Detecting quench in HTS magnets with LTS wires — a theoretical and numerical analysis

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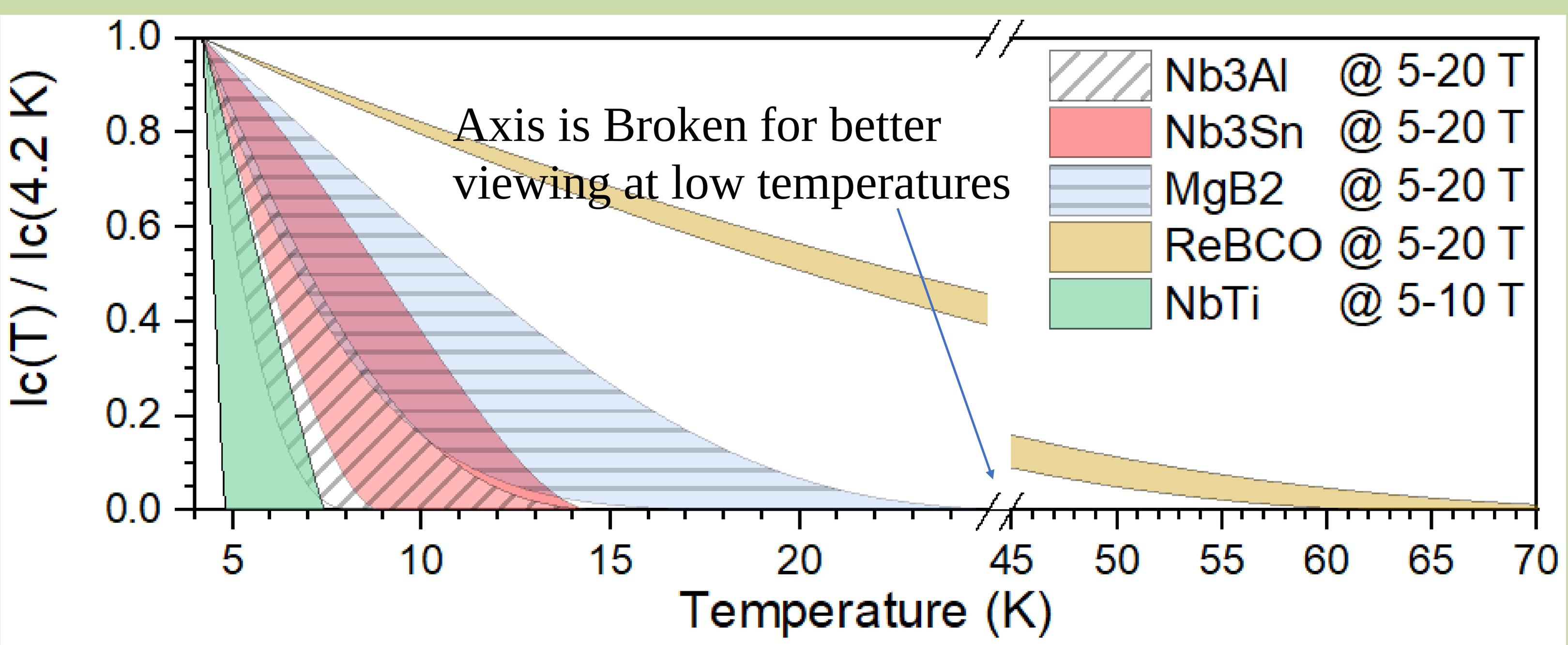
Abstract

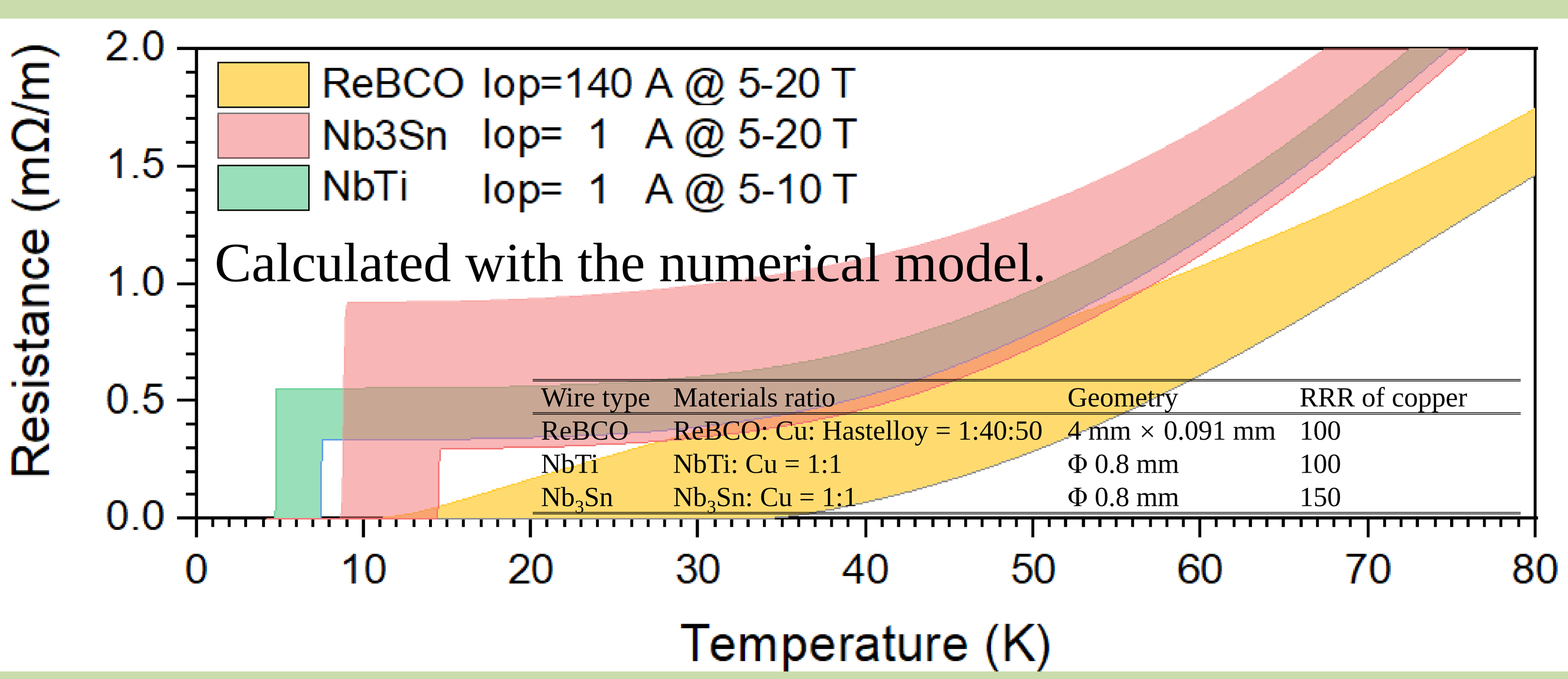
Using a co-wound and insulated NbTi low temperature superconducting (LTS) wire to detect quench in coils wound with ReBCO high temperature superconducting (HTS) tapes has recently been experimentally proved, yet a theoretical study is still needed to further develop this technique and make it prepared to be applied more generally in high field accelerator magnets. By theoretical and numerical analysis, we confirm a few important facts:

1. It is the significant difference in the $I_c(T)$ relation between LTS and HTS but not the normal zone propagation velocity (NZPV), that makes LTSs good quench detectors;
2. LTS quench detectors should have low matrix fraction or high matrix resistivity;
3. Heat conduction between cable and detector is important, but a poor condition is tolerable;
4. At field up to 15 T, Nb_3Sn, Nb_3Al and MgB_2 all show good potential as quench detectors, and some degradation in wire performance is also acceptable.

A theoretical explanation



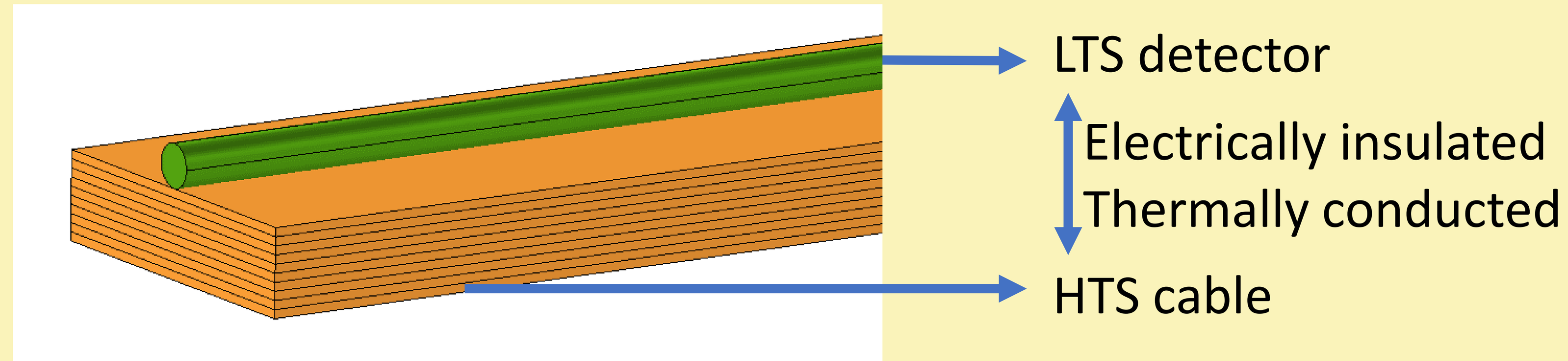
➢ The variation of critical current as function of temperature and magnetic field is significantly different for ReBCO and several LTS materials.



➢ The resistance (per unit length) of LTS wires dramatically increases once T_{cs} is exceed. For ReBCO it's much more gently.

Numerical analyses

- **A classic 1-D numerical model**



Temperature variation — Longitudinal heat conduction — Heat exchange between HTS cable and LTS detector — Applied heat — Joule Heating

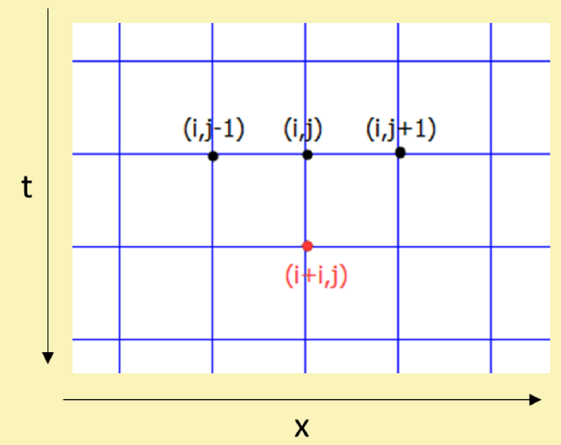
$$A_i\rho_i Cp_i\frac{\partial T_i}{\partial t}-\frac{\partial}{\partial x}\left(A_i k_i\frac{\partial T_i}{\partial x}\right)+\sum_{m=1}^{N}\frac{(T_j-T_m)}{H_m}=\dot{q}'_{ext}+\dot{q}'_{Joule}$$

Equipotential between superconductor and metal

$\dot{q}'_{Joule}$ (T, B, I_s) is solved by an Iteration method

$$\begin{cases}\dot{q}'_{Joule}=I_sE_s\\ E_s=E_0\left(\frac{I_s}{I_c}\right)^n\\ \eta_n\frac{I_s-I_{sc}}{A_n}=E_0\left(\frac{I_{sc}}{I_c}\right)^n\end{cases}$$

Solve it by finite-difference method (FDM)



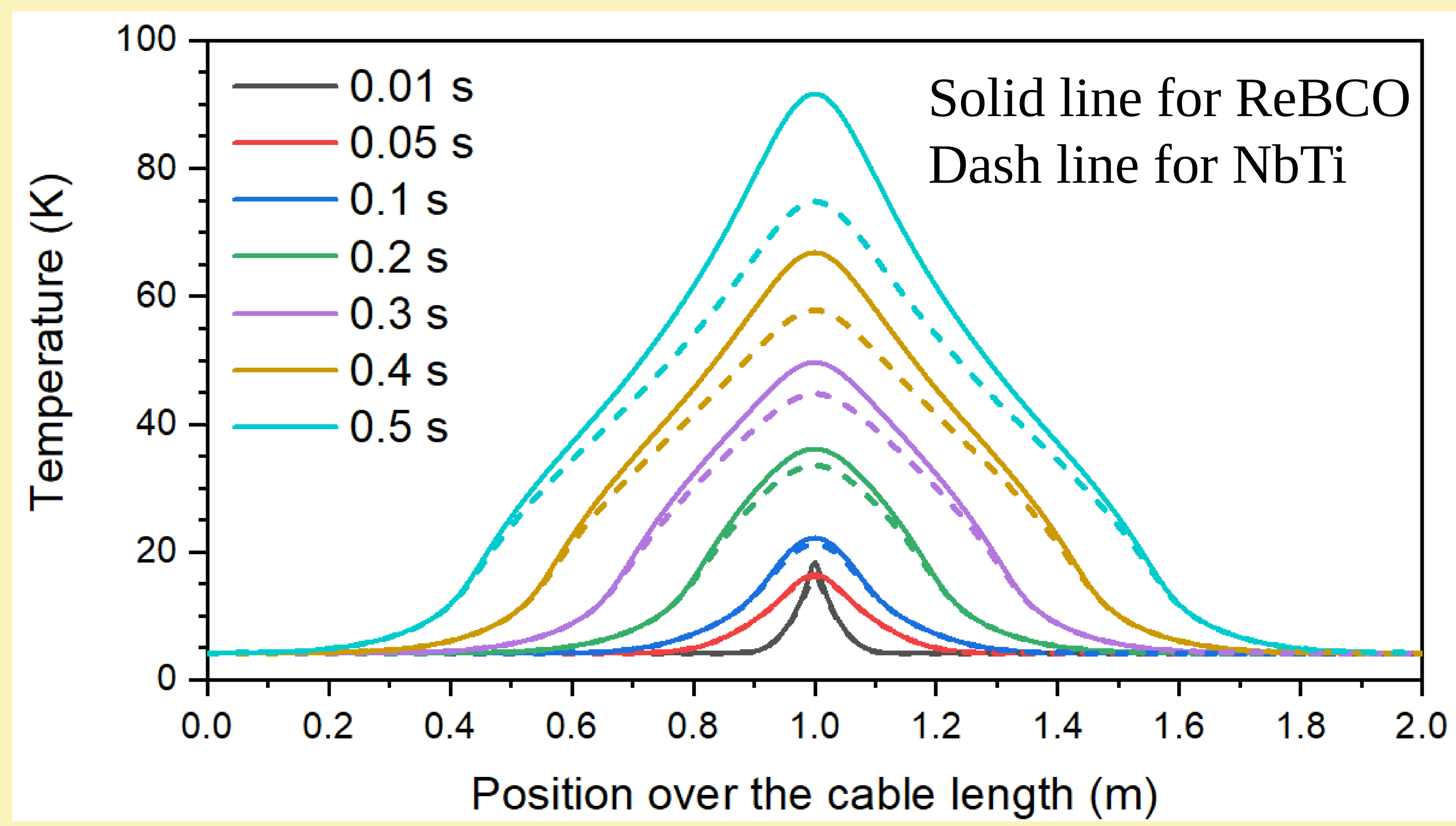
$$T_{i+1,j}=T_{i,j}+\frac{\Delta t}{A_s\rho_s C_s}\left\{\frac{A_s(k_{i,j+1}-k_{i,j-1})(T_{i,j+1}-T_{i,j-1})}{2\Delta x^2}+\frac{A_s k_{i,j}(T_{i,j+1}+T_{i,j-1}-2T_{i,j})}{\Delta x^2}+\sum_{m=1}^{N}\frac{(T_{i,m}-T_{i,j})}{H_m}+\dot{q}'_{ext}+\dot{q}'_{Joule}\right\}$$

Ref: L Bottura et al, Cryogenics 40 (8-10), 617-626 (2000)

- **An example at 5 T with NbTi quench detector**

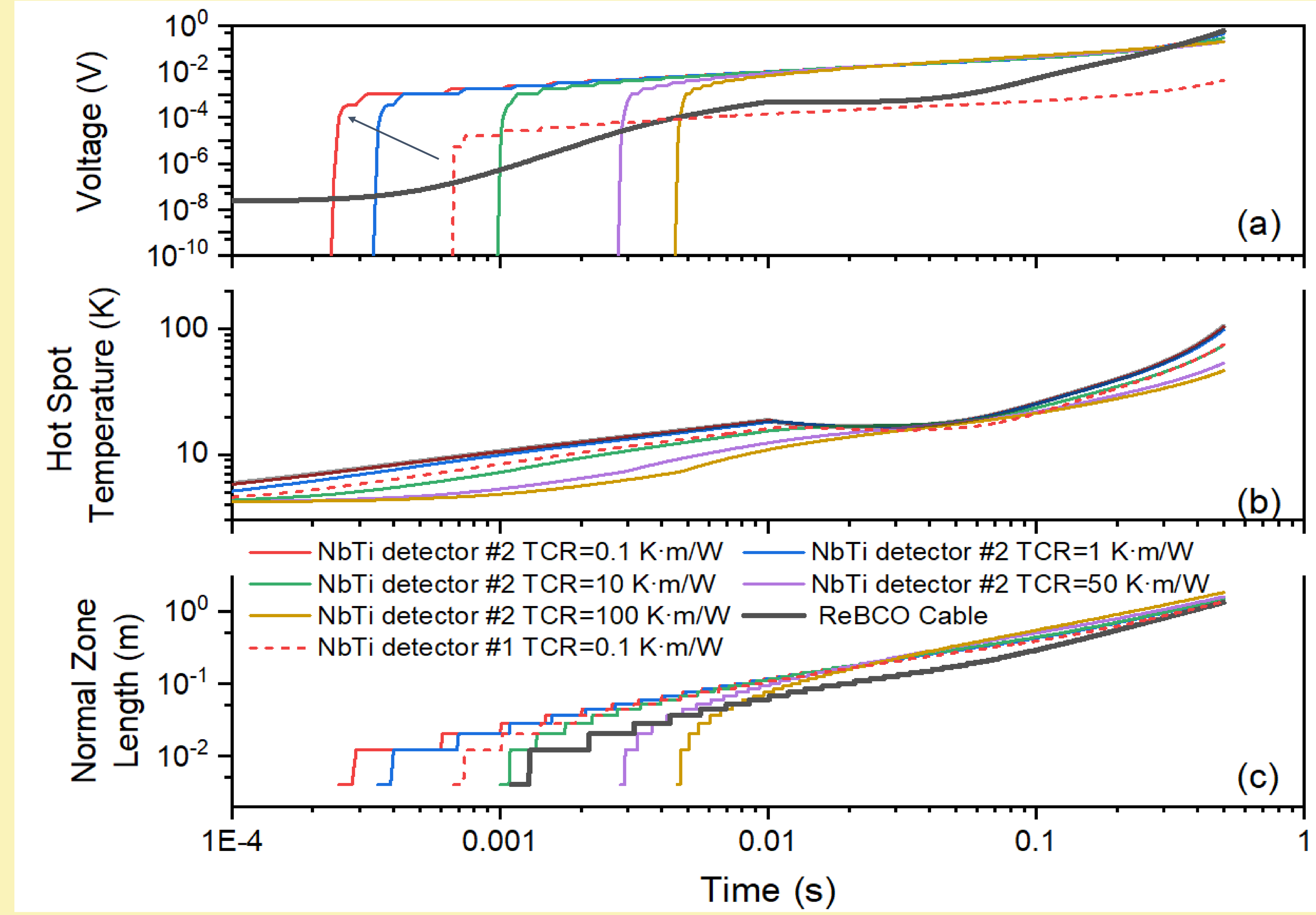
Specifications of ReBCO cable and NbTi quench detectors

Wire Type	Materials ratio	Geometry	Ic at 4.2 K and 5 T	Tcs with Iop
ReBCO Cable	ReBCO: Cu: Hastelloy = 1:180:50	4 mm × 0.231 mm ×10	4518 A	~10.9 K for Iop=0.8Ic
NbTi detector #1	NbTi: Cu = 1:1	Φ 0.8 mm	616 A	~7.40 K for Iop=1 A
NbTi detector #2	NbTi: Cu = 1:0.5	Φ 0.12 mm	77 A	~7.36 K for Iop=1 A



➢ Temperature profile of NbTi detector follows that of ReBCO cable;

➢ The small current in NbTi is not able to drive its normal zone to propagate. It has almost the same normal zone length as ReBCO.



➢ Voltages in NbTi detectors rise rapidly once its T_{cs} is exceed and normal zone occurs, regardless of its length.

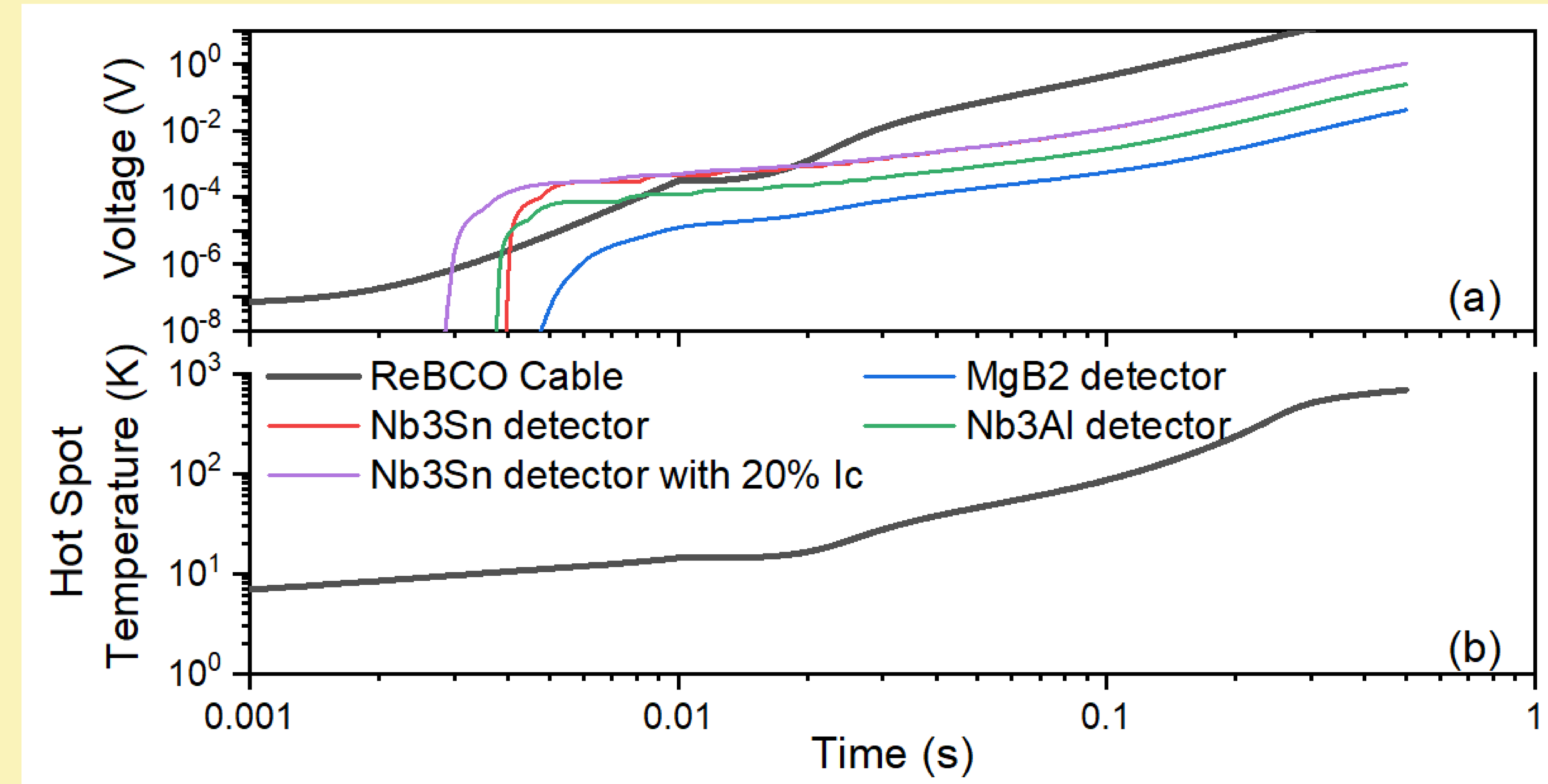
➢ NbTi wire with higher normal resistance has better sensitivity.

➢ Poor thermal conduction between ReBCO cable and NbTi wire can worsen the sensitivity, but quench can still be detected in ms.

- **For high field application**

Specifications of ReBCO cable and LTS quench detectors relevant to 15 T application

Wire Type	Materials ratio	Geometry	Ic at 4.2 K and 15 T	Tcs with Iop
ReBCO Cable	ReBCO: Cu: Hastelloy = 1:40:50	4 mm × 0.091 mm ×72	15900 A	~10.2 K for Iop=0.8 Ic
Nb_3Sn detector	Nb_3Sn: Cu = 1:0.33	Φ 0.4 mm	44 A	~11 K for Iop=1 A
Nb_3Al detector	Nb_3Al: Cu = 1:1.5	Φ 0.507 mm	133.4 A	~9.9 K for Iop=1 A
MgB_2 detector	MgB_2: Cu = 1:6.63	Φ 0.83 mm	4.4 A	~10.2 K for Iop= 1A



➢ As expected, voltages in three LTS detectors all increase rapidly at Tcs.

➢ Losing 80% Ic, Nb3Sn can still work fine as quench detector.

➢ The voltages in Nb_3Al or MgB_2 wire should be much higher in real case, since their matrix are usually Nb or Monel, both of which have much higher resistivity than Cu. For $Nb3_3Sn$, higher voltage can be achieved by removing Cu.

Outlook

- Detecting quench in HTS magnets with LTS wires seems a promising approach to release the challenge of quench protection of a HTS magnet. This is especially true fore accelerator magnets with high conductor current density.
- Next, we will try to find or make proper LTS quench detectors and test this ideas at our HTS insert coil. Many technical problems are expected, like installation of reacted and insulated wires with good thermal conduction to the HTS coil.