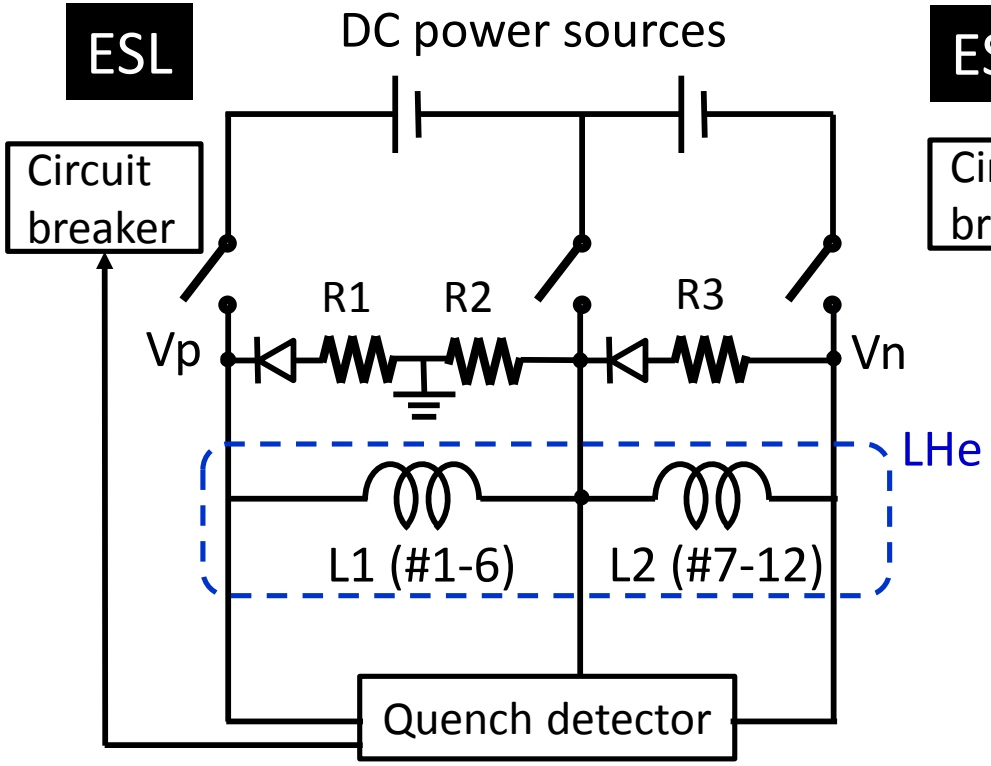
Coil #4 quench test results

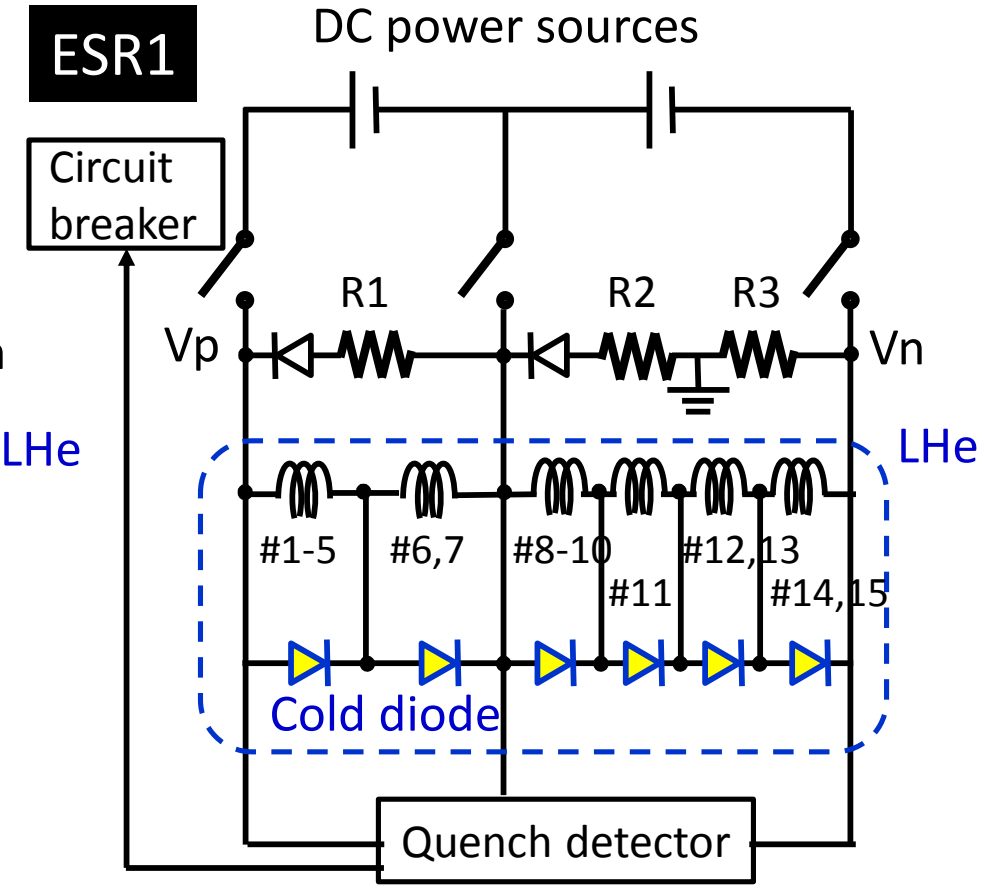


Trigger point of quench detector

Summary

Final design of quench protection system





	R1(Ω)	R2(Ω)	R3(Ω)
ESL	0.465	0.345	0.12
ESR1	0.34	0.074	0.414