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Magnet Technology and Conductor for Future High-field Applications

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Key Issues in HTS Magnet and Conductor Technology Toward Various Applications

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Magnet technology development needs

- I focus on following key issues.
  - Degradation, stability against thermal disturbance, and quench protection
  - Ac losses
  - Shielding-current-induced field (SCIF)
- I will not talk something new, but I would like to point out what we tend to overlook or to misunderstand.

Degradation, stability, and quench protection

We have to sort out

degradation leading to quench,

stability against thermal disturbance,

quench protection.

Degradation leading to quench

- Many people burnt their coated-conductor coils.
- They say, "Quench protection of coated-conductor coils are difficult." but …
- What are the causes of their quenches?
- Their answers are often "degradation such as local defect or delamination." If so, …
- Is it worth protecting degraded coils?
- In such cases, their essential problems are how to mitigate degradation not to protect against quench.

In case of LTS magnets

- Because of very small enthalpy margin, an LTS magnet easily quenches by tiny thermal disturbance: inferior stability against thermal disturbance
- An example of tiny thermal disturbance leading to quench is conductor slip on the bobbin, whose prediction is almost impossible.
- We allow quench and protect magnet from burn out by so called “quench protection”.
- Magnet protection = quench protection

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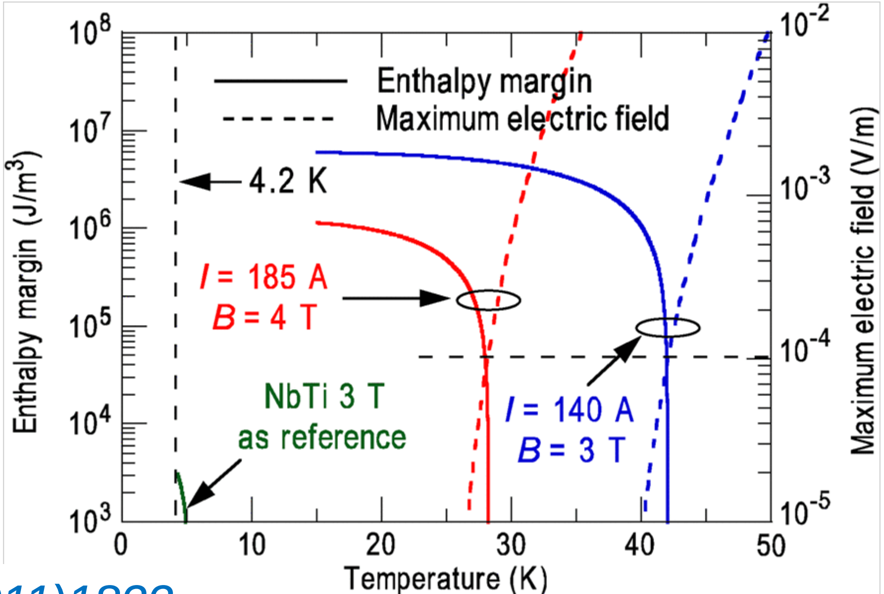
Stability against thermal disturbance (HTS)

- Superior stability against thermal disturbance
- If degradation is overcome, what makes quench?
  - Failure of cryocooler? Beam loss?
  - Lack of common clear answer

Enthalpy margin of HTS magnets is several order of magnitude larger than that of LTS magnets



Takahashi et al. IEEE-TAS21(2011)1833

Magnet protection (HTS)

There might be choices …

1. Since the cause of quench is very rare …
   - Operate magnet with enough margin
   - Reduce the cause as much as possible
     - eg. beam collimator and shield in particle accelerator
   - Monitor magnet, and if something wrong is monitored, shut down magnet = magnet protection before quench
2. Implement "quench protection" (after quench), because we cannot predict what happens.

Increasing critical current is not the “Superman.”

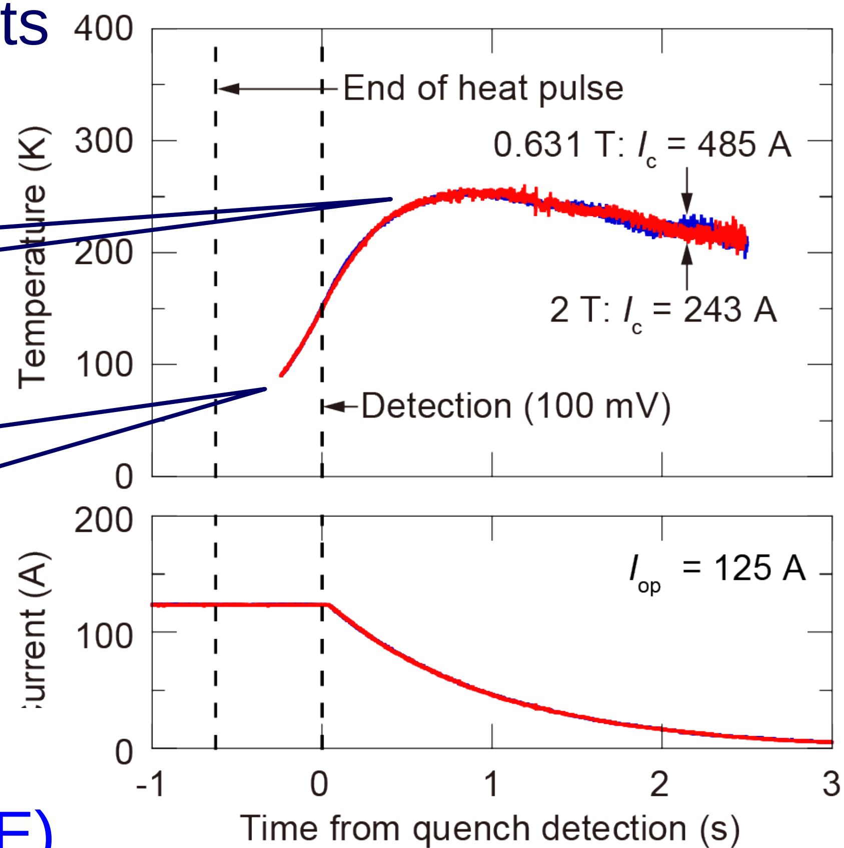
Effect of increasing critical current

Quench and protection experiments with I_c = 243 A and 485 A

Increasing I_c does not reduce hot-spot temperature.

Increasing I_c increases MQE
- 0.59 J @243 A
- 0.78 J @485 A

$$T_g = T_c - (T_c - T_0)\frac{I}{I_c(T_0)}$$



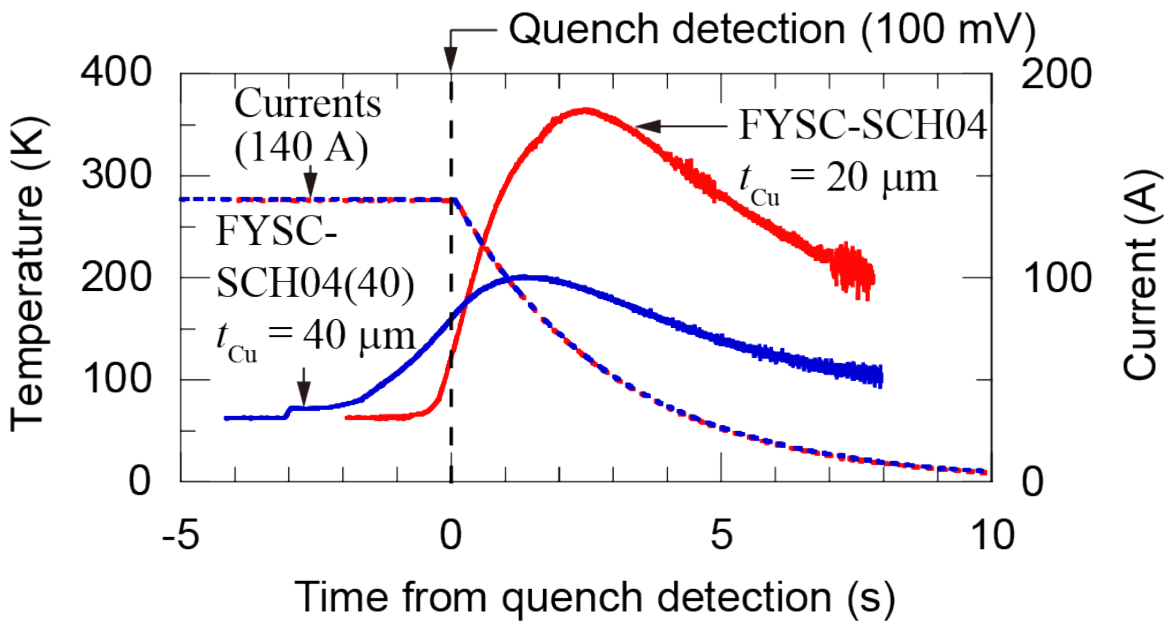
- Increasing critical current is improve stability (increasing MQE)
- But, it is meaningless for protection.

Luo et al. IEEE-TAS under review

Effect of copper stabilizer

20 μm plated copper

40 μm plated copper



Luo et al. Tue-Mo-Po2.10-03

Protection is dominated by copper current density which determines Joule heating rather than critical current density.

Ac loss

The ac loss of HTS is large. Don't compete with LTS where LTS is sufficient.

Ac losses of HTS and LTS and cooling efficiency

	LTS	HTS
Dimension of superconductor	1 μm	1 mm
Relative magnitude of ac loss	1	1,000
Cooling efficiency	1/1,000 @4.2 K	1/10 @77 K
Relative required power removing ac losses	1,000	10,000

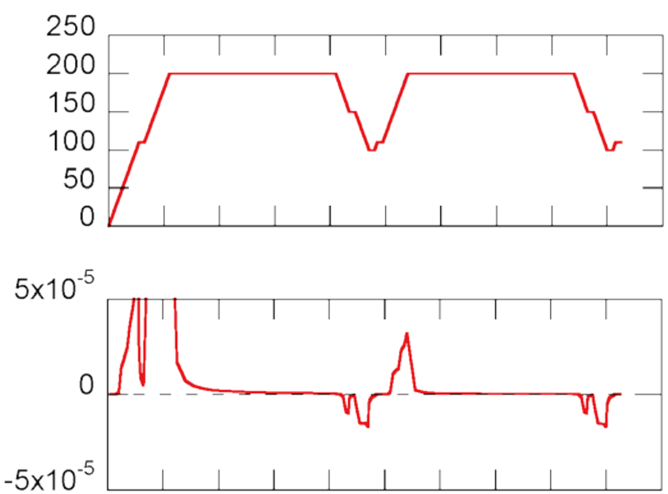
But the larger temperature margin of HTS is attractive in magnets generating time-dependent magnetic field if we can obtain enough cooling power for its ac loss.

Shielding-current-induced field

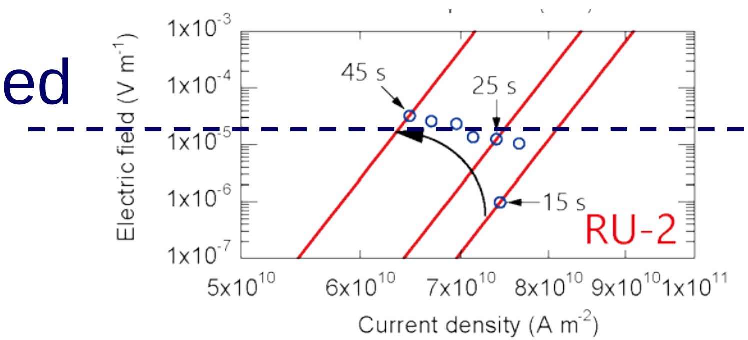
The mitigation of SCIF in magnets which have to generate time-dependent magnetic field is another challenge.

SCIF in magnets generating time-dependent magnetic field

- Current density is determined by d*B*/d*t* and resistivity of (*E*-*J* characteristic), and then shielding current depends on dB/dt.
- Shielding current depends on I_t/I_c.



E determined by d*B*/d*t*



E-*J* curve of SC: function of time-dependent *B*

Amemiya et al. SUST29(2016)024006
Li et al. IEEE TAS28(2018)4601105

Key points as summary

- ✓ Copper current density is much more important than critical current density for quench protection.
- ✓ Ac loss in HTS is large, but its larger temperature margin is attractive in magnets generating time-dependent magnetic field.
- ✓ Mitigation of SCIF in magnets generating time-dependent magnetic field is a challenge.