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Quench Propagation and Degradation limits of Pre-strained HTS Tapes triggered by a spot heater

Xingzhe Wang

Cooperation： ***Yujing Tong, H. Du, J. Chen, H. Qin***

Key Lab. Mechanics on Western Disas. Envir., MoE

College of Civil Engineering and Mechanic

Lanzhou University, China

Outlines

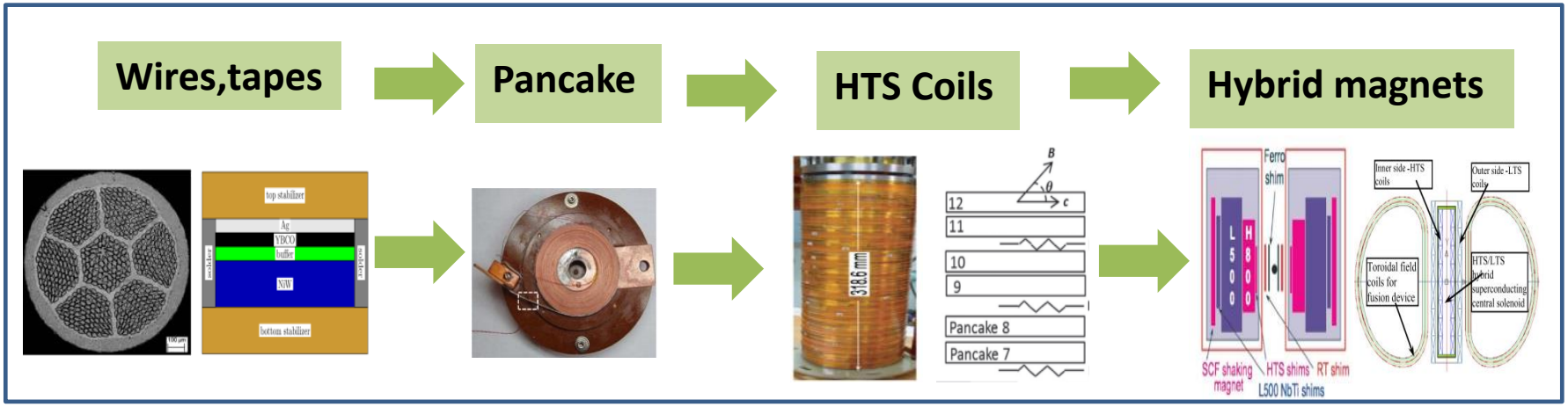
- **Background and motivation**
- **Experiment study**
  - ***Quench behaviors in pre-strained HTS tapes***
  - ***Quench degradation limits of pre-strained HTS tapes***
- **Theoretical predictions & results**
- **Conclusion**

Background and motivation

- Advantages of HTS

HTS { ■ Higher T_c, Better stability
■ Higher I_c in high field (>18T) } > LTS

- Applications



- ✓ Coat conductor
- ✓ Fault current limiter (FCL)
- ✓ High field supercondcutor magnets (> 23T)

Hideaki Maeda et al, IEEE trans. AS.2014. Yukikazu Iwasa et al, IEEE AS.2015.
M Breschi SuST.2016 J. X. Zheng et al, IEEE AS.2016

Background and motivation

- Remained problems

- ☐ Low temperature
- ☐ High operation current
- ☐ High magnetic field

Operation faults

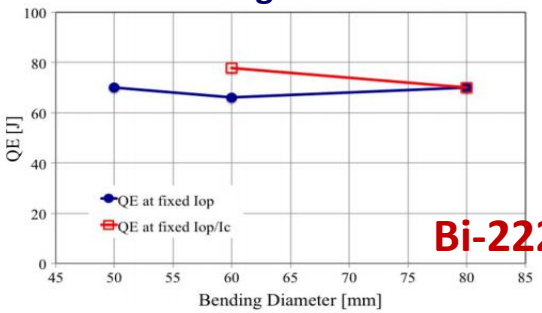
Quench ?

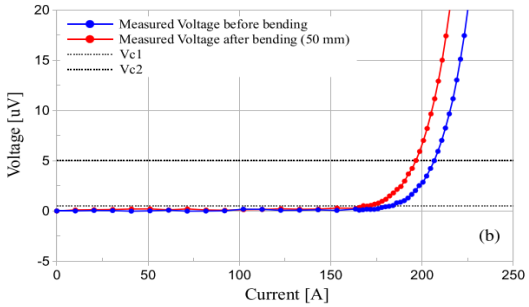
- Slow NZPV (quench propagation velocity) [e.g, ~mm/s, cm/s]

Complex stress state (thermal stress/strain, Lorentz force, etc.)

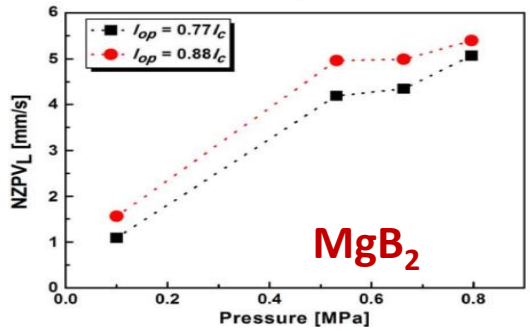
- Quench induced degradation [local overheat]

Bending deformation





Marco Breschi, et al , IEEE (2016)



Kim, K. L. et al, IEEE (2012)

Background and motivation

- Remained problems

- ☐ Low temperature
- ☐ High operation current
- ☐ High magnetic field

Operation faults

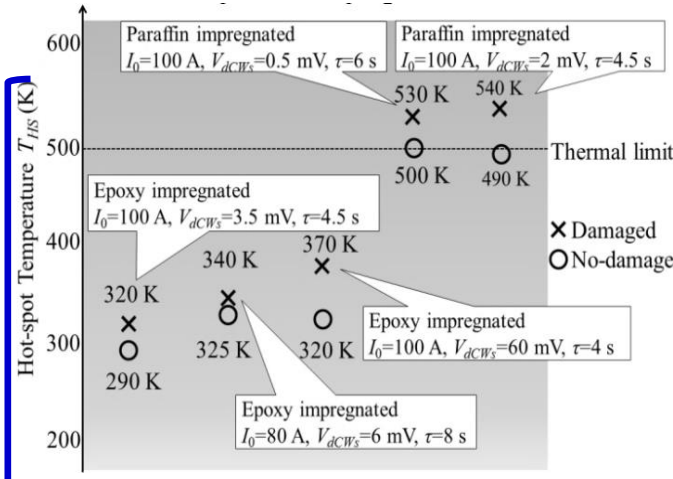
Quench ?

- Slow NZPV (quench propagation velocity) [e.g, ~mm/s, cm/s]

Complex stress state (thermal stress/strain, Lorentz force, etc.)

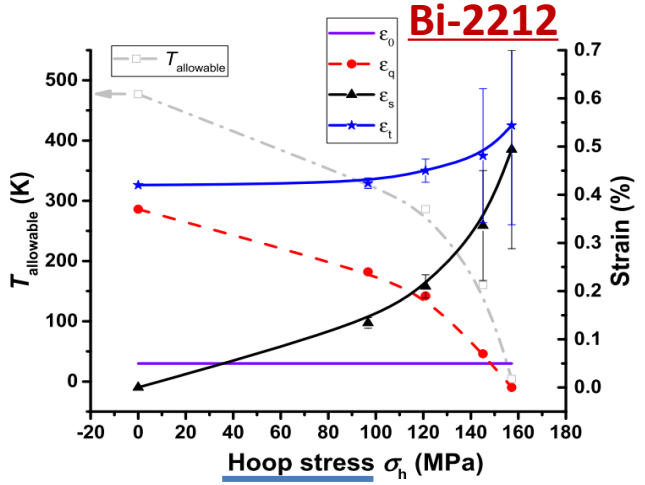
- Quench induced degradation [local overheat]

YBCO



T. Ariyama . et al, IEEE (2017)

Bi-2212

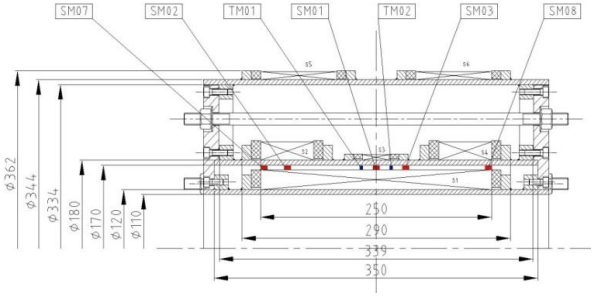


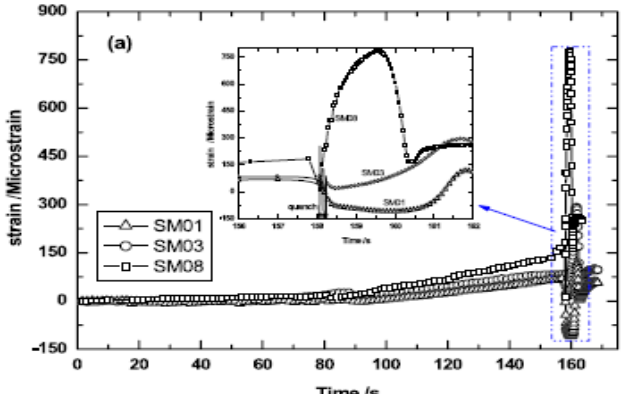
Liyang Ye. et al, SuST (2017)

Background and motivation

- Quench ⇔ Strain/Stress

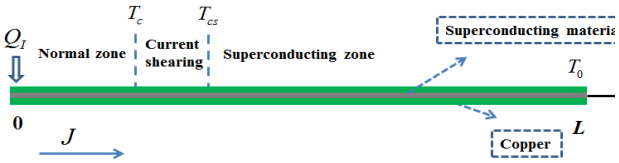
NbTi Magnet



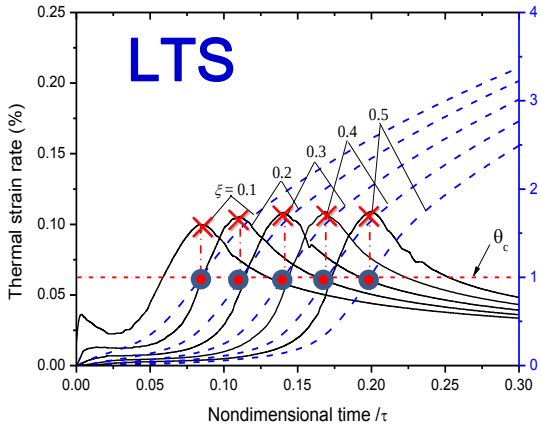


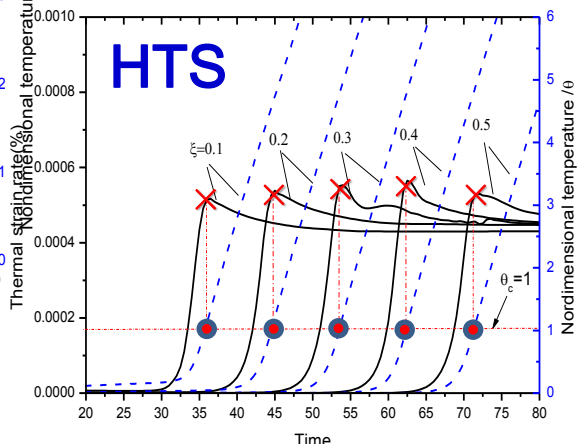
X. Wang, M. Guan, et al. SuST (2012)

➢ **A theoretical study** ***on thermoelastic strain responds when a quench*** **occurs**



$$\begin{cases} \rho c(T)\left(\frac{\partial T}{\partial t}+t_0\frac{\partial^2 T}{\partial t^2}\right)=\frac{\partial}{\partial x}\left[(k(T)\frac{\partial}{\partial x}\right]T+Q_J-\beta_0\frac{\partial^2 u}{\partial x\partial t}+t_0\frac{\partial}{\partial t}(Q_J \\ \rho\frac{\partial^2 u}{\partial t^2}=(\lambda+2\mu)\frac{\partial^2 u}{\partial x^2}-\beta_0\frac{\partial T}{\partial x} \end{cases}$$





Y. Tong, M. Guan, X. Wang, SuST (2017)

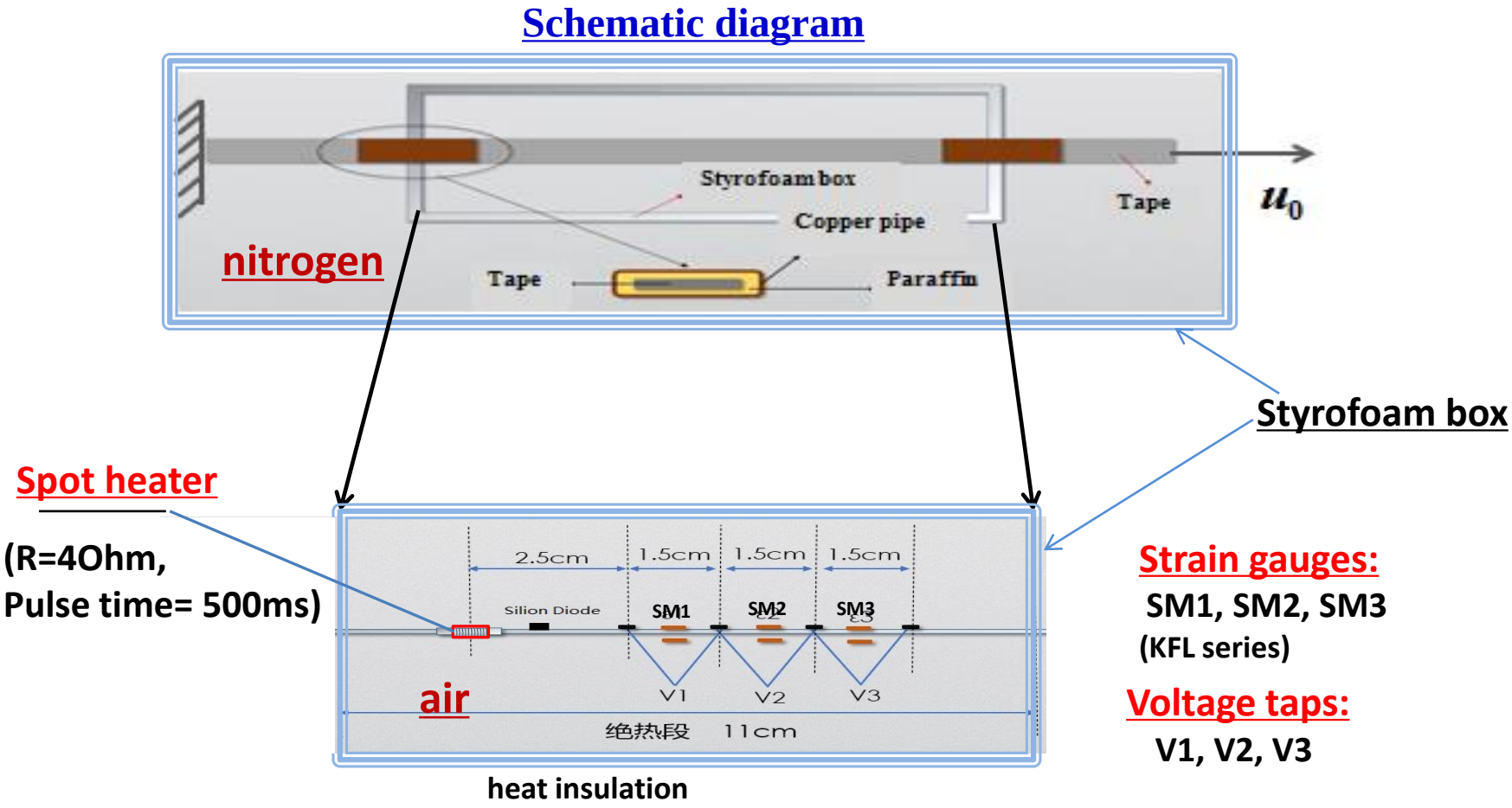
Motivation:

- A strain/stress station for a HTS structure
  ——***Pre-strain*** (simple case)
- A simple HTS structure —— ***Tape (YBCO, Bi-2223)***

- ***How about the pre-strain influence on the quench for a HTS tape triggered by a spot heater?***
- ***Is there any change on the quench induced degradation for the pre-strained tape?***

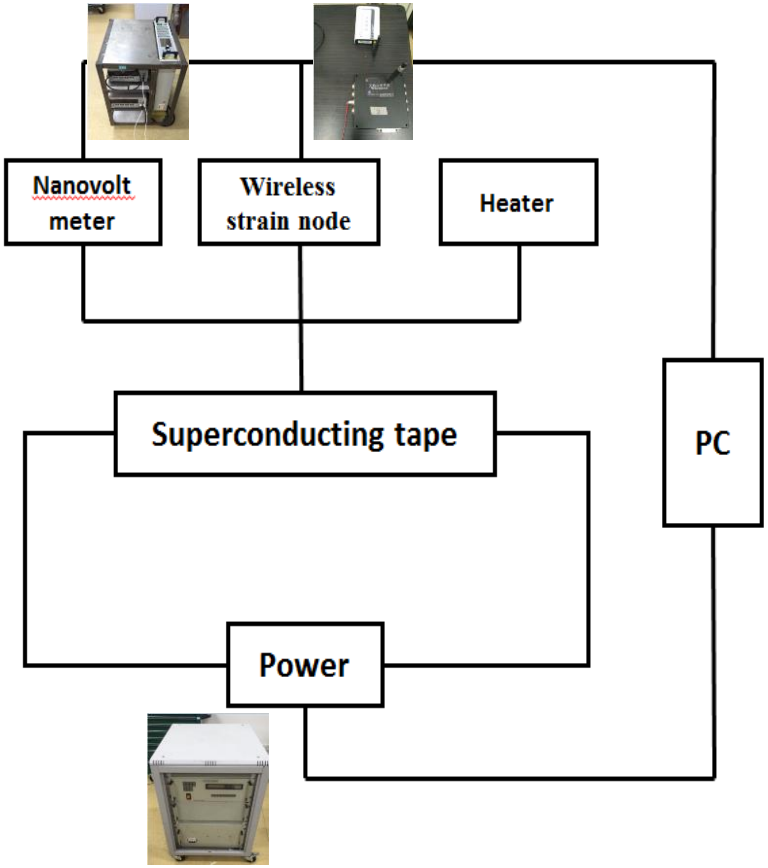
Quench propagation behaviors in pre-strained HTS tapes

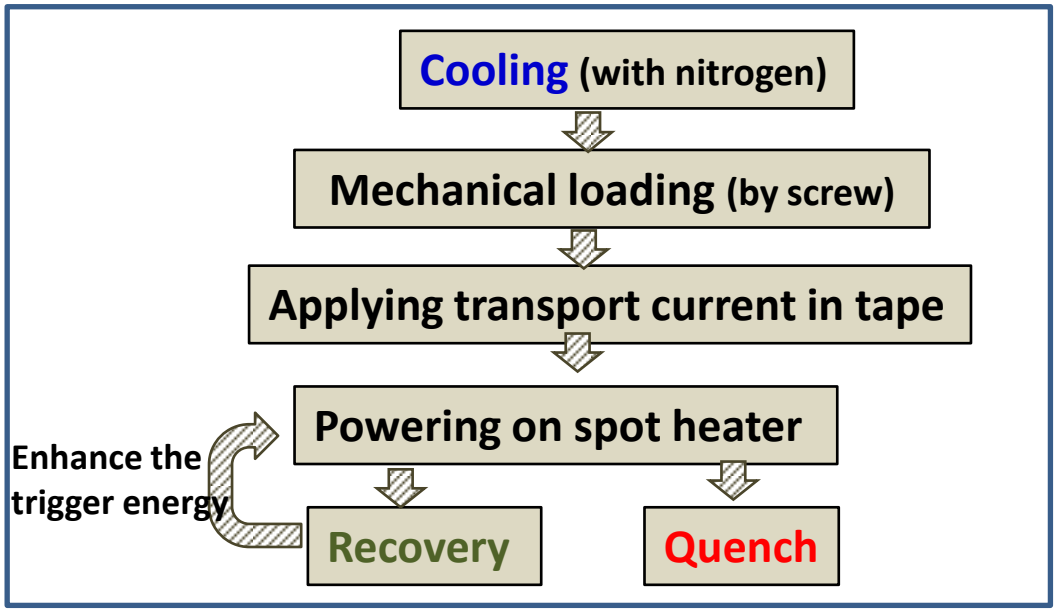
- Experimental setup



Quench propag. behaviors in pre-strained HTS tapes

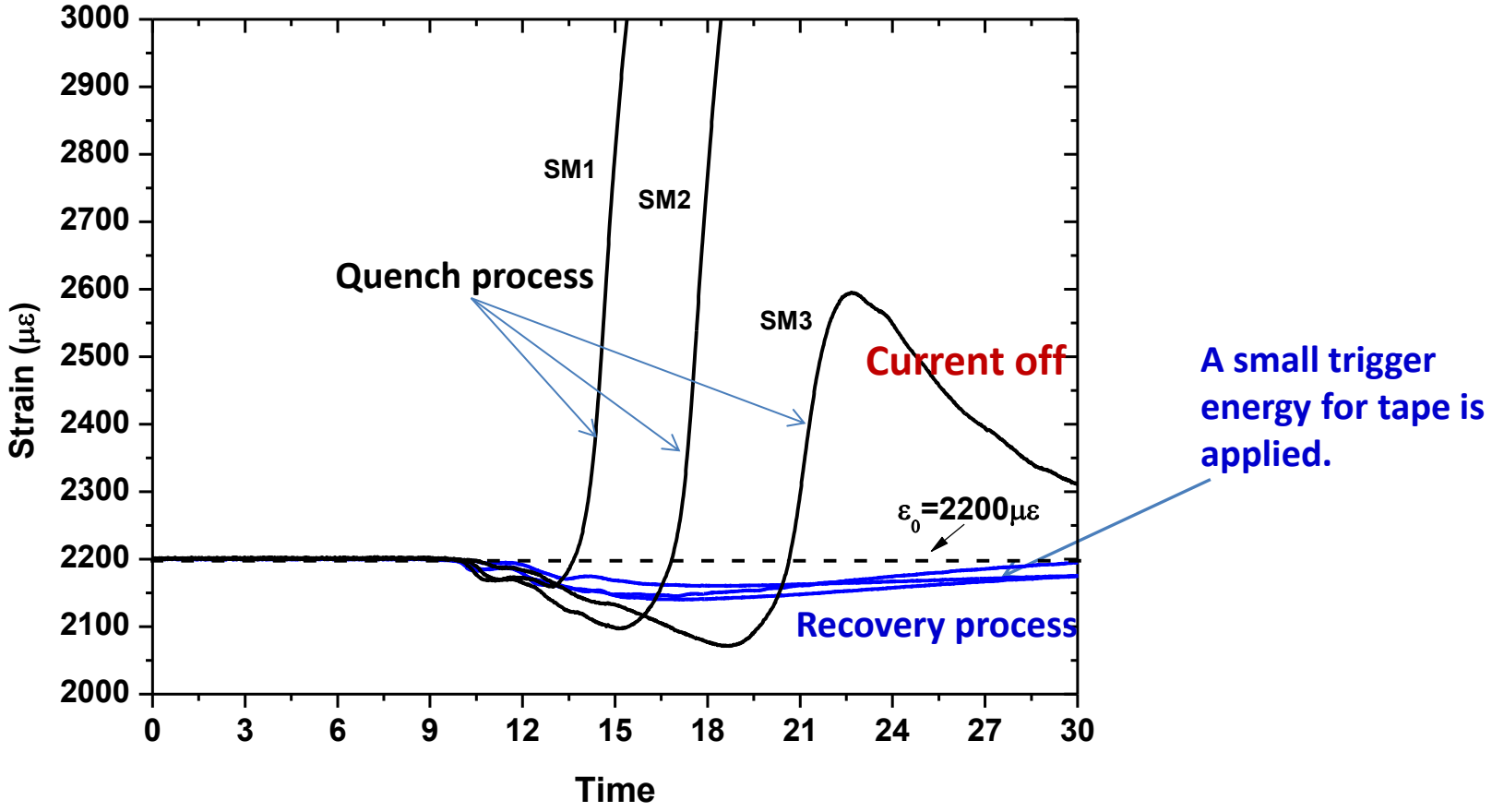
- Experimental detail and procedure





Quench propag. behaviors in pre-strained HTS tapes

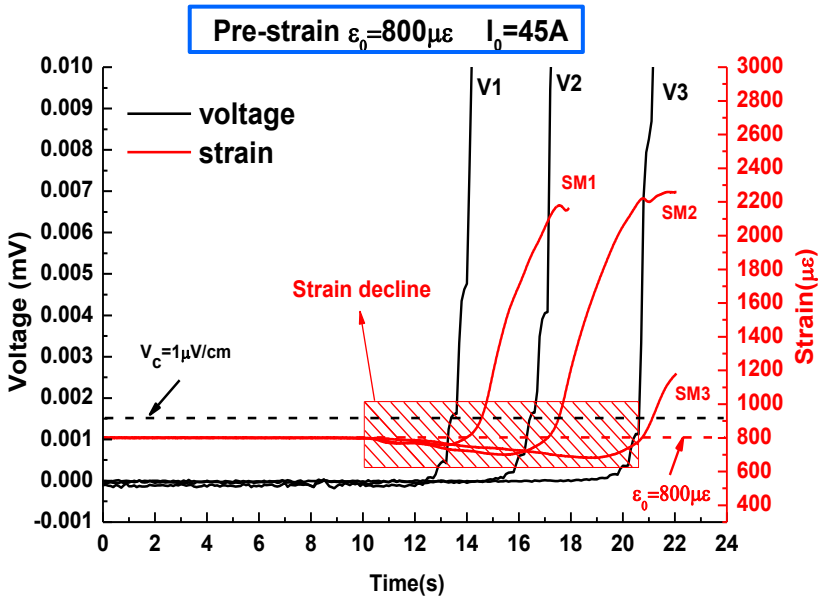
- The distinguish between quench and recovery process

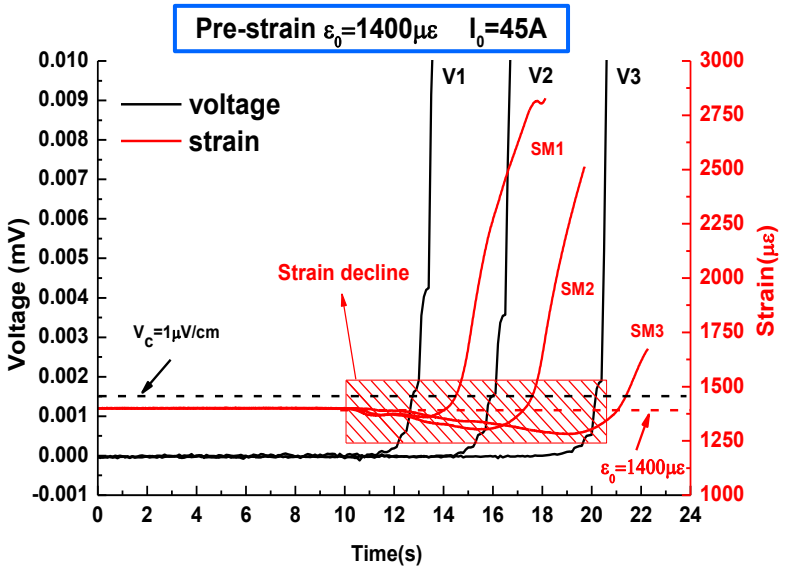


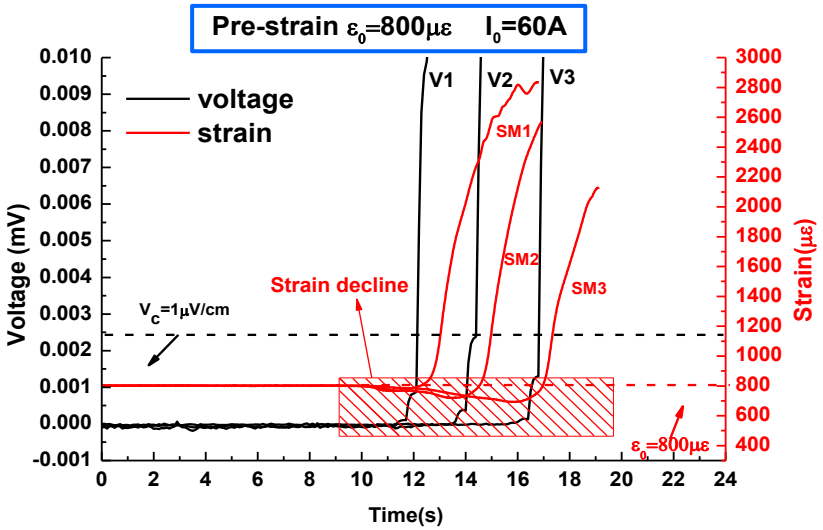
- ✓ In the case of a recovery process (no quench), the strains recorded by three gauges show small declines and then increases with a small value.
- ✓ In the case of a quench process, the strains have obvious declines and then increase quickly to larger values due to the temperature rising and quench propagation.

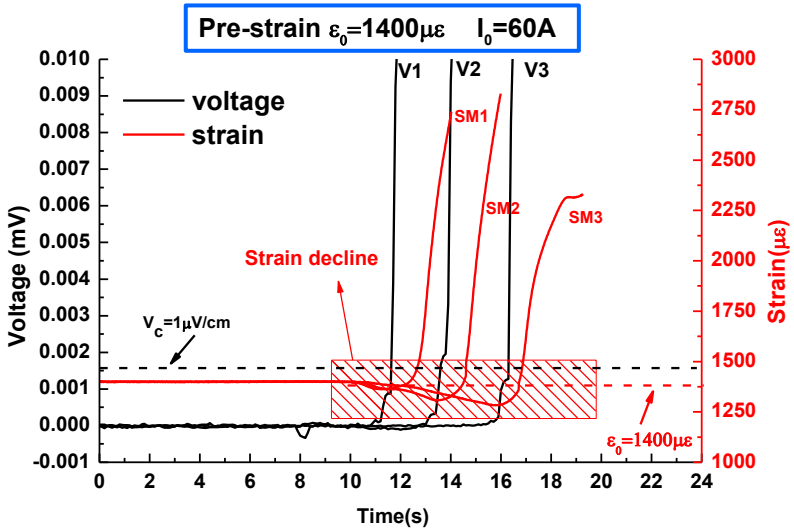
Quench propag. behaviors in pre-strained HTS tapes

- Voltage and strain behaviors during quench





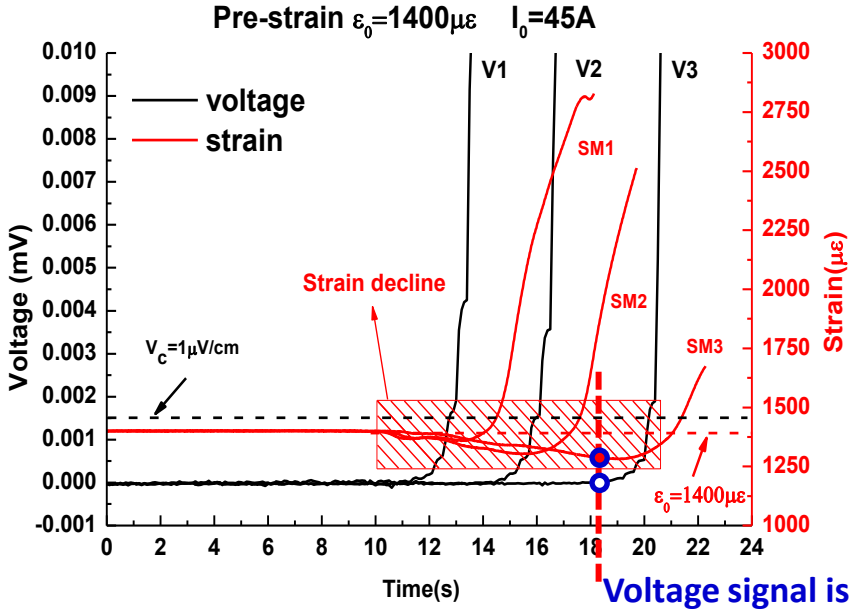




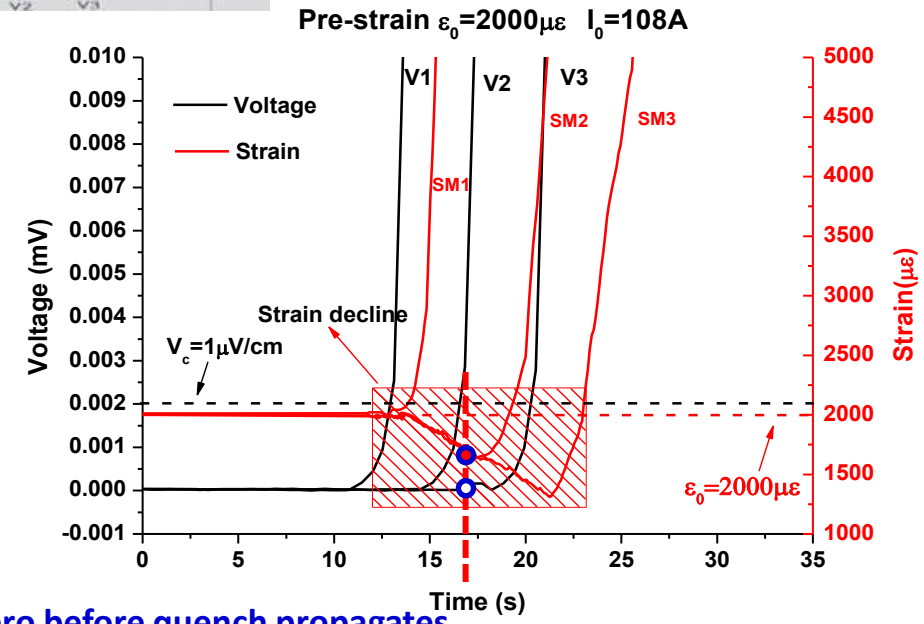
Quench propag. behaviors in pre-strained HTS tapes

- Voltage and strain behaviors during quench

YBCO



Bi-2223

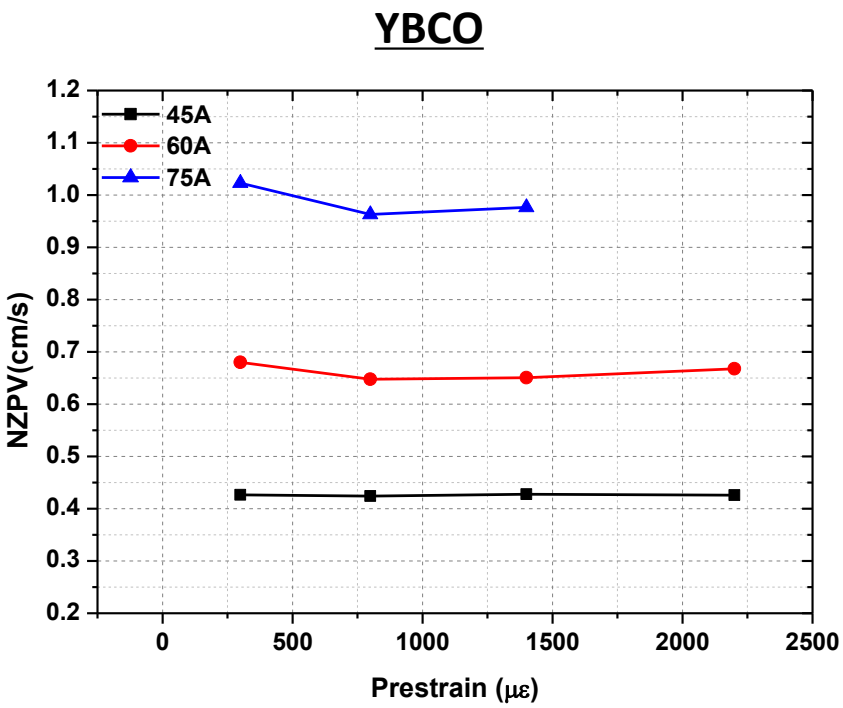


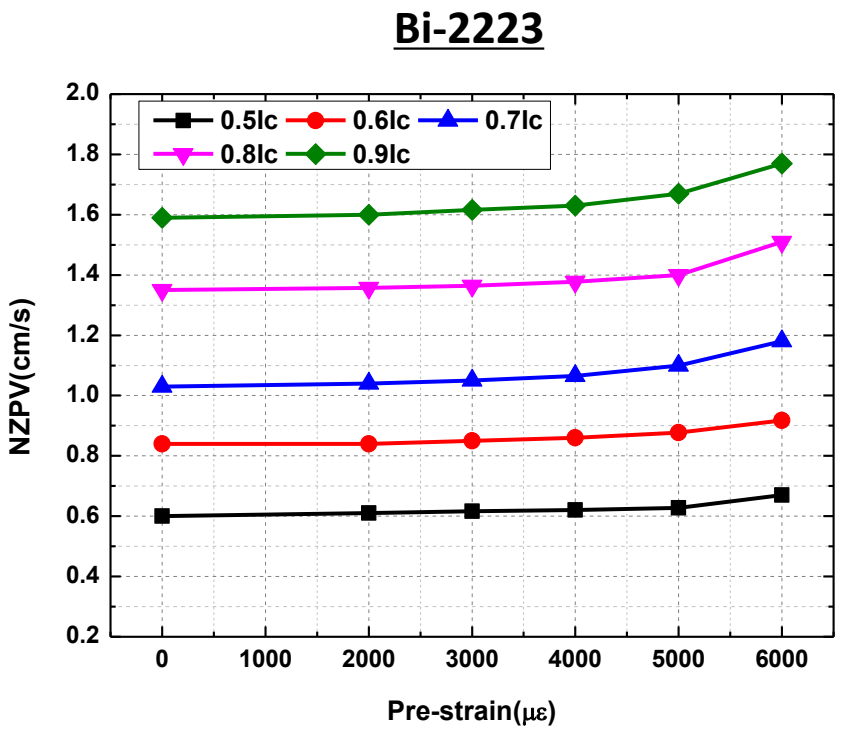
Voltage signal is zero before quench propagates this point detected by voltage probes.

- ✓ **There shows a quick and large voltage increase while the strain decreases firstly and then increases quickly to a large value. ——*the quench can observed by voltage signals, also by strain changes.***
- ✓ **An import observation: at a point far away from the spot heater, before the quench propagates to this point, the voltage signal is always zero, however, an obvious strain decline can be measured *(with a quite larger values than the one for a recovery case)*.**

Quench propag. behaviors in pre-strained HTS tapes

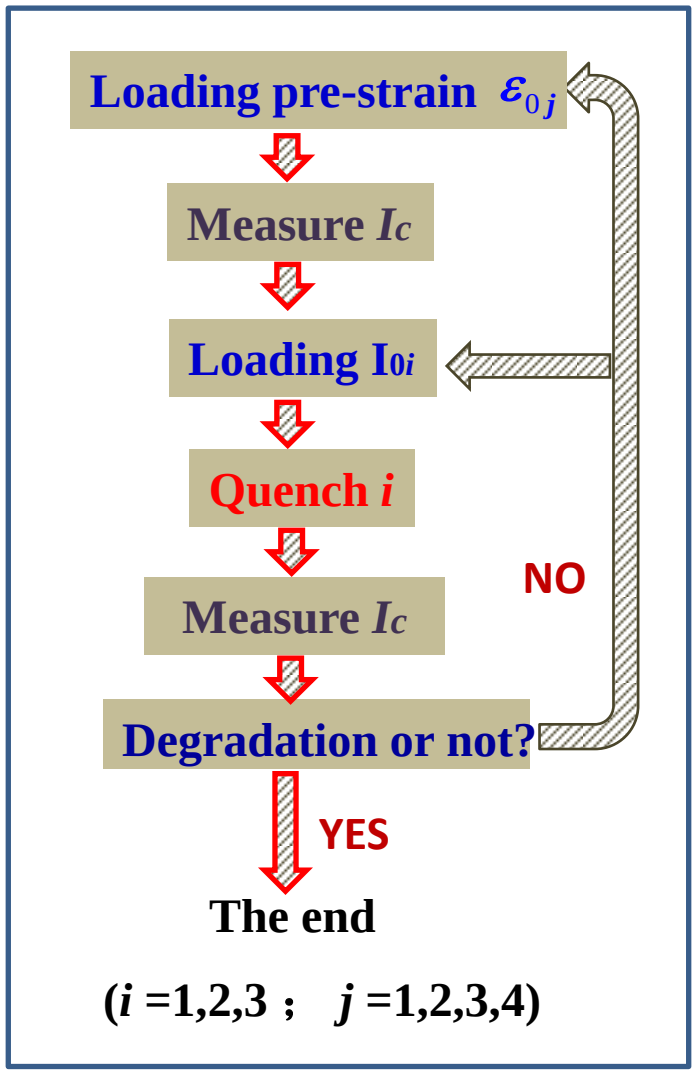
- The normal zone propagation velocity



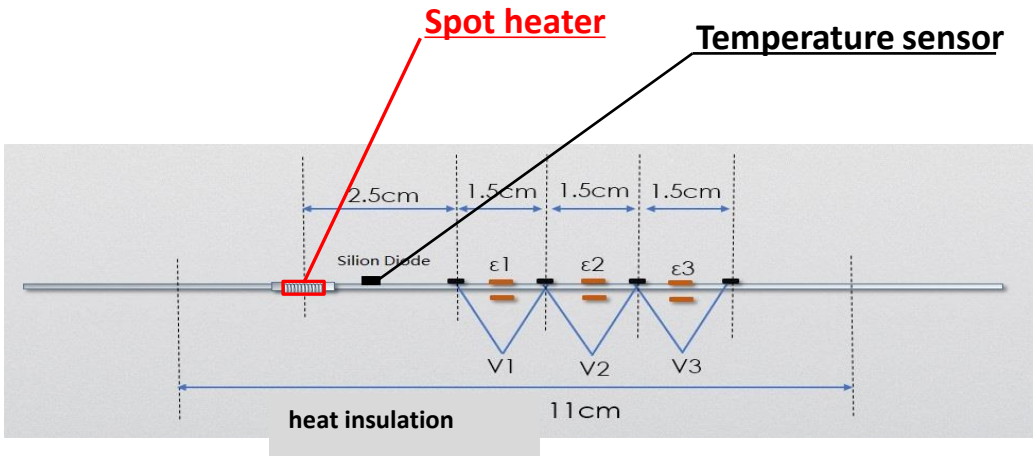


Quench degradation limits of pre-strained HTS tapes

- Experimental setup and procedure



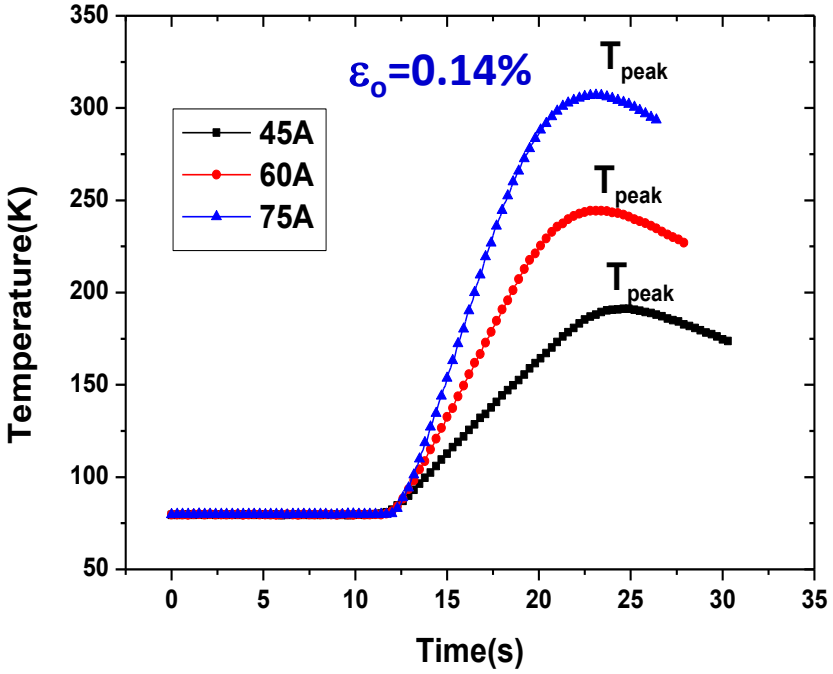
Measurement schematic diagram

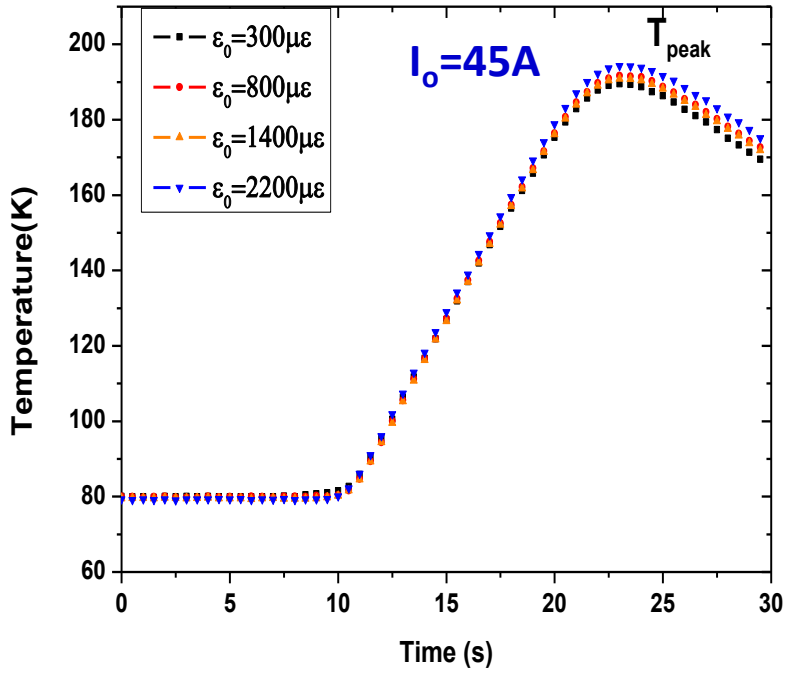


A temperature sensor (*silicon diode, fastest thermal response time*) is placed near the spot heater and used for measurement of the maximum temperature in the quench area of the HTS tape.

Quench degradation limits of pre-strained HTS tapes

- The hot spot temperature evolution under different transport currents and pre-strains

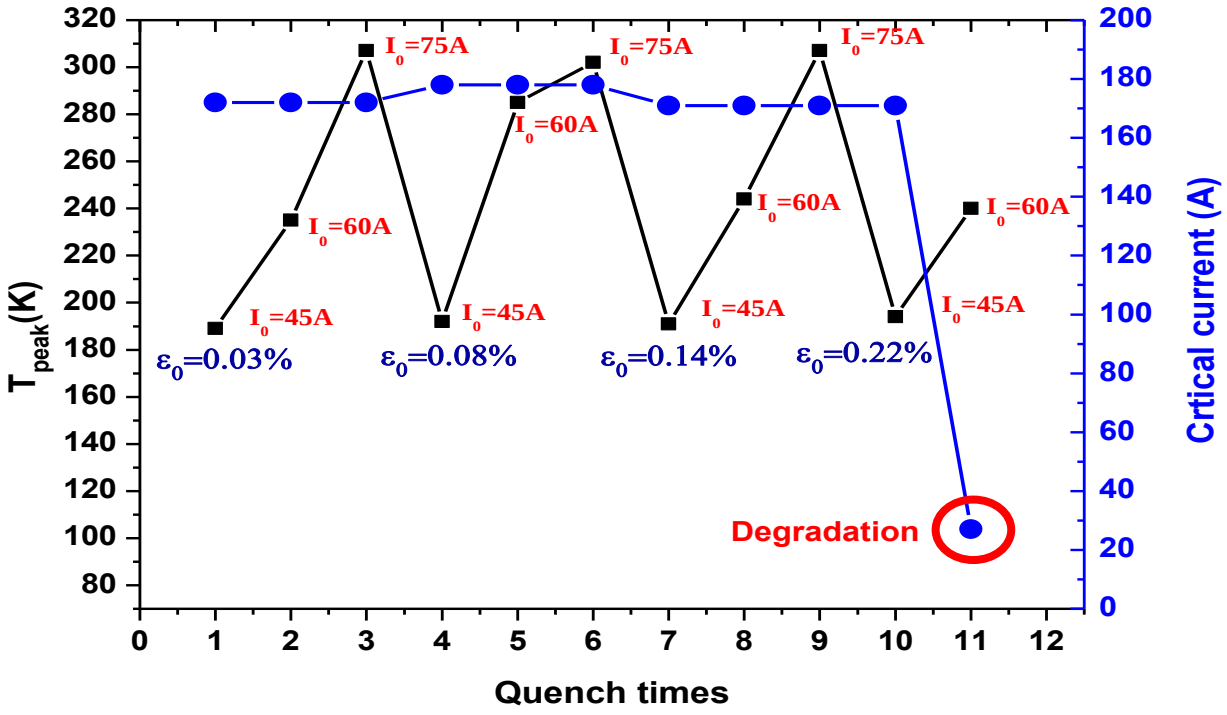




✓ T_{peak} at the hot spot in quench area increases with the transport currents in the tape, while it shows little increase with different pre-strains.

Quench degradation limits of pre-strained HTS tapes

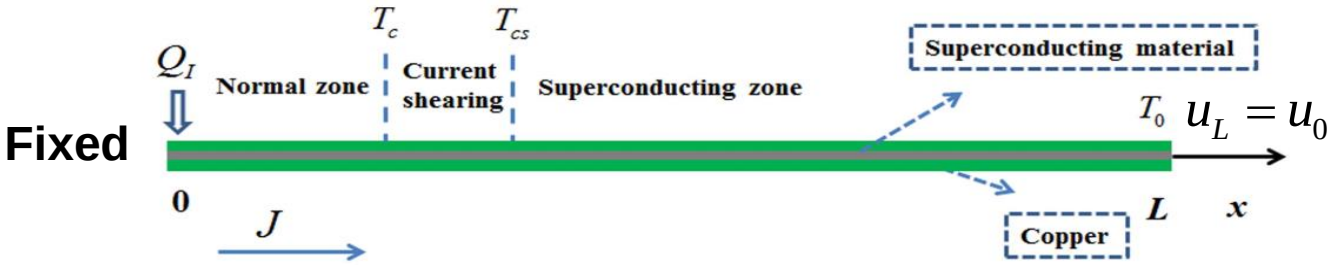
- The hot spot temperature and critical current in a quench cycle test



- ✓ **The quench degradation doesn't occur until 11 cycle quench tests as applied pre-strain is above 0.22%, the critical current in reduced from 178A to 25A.**
- ✓ **The degradation maybe causes mainly by the decrease of critical current of the pre-strained HTS tape .**

Thermoelastic strain responds during a quench

- Theoretical model and fundamental formulas



Heat conduction equation

$$\rho c(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left((k(T)\frac{\partial}{\partial x})T + Q_J\right.$$

Wave equation

$$\rho\frac{\partial^2 u}{\partial t^2} = (\lambda + 2\mu)\frac{\partial^2 u}{\partial x^2} - \beta\frac{\partial T}{\partial x}$$

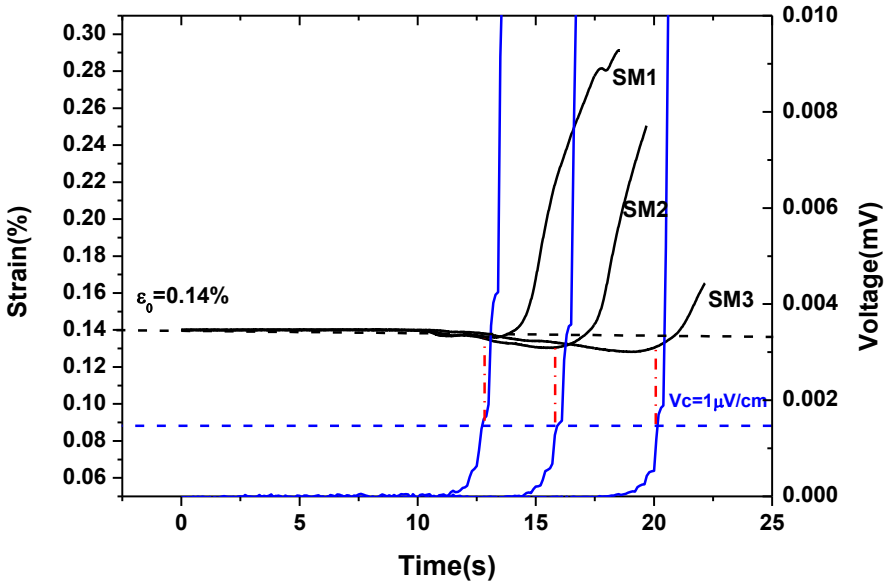
$$\begin{bmatrix} \mathbf{M}_{mm} & \mathbf{0} \\ \mathbf{M}_{Tm} & \mathbf{M}_{TT} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}^{(e)} \\ \ddot{\mathbf{T}}^{(e)} \end{Bmatrix} + \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{C}_{Tm} & \mathbf{C}_{TT} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{u}}^{(e)} \\ \dot{\mathbf{T}}^{(e)} \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_{mm} & -\mathbf{K}_{mT} \\ \mathbf{0} & \mathbf{K}_{TT} \end{bmatrix} \begin{Bmatrix} \mathbf{u}^{(e)} \\ \mathbf{T}^{(e)} \end{Bmatrix} = \begin{Bmatrix} \mathbf{Q}_m^{(e)} \\ -\mathbf{Q}_T^{(e)} \end{Bmatrix}$$

Comsol_PDE module

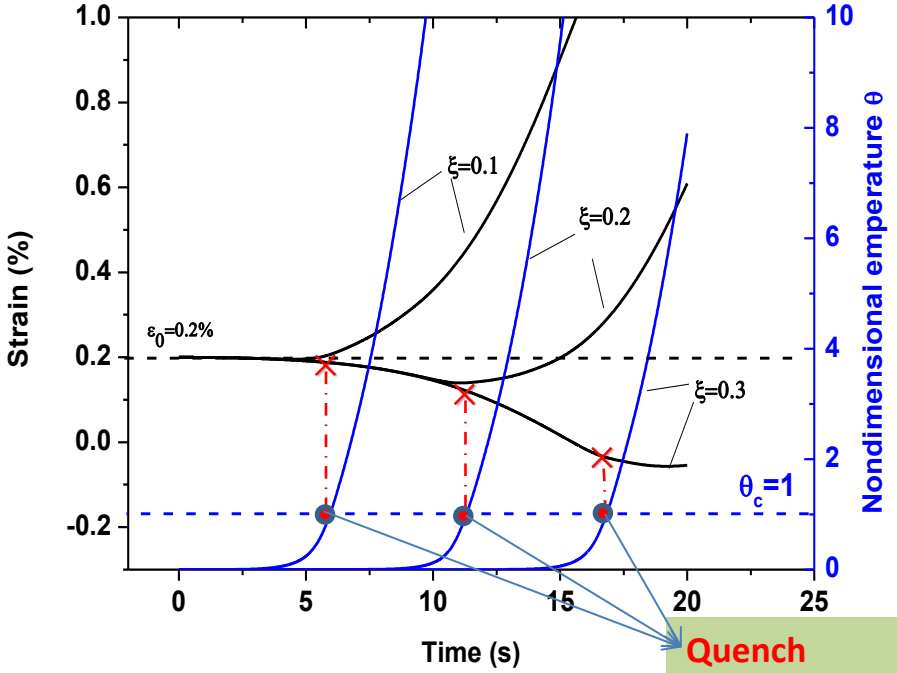
Thermoelastic strain responds during a quench

- The strain decline behaviors during quench

Experimental oberservation (YBCO)



Numerical results (YBCO)

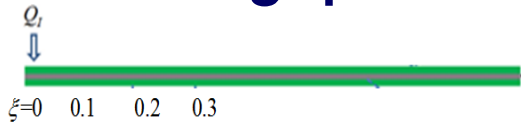


Quench determined by critical temperature θ_c=1.

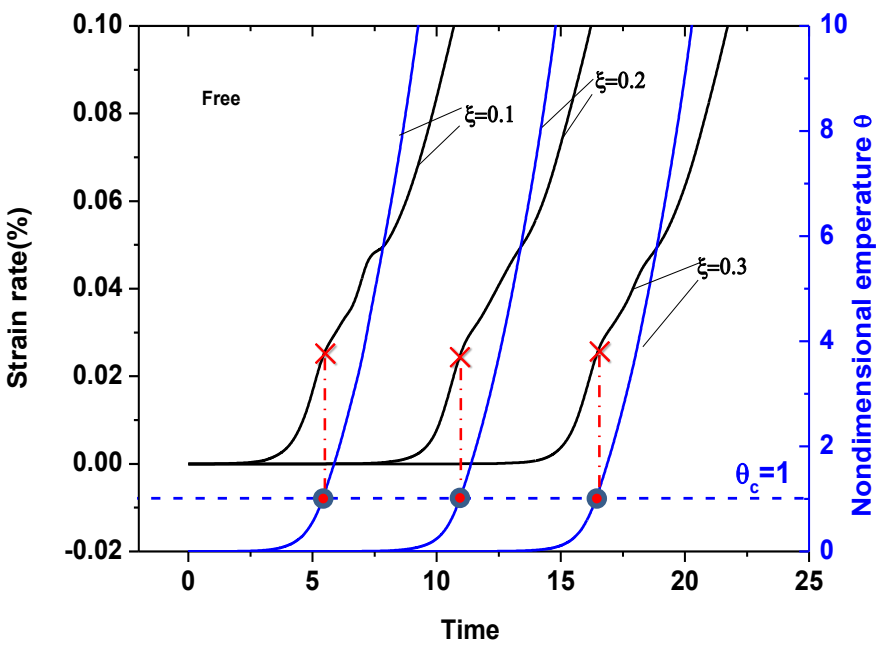
✓ **Numerical results show the similar predictions on strains in the HTS tape as the ones of experiment: occur decline behaviors during quench propagation, which agrees with the experimental results qualitatively.**

Thermoelastic strain responds during a quench

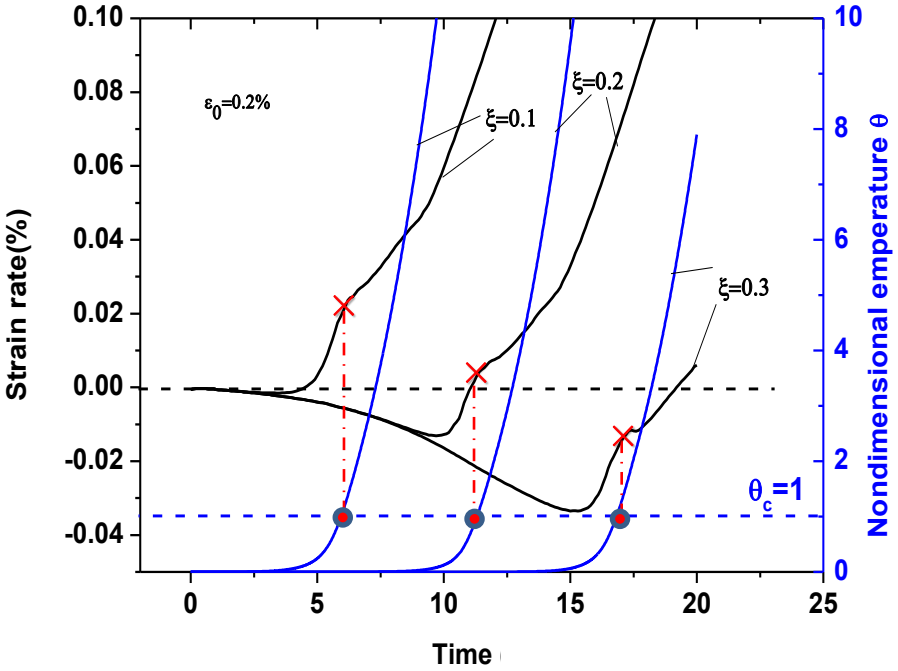
- The strain-rate behaviors during quench



Free-strain *(One end of the tape is free)*



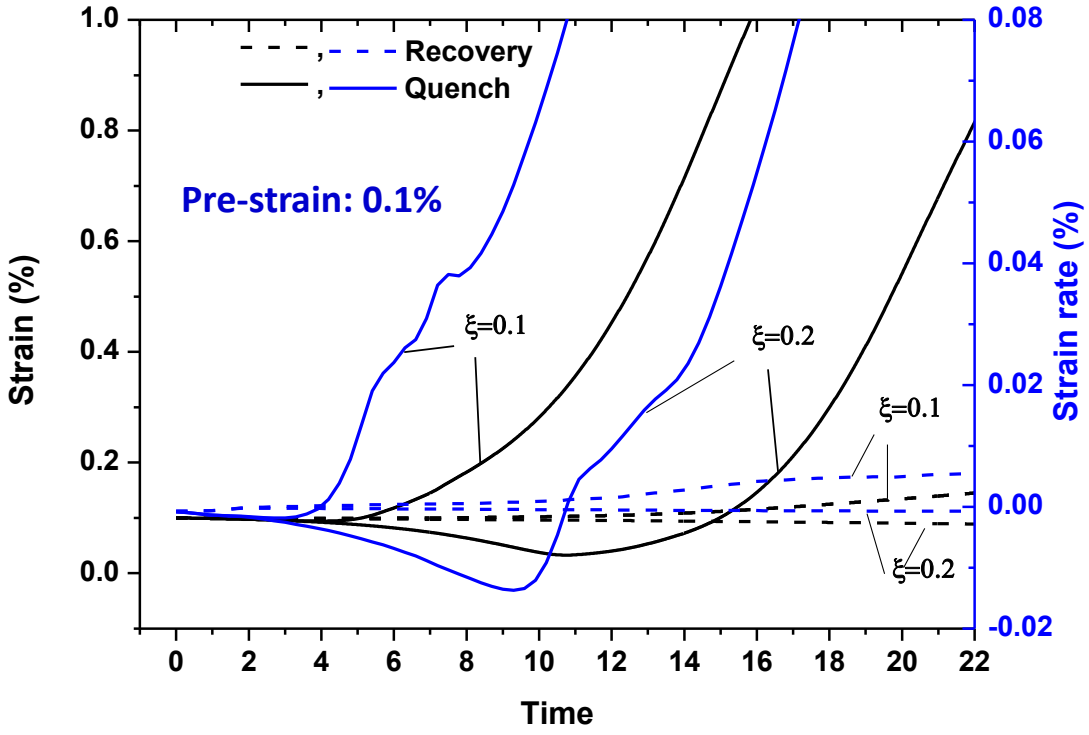
Pre-strain 0.2%



- ✓ **Compared to the strain behaviors, when a quench occurs, the strain-rate shows a little visible change with its slope (at this moment the strain being in a decline stage).**
- ✓ **Compared to the case of free-strain, the quench occurs at the slope change of strain-rate for the pre-strained tape as the strain-rate being in an increase stage.**

Thermoelastic strain responds during a quench

- The distinguish between quench and recovery



- ✓ **Numerical predictions on the quench and recovery process for a HTS tape with pre-strain 0.1% qualitatively agree with experiment observations.**
- ✓ **The strain or strain-rate shows obvious increase as a quench occurs, while they are in a small value change as a recovery process.**

Conclusion

- An experiment study was conducted for a pre-strained HTS tape to investigate its strain behaviors during a quench process. Compared to the strain feature for a recovery process, for a quench trigged by a spot heater, the strain firstly obviously declines and then increases quickly even for the region where the quench propagation does not reach.
- For a YBCO tape, the pre-strain has not obviously influence on the NZPV while the operation current in the tape always does; a high pre-strain will make a quench degradation. For the Bi-2223 tape, the pre-strain enhances the NZPV lightly.
- At a point far away from the spot heater, before the quench propagates to this point, the voltage signal is always zero, however, an obvious strain decline can be measured.——*It may be a possible way to propose an "early warning" for a quench with strain observation.*
- A theoretical prediction gives some features on the strain and strain-rate for the pre-strained HTS tape during a quench, which qualitatively agrees with experimental measurements.

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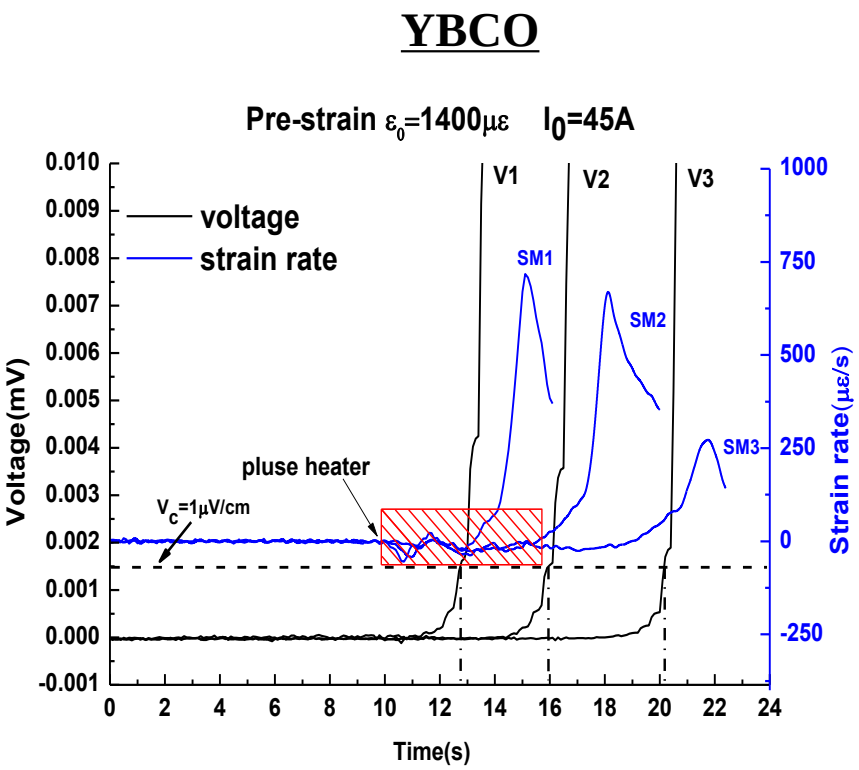
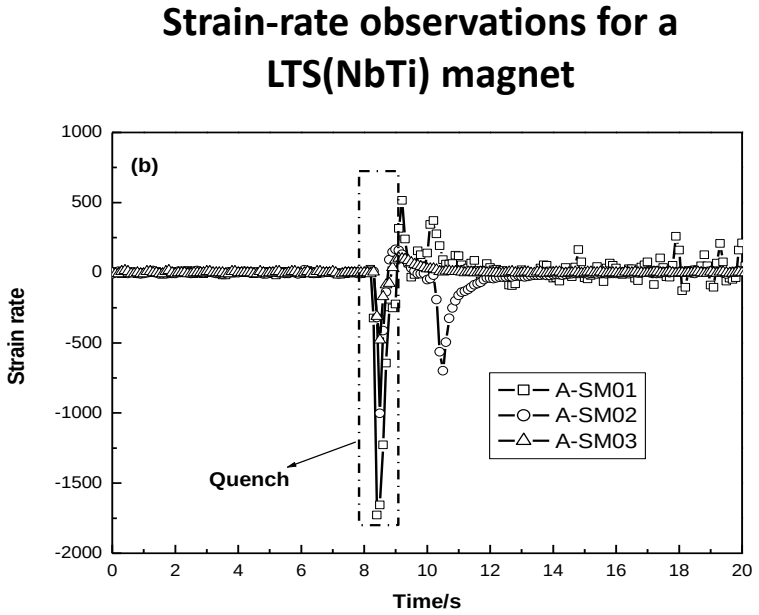
Thanks for
your
attentions !
積 石 堂

Quench propaga. behaviors in pre-strained HTS tapes

- Strain rate behaviors during a quench





✓ The strain-rates during a quench occurs have been presented, which show some obvious changes as the strains. The regular results are not clear compared to the one for a LTS magnet.