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Introduction

- *Institute of Basic Science (IBS)* building a heavy ion particle accelerator, Rare isotope Accelerator complex for ON-line experiment (RAON).

- Total 13 units of Low-Temperature Superconductor quadrupole triplet made by *JH Engineering* will be deployed to control the beam line in the Inflight-Fragment separator of RAON facility.

- To achieve compact, accurate, and stable system,
  - One unit of triplet magnet system to be operated in one single cryostat.
    - 5 magnets: 3 triplets, 1 Hexapole, and 1 Octupole.
  - A serpent-like Hexapole, and Octupole magnet are inside the unit for field correction.
  - Superferric type quadrupole of high thermal capacity to be used.

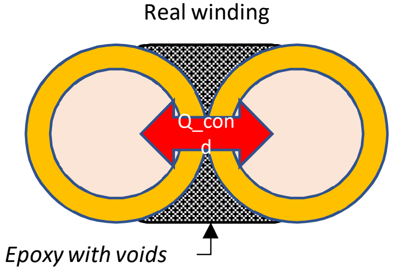
- This research performs numerical analysis of the triplet magnet system.

System Information – Conductor

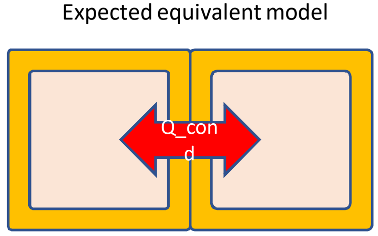
- Same NbTi wire for all magnet.

Conductor Property	Value
Superconductor	NbTi
Bare wire diameter	1.02 mm
Insulated diameter	1.10 mm
Insulation material	Formvar
Cu/SC ratio	4.3
RRR	120
Breakdown Voltage	**2000 V**
Critical current @ 4.2 K, $10^{-14}\Omega\cdot m$	
at 3 T *at* 4 T *at* 5 T	685 A 570 A 470 A

< Conductor Properties >



$$Q_{cond} = kA_{contact}\frac{\Delta T}{\Delta x}$$

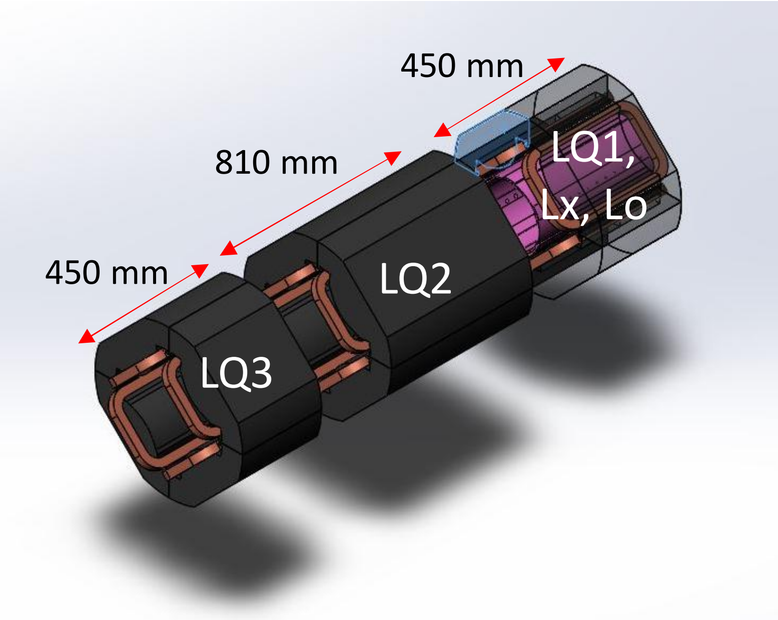


$$Q_{cond} = (c.f.) \times kA\frac{\Delta T}{\Delta x}$$
$$(0 < (c.f.) \le 1)$$

- Epoxy impregnation (thermal contact) modeled with a contact factor (c.f) which represent the imperfect contact between neighboring windings.

System Information – Quadrupole

- Three quadrupoles(LQ*n)*, one hexapole (Lx), and one octupole (Lo) operated by independent power supply.
- Dimensions of the shorter quadrupole LQ1, and LQ3 identical.
- LQ2, longest, **stores largest amount of energy.**

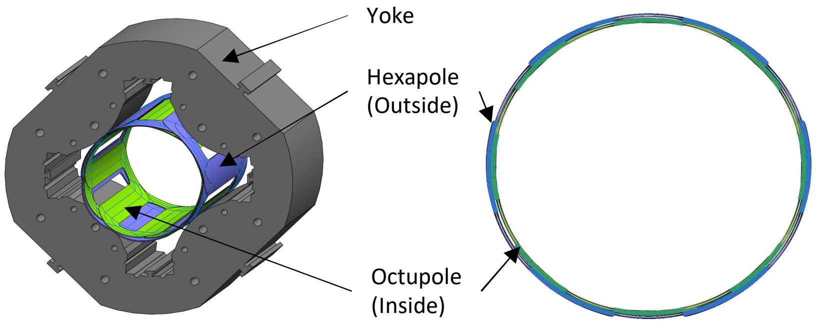


<An overview of a quadrupole triplet magnet designed by JH Egineering>

Parameters	LQ1, LQ2, LQ3
Coil nominal length [mm]	632, 992, 632
Yoke length [mm]	450, 810, 450
Effective length [mm]	550, 900, 550
Pole tip radius [mm]	180
Yoke outer radius [mm]	420
Coil winding cross-section height, width [mm]	44, 44
Total turns	1600
Maximum Iop [A]	165
Bmax in the coil @ Iop,max [T]	3.6
Operating temperature, Top [K]	4.2
Yoke mass [ton]	1.16, 2.08, 1.16
Yoke material	Silicon Steel Non-Grain-oriented (50PN1300)

System Information – Hexapole and Octupole

- Hexapole (Lx) and octupole (Lo) inside of LQ1 pole tip.
- Serpentine coils with only **one single loop.**
- Two coils, for delicate field correction, operated with independent power supplies.



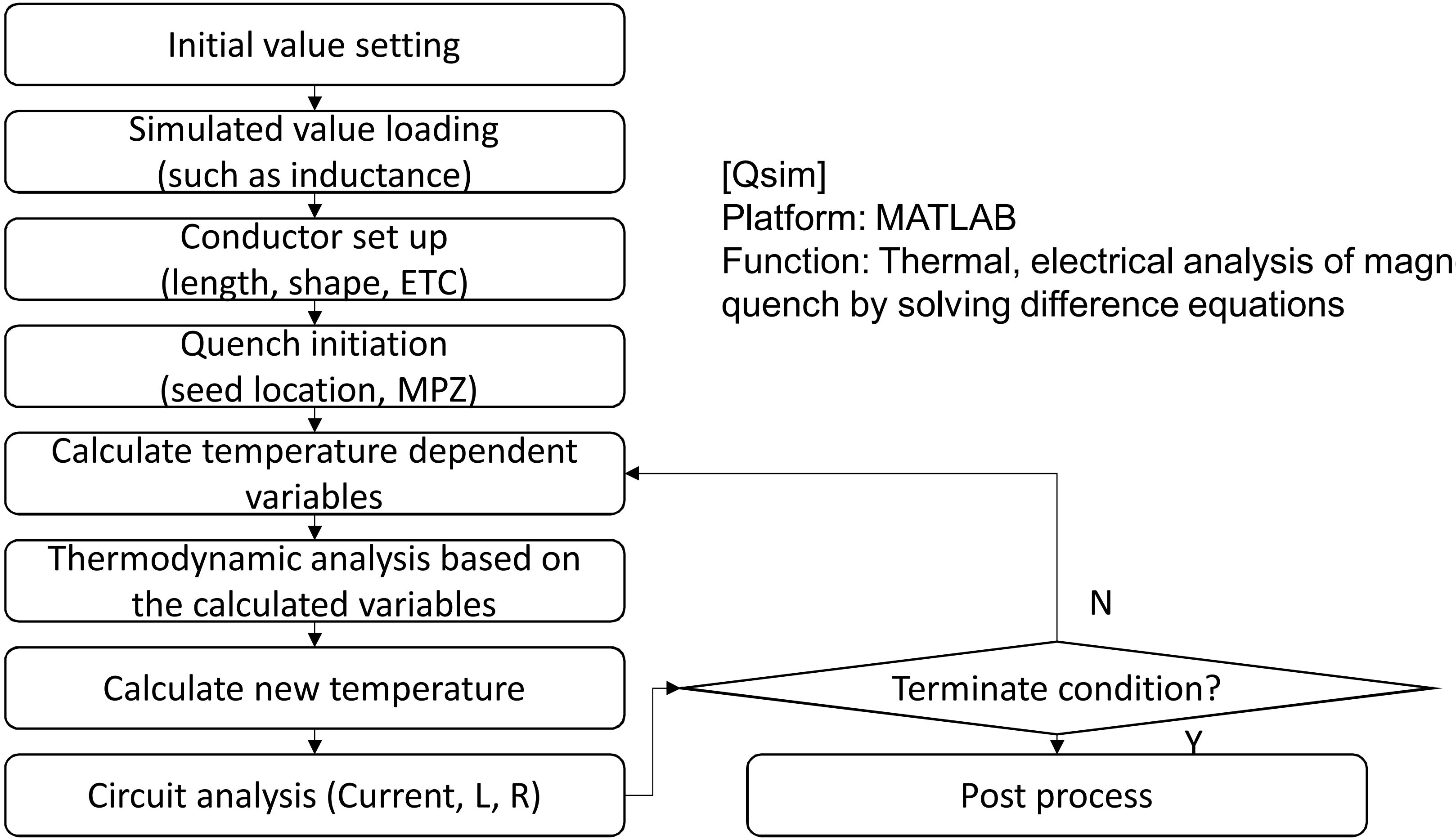
< Overview of Hexapole and Octupole >

Properties	Lx	Lo
Desired effective length [mm]	550	550
Designed effective length @ 40% operation [mm]	551.0 (@ 40 A/mm²)	549.6 (@ 48 A/mm²)
Simulated inductance [H]	0.298	0.176

< Properties of Hexapole and Octupole >

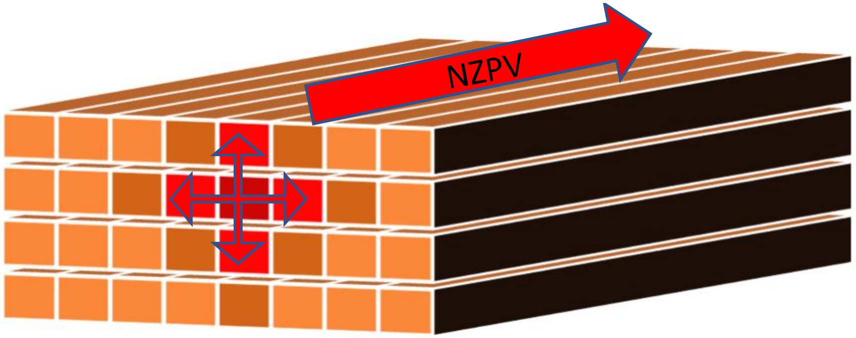
Simulation Method

- A FDM based simulation program (Qsim) is developed.



[Qsim]
Platform: MATLAB
Function: Thermal, electrical analysis of magnet quench by solving difference equations

Simulation Method



$$U_\ell \simeq \frac{J_m}{C_m(\tilde{T})}\sqrt{\frac{\rho_m(\tilde{T})k_m(\tilde{T})}{T_t - T_{op}}}$$

Heat transfer $\frac{dQ}{dt} = -h \cdot A \cdot (T(t) - T_{\text{env}}) = -h \cdot A\Delta T(t)$

< Quench propagation modeling of 'Qsim' code >

- Quench propagation modeled in two ways
  - Longitudinal direction: Calculating Normal Zone Propagation Velocity.
  - Transverse direction: Thermal, neighboring wires.
  - Semi-3D simulation.

- Magnet inductance varies with operation current because of saturated iron yoke.
- Inductance matrix pre-calculated by simulation.

Iop (A)	LTotal (H)	L1 (H)	L12 (H)	L13 (H)	M12 (H)	M13 (H)
5	46.8	7.59	19.86	14.04	2.34	-0.57
25	46.83	7.6	19.87	14.05	2.34	-0.57
45	46.33	7.6	19.84	14.05	2.32	-0.57
65	38.91	7.55	18.56	14.01	1.73	-0.55
85	31.32	7.11	15.25	13.51	0.52	-0.35
105	27.08	6.19	13.06	12.08	0.34	-0.15
125	24.27	5.5	11.66	10.76	0.33	-0.13
145	22.23	5.01	10.64	9.79	0.31	-0.12
165	20.75	4.64	9.88	9.06	0.3	-0.11

< Inductance of LQ2 magnet with respect to the operation current >

Analysis Assumptions

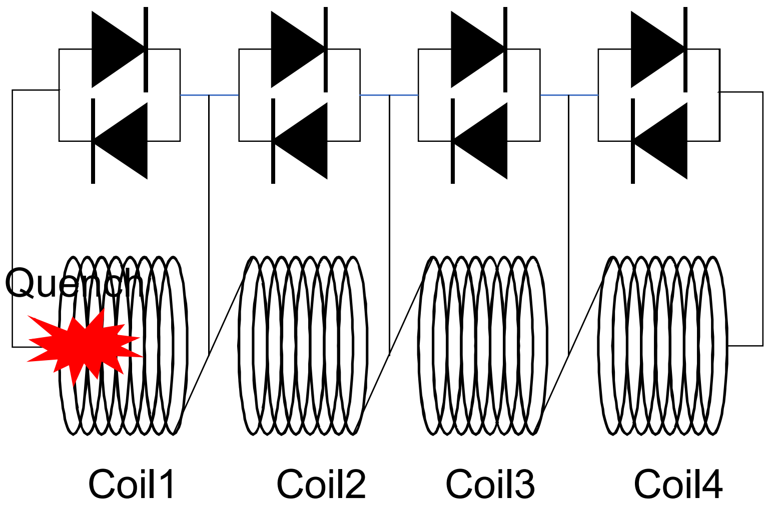
- System critical values: breakdown **voltage (2 kV);** peak **temperature (150 K)**
- Adiabatic cooling condition.
- Contact factor (*c.f.*): 0.9 for quadrupoles (experimental value).

  Much lower in hexapole and octupole (discussed [page 15]).
- Quadrupole quench analysis focused on LQ2 magnet, having the largest energy.
  - In other words, **LQ1 and LQ3 will be safe if LQ2 is safe.**
- The quench occurred in the maximum operating currents:
  - [165 A] for quadrupole, [150 A] for hexapole, and [180 A] for octupole.
- Power supply (P/S) shuts down, or diodes turn on immediately after a quench event.

Results – Quadrupole Quench Simulation [Case 1]

- LQ2 magnet quench scenario simulated.
- Single quadrupole divided into 4 coil sections (one section per pole).
- Worst-case scenario for the division method

  : quench confined to only one single pole (Coil)



< Protection circuit diagram of the quadrupole >

Assumptions

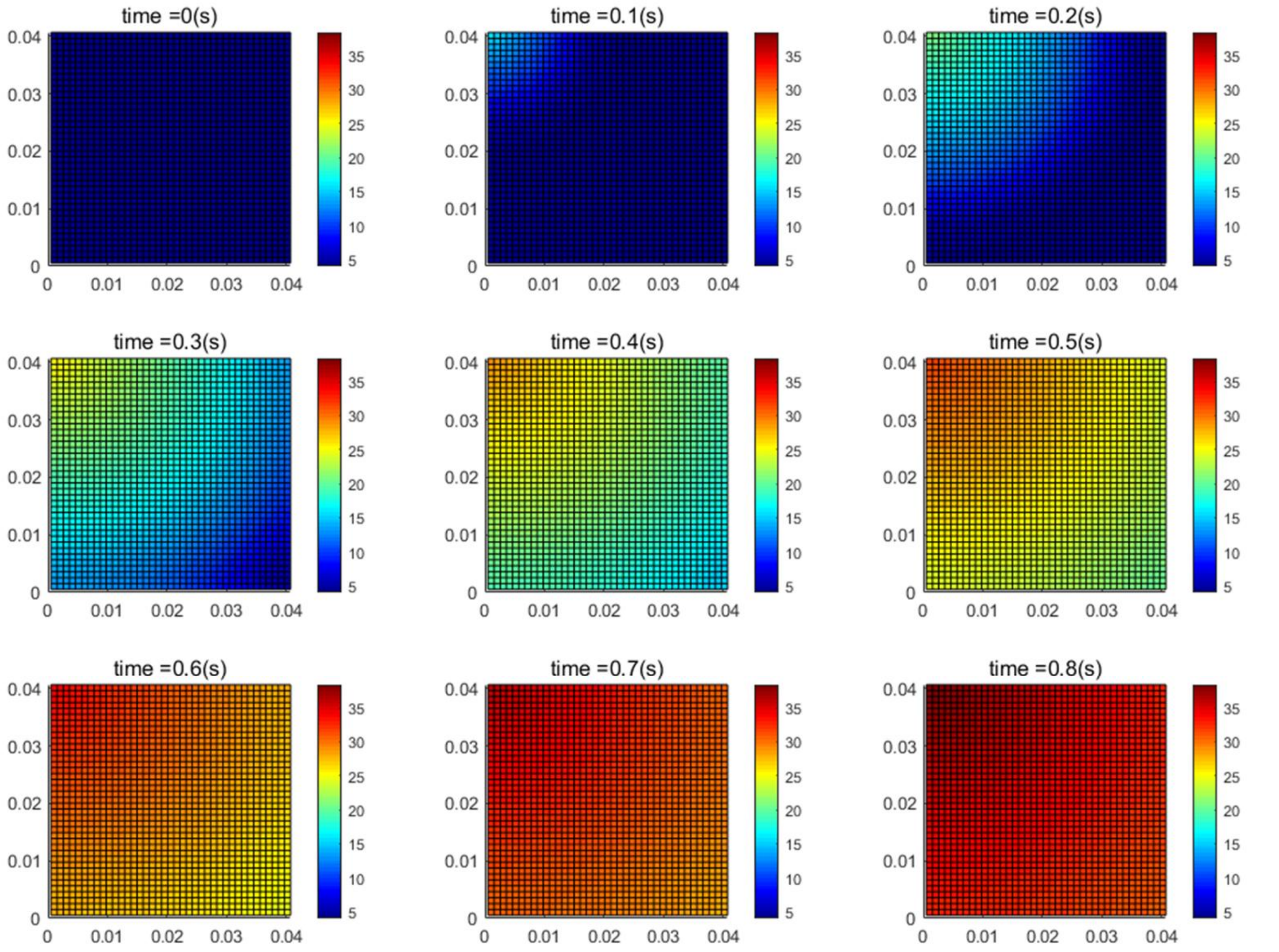
- Each coil has own closed loop with ideal diode
- The inductance matrix is calculated from FEM simulation.

Inductance matrix

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} R_1 & 0 & 0 & 0 \\ 0 & R_2 & 0 & 0 \\ 0 & 0 & R_3 & 0 \\ 0 & 0 & 0 & R_4 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} + \begin{bmatrix} L1 & M12 & M13 & M14 \\ M12 & L2 & M23 & M24 \\ M13 & M23 & L3 & M34 \\ M14 & M24 & M34 & L4 \end{bmatrix} \begin{bmatrix} \dot{i}_1 \\ \dot{i}_2 \\ \dot{i}_3 \\ \dot{i}_4 \end{bmatrix}$$

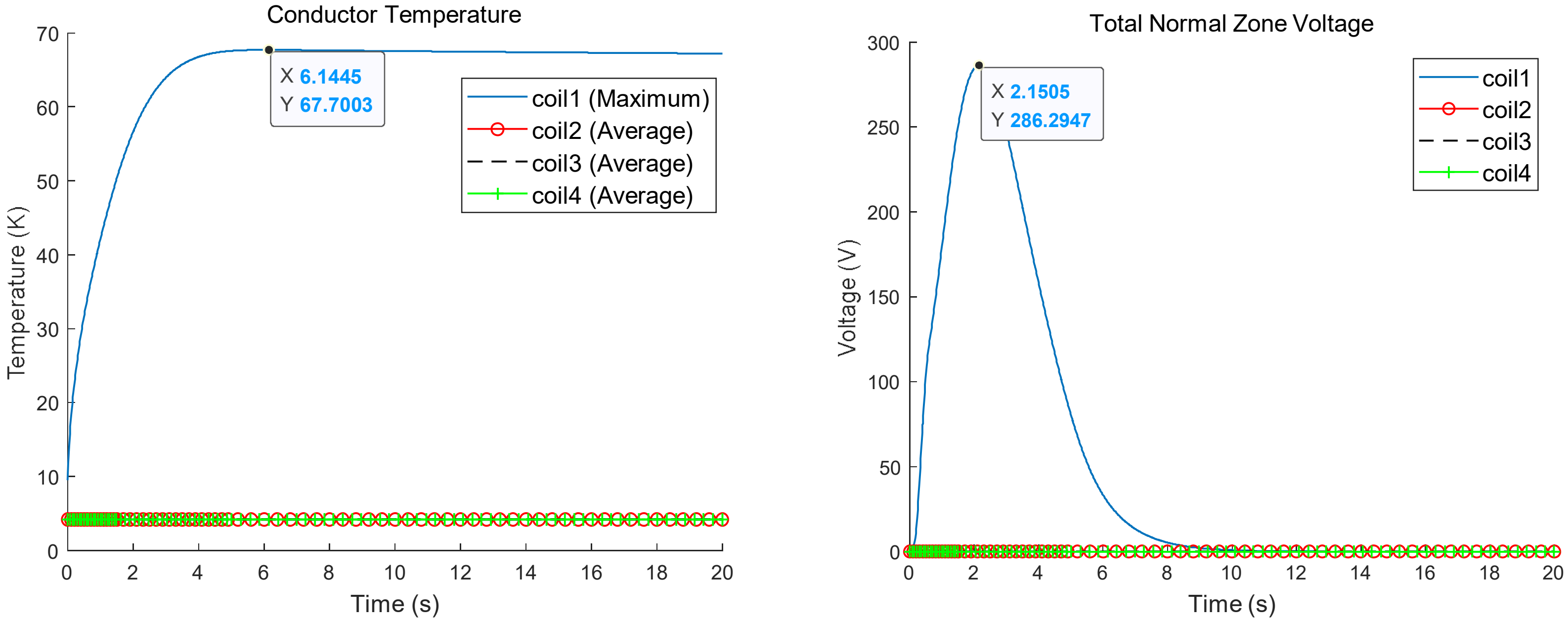
Resistance of coils

Result – Quadrupole Quench Simulation Case 1



< Temperature distribution of inside winding >

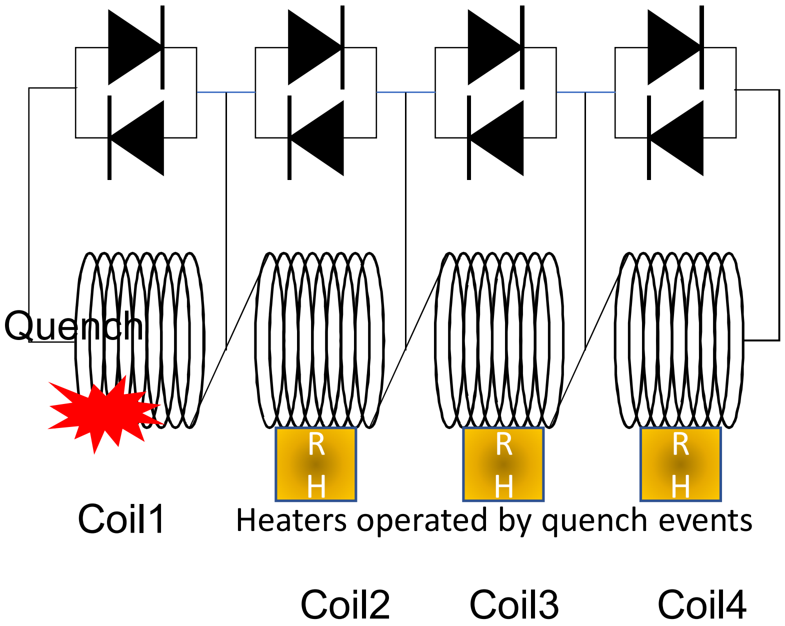
Result – Quadrupole Quench Simulation Case 1



- Most conductor quenched before 0.4 s.
- Even if the P/S does not shut down, protection diode will turn on very quickly.
- Peak temperature raised to **68 K**, much less than the critical limit.
- Peak voltage due to normal zone: **286 V.**

Results – Quadrupole Quench Simulation Case 2

- In realistic situation, Coils2-4 effected by Coil1 quench by electromagnetic coupling
- Electromagnetic interaction quenches Coils2-4 (diode turn on, or AC loss)
- Virtual model of quench heater (1 W, initial) simulates realistic situation.

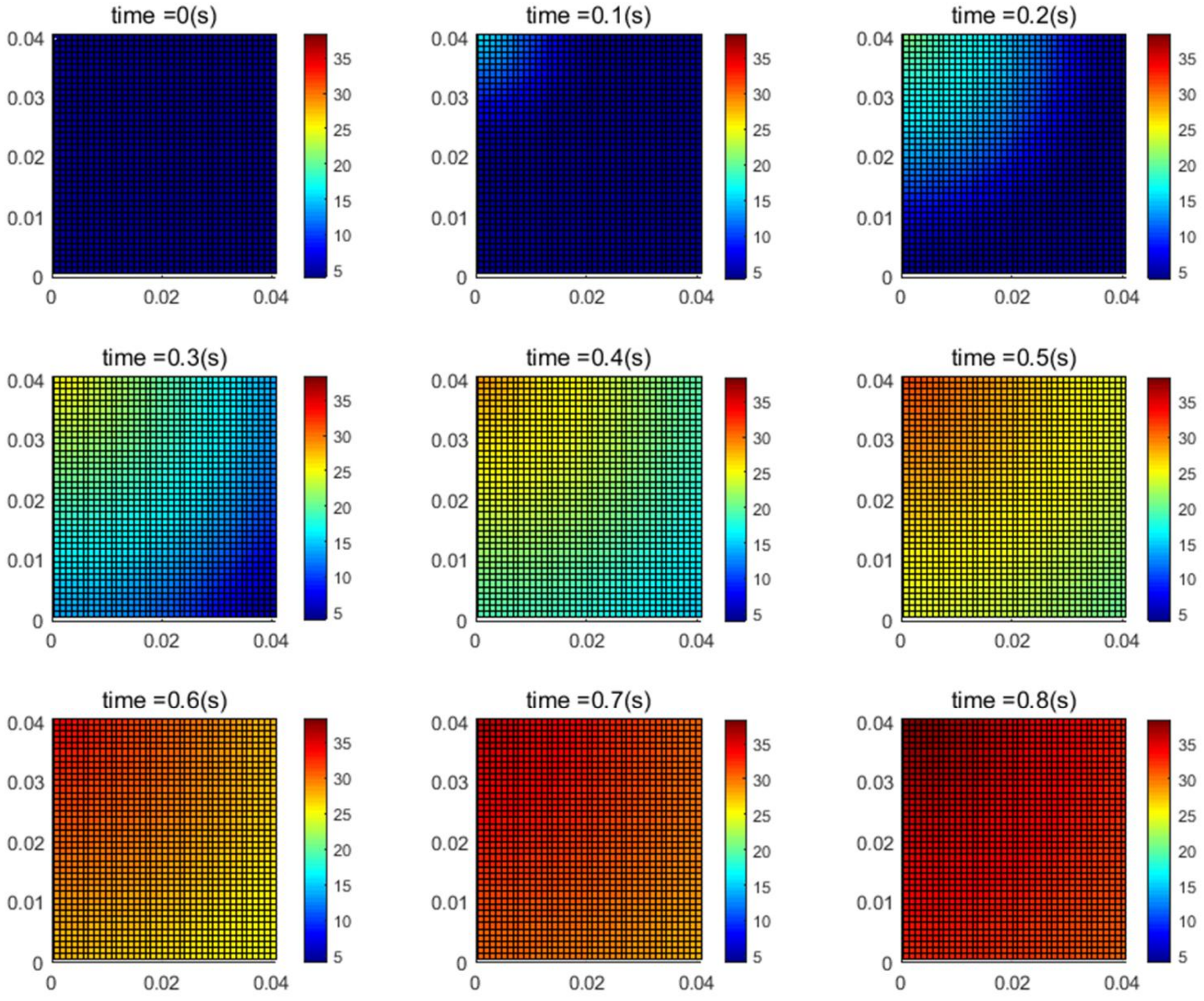


Additional Assumptions

- Quench heater activated right after the quench.
  - Semi-passive heater operation.
- Heater attached to the entire innermost layer area to quench the innermost layer

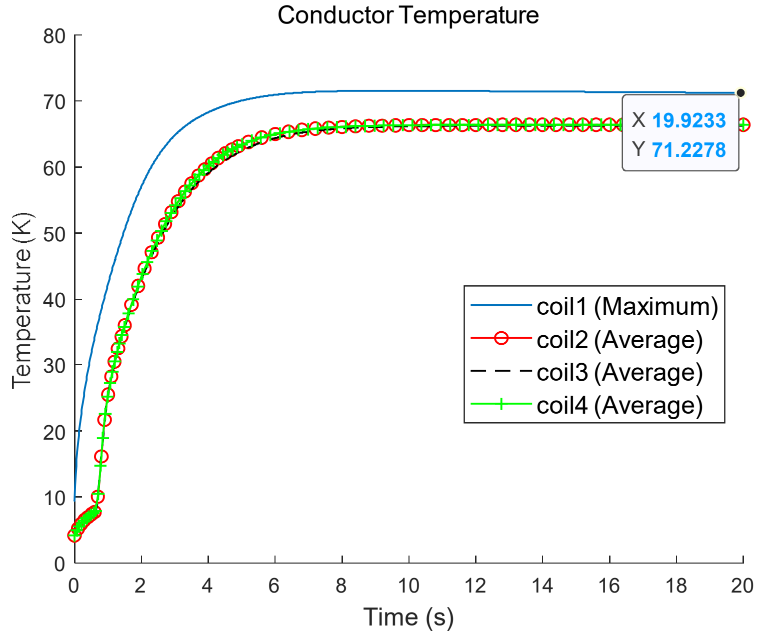
  = *Evenly distributed energy*

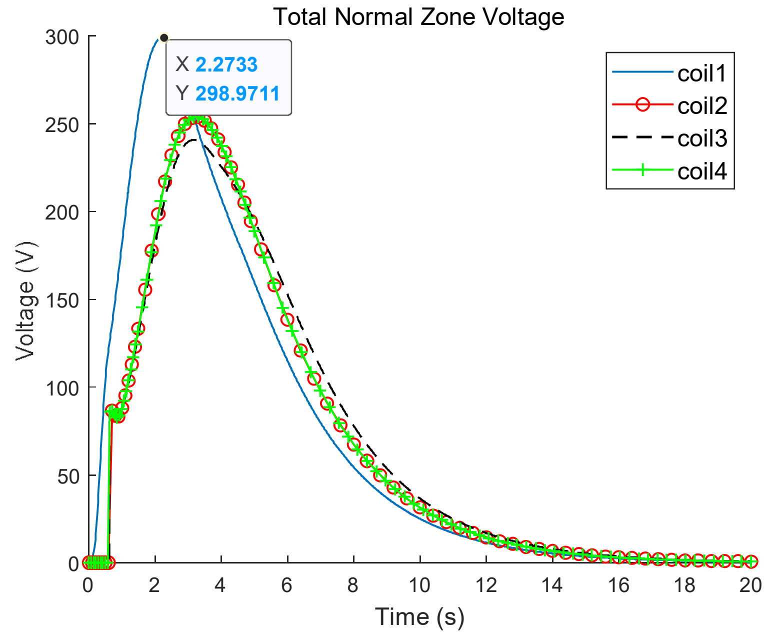
Result – Quadrupole Quench Simulation Case 2



< Temperature distribution of inside winding >

Result – Quadrupole Quench Simulation Case 2



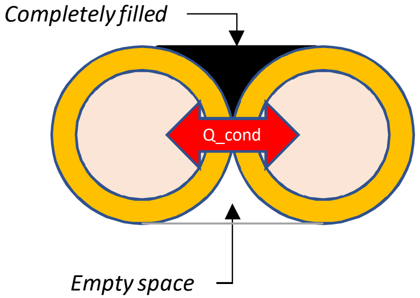


- Most conductor quenched before 0.4 s.
- Decaying currents in Coil2-4 energizing Coil 1.
- Peak temperature increased to 71 K, higher by **_3 K_** compared to *Case 1*.
- Peak voltage is 298 V, a **_12 V_** increase compared to *Case 1*.
- **No significant differences** in more realistic situation.

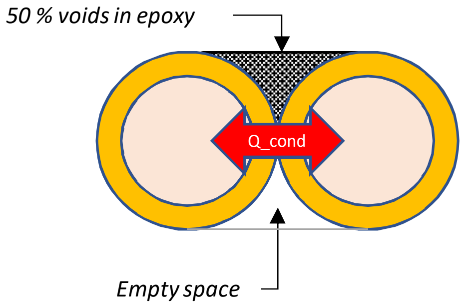
Result – Hexapole and Octupole

- Because of a serpentine winding structure, thermal contacts inside the hexapole and octupole not as good as in the quadrupole winding.
  : Contact factor (*c.f.*) much lower than 0.9 (quadrupole, experimental value).

	Hexapole		Octupole	
Inductance [H]	0.295		0.178	
Operation Current [A]	150		180	
Conductor Length [km]	1.6		1.5	
Contact Factor (c.f.)	*0.25*	*0.5*	*0.25*	*0.5*
Peak Temperature[K]	45	41	43	40
Peak Voltage[V]	22	24	22	25



< c.f.=0.5, only half side impregnated >



< c.f.=0.25, even the half impregnated side has 50 % voids >

- However, the internal heat transfer is much worse than the quadrupole (e.g., *c.f.=0.25*), the total energies stored in the hexapole and the octupole **low enough** not to damage both coils.

Conclusion

- LTS Quadrupole Triplet Magnet System for the IBS RAON Inflight-Fragment Separator briefly introduced

  – specifications, configuration, and magnet quench behavior

Cases	Peak Temperature [K]	Peak Voltage [kV]
Critical limits	**150 [K]**	**2.0 [kV]**
Case1: LQ2 w/o Heater	68 [K]	0.29 [kV]
Case2: LQ2 w/ Heater	71 [K]	0.29 [kV]
Hexapole with *c.f.*=0.25	45 [K]	0.02 [kV]
Octupole with *c.f.*=0.25	43 [K]	0.02 [kV]

❑ Based on our simulation results, we conclude that the magnet, equipped with internal protection diode and thus self-protected, will operate safely