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Dynamic strain characteristics and responds in a LTS sextupole magnet during excitation and spontaneous quench

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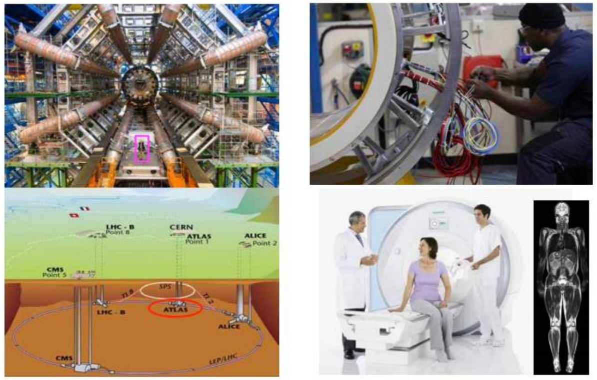
Outline

- Introduction
- Experimental detail
- Observation results and discussions
- Conclusion

Introduction

- Currently, HTS/LTS magnets are emerging as the smart candidate for engineering applications at high magnetic fields and particle accelerators community.

Magnet Engineer's



High Energy Physics

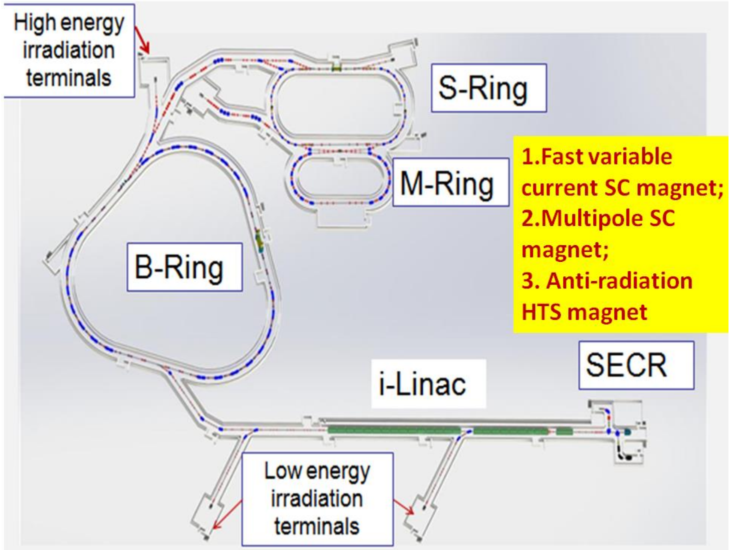
MRI Magnet

Adrian Thomas, Siemens

Gurt Mulder, Philips

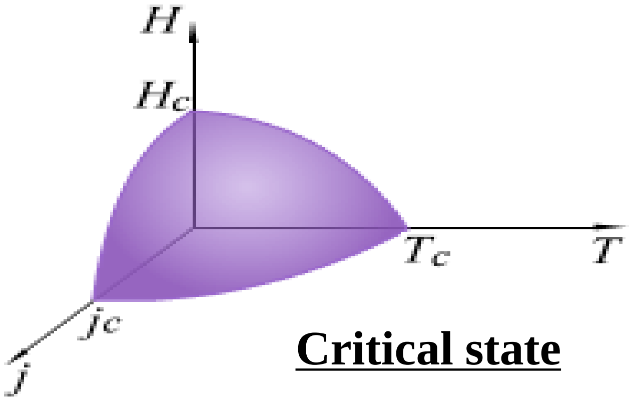
- For example, at IMP/CAS, a Heavy Ion Advanced Research Facility (HIAF), is being constructed.

In HIAF, many kinds of SC magnets will be included: from the ECR ion source, injector superconducting LINAC to boster storage ring.



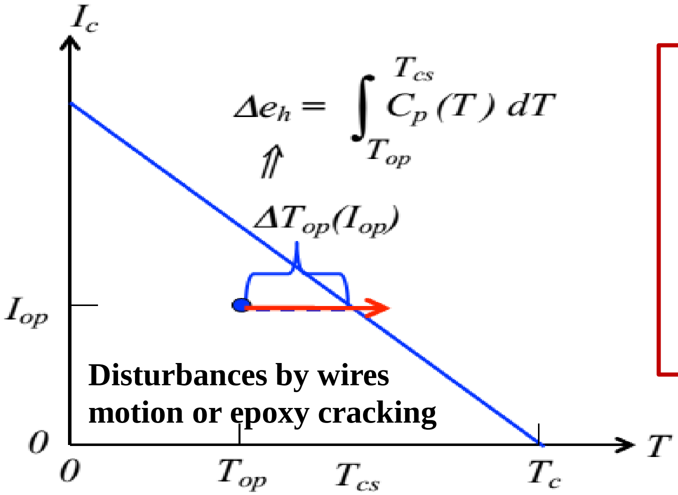
1.Fast variable current SC magnet;
2.Multipole SC magnet;
3. Anti-radiation HTS magnet

- **Superconductor is confined by magnetic field, temperature, and current. Beyond one of such critical values, a quench will appear unavoidably.**



Critical state

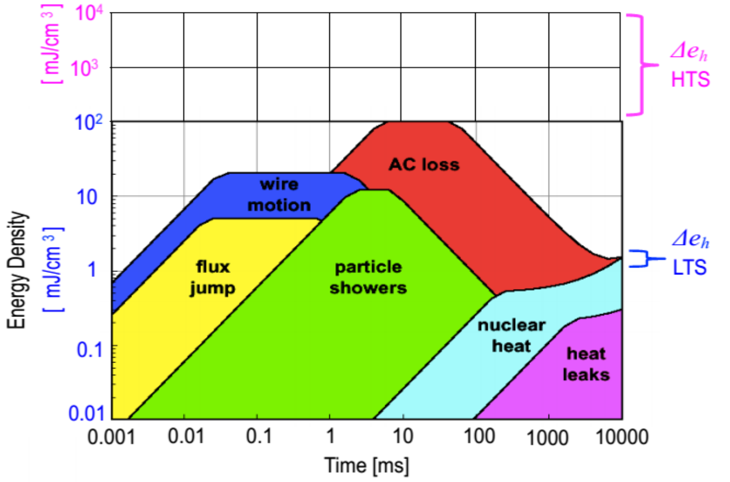
- **During a quench, however, the temperature inside the superconductor can not remain constant during a excitation, this is because that disturbances such as wires motion or epoxy cracking can upset the thermal equilibrium, particularly of LTS magnets.**



Disturbances by wires motion or epoxy cracking

Energy by wires motion is the major cause for premature quench of LTS magnets.

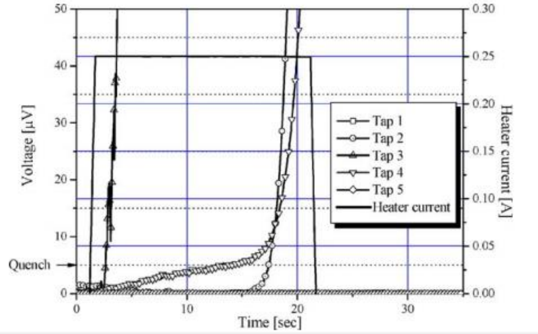
Energy Density Spectra*(Yuki Iwasa's PPT)*



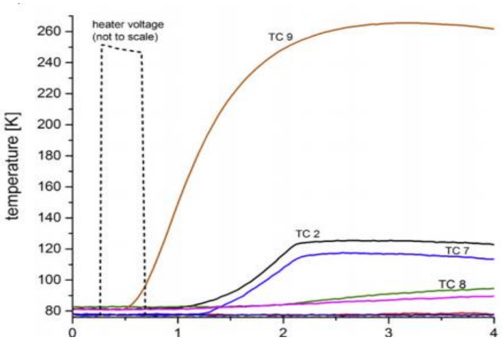
◆ **Furthermore, many works reveal that most mature quench detection methods were developed and applied based on detected mutation signals during a instaneous quenching.**

A summary on quench detection methods

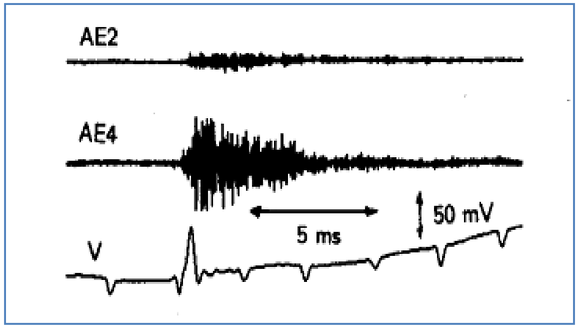
Method	Principle	Advantage	Disadvantage
the resistive voltage detection	instantaneous voltage/power	Principle is simple	electromagnetic noise
Temperature rise detection	Fast heat generation in the normal region	Intuitive	Complicated arrangement for sensors
acoustic emission	AE signals and voltage induced by a mechanical event	Non-contact	Qualitative
Pressure detection	Rapid Helium pressure	high threshold	Delayed detection
Flow rate	Helium gas flow rate	Little sensors	False alarm



Voltage signals during a quenching
(D.K. Bae et.al,2016)



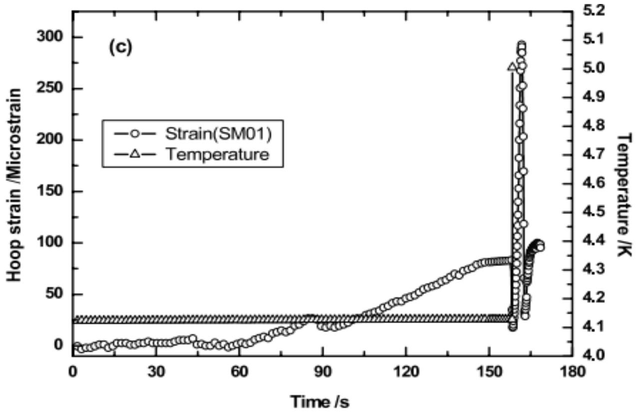
Temperature signals during a quenching
(F. Scurti et.al,2016)



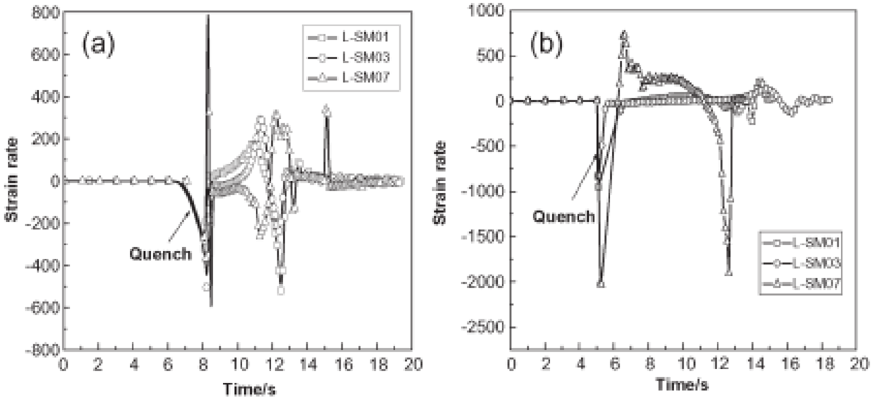
AE and voltage signals during a quenching
(O. Tsukamoto, M.F. Steinhoff, Y. Iwasa, 1981)

Common : These quench detection methods all indicate that a quenching process belong to obvious dynamic behaviors!

- **In 2012, based on strain measured during excitation of a LTS coil,we observe the notable abrupt strain (or strain rate) change during a quenching. Therefore, we also try to propose feasibility of strain-based quench detection.**
- **However, we only focused on quasi-static response on strain signals during a quenching due to the limitation of measurement technology and signal acquisition rate with high frequency.**



Observed notable abrupt strain during a quenching

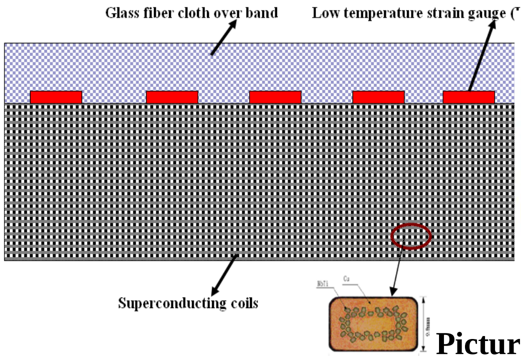


Observed notable abrupt strain rate during a quenching

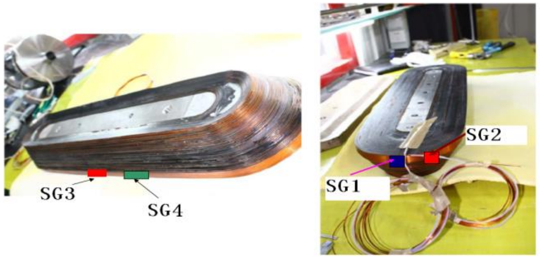
Since wires motion are the major cause for premature quench of LTS magnets, in this work, we will try to report in detail the dynamic strain responds and characteristic of a LTS coil during a quenching.

Experimental detail

- ✓ In our test, the strains are measured by using a half-bridge circuit composed of a cryogenic strain gauge and dummy one, they were all placed between the glass fibre cloth and the wires;

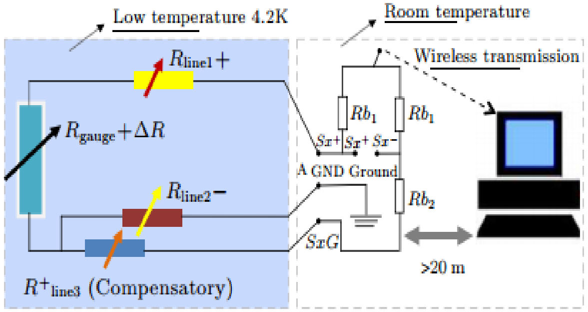


Schematic diagramof the magnet showing sensors laid within the glass fibre cloth

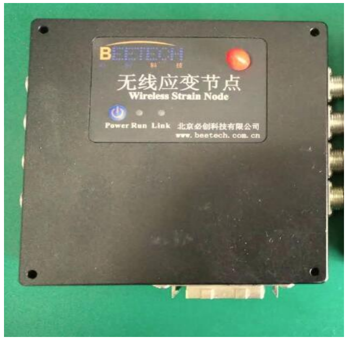


Picture of layout of the strain gauges sensors

- ✓ A fast wireless data acquisition system with a resolution of 1 ms was used to capture strains during the excitation, pre and post quench processes

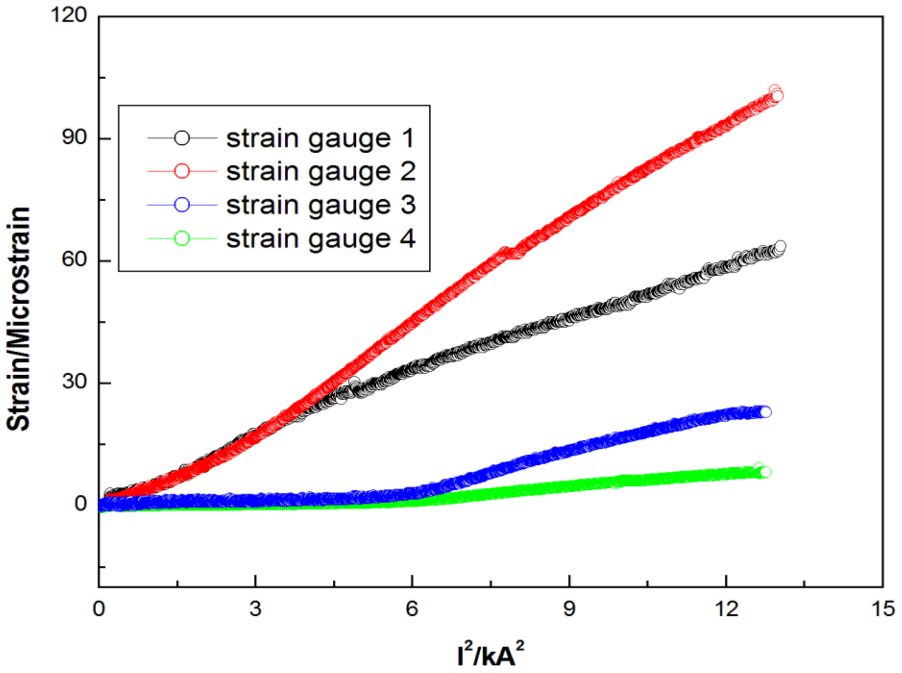


Circuit diagram for half-bridge strain measurement



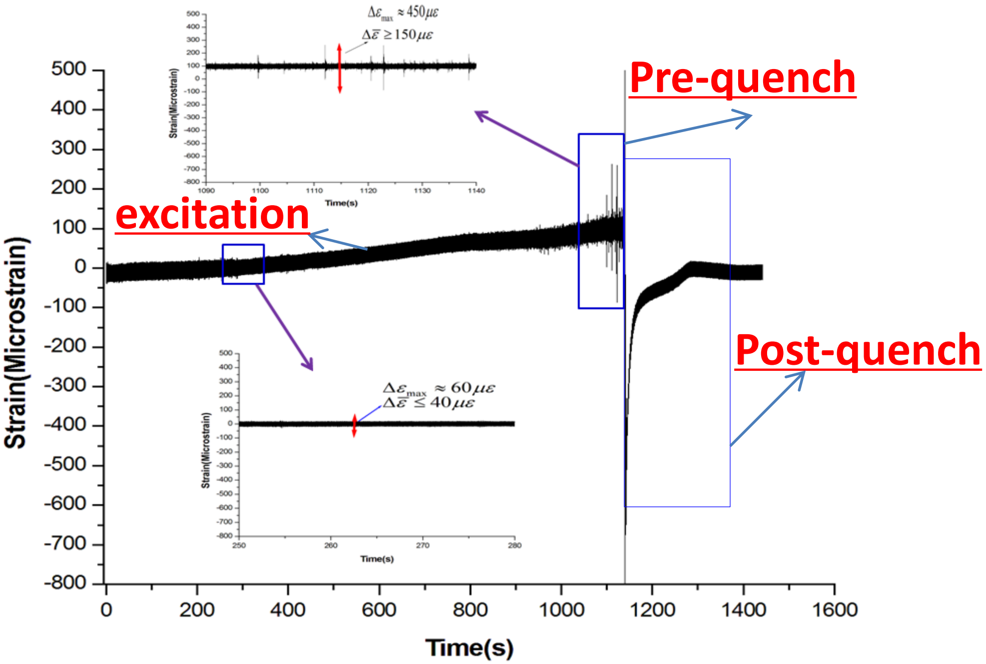
fast wireless data acquisition system

Observation results and discussions

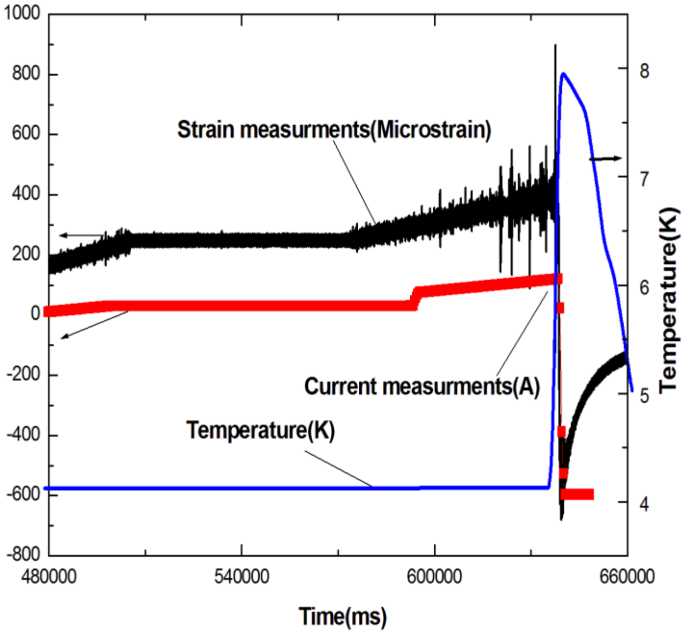


A typical strain–current-squared plot for four detection locations

The linear trend of the strain components as the current-squared is shown. The tested data show better agreements with traditional predictions. This can also confirm our strain measurment system.



<u>Measured strain signals(SG2) during the excitation, pre and post quench processes</u>

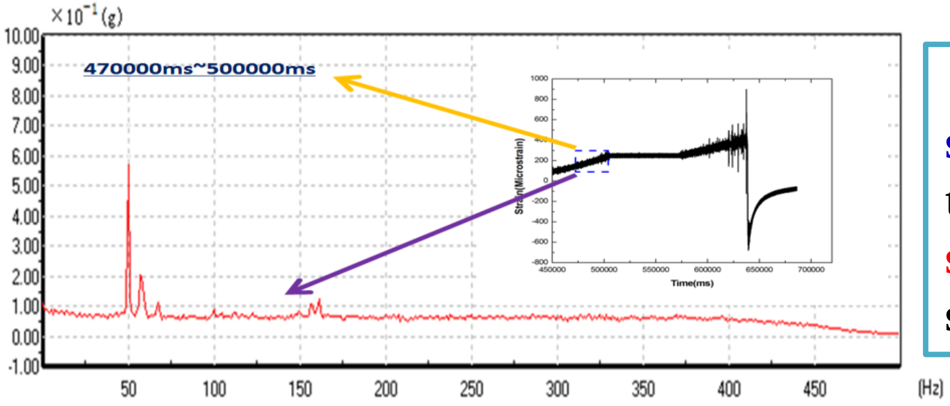


<u>Measured strain signals (SG2) , temperature, and current during quench test</u>

One can see that the strain in the coil were detected stably, when the transport current is still increases gently.

At pre-quench, many oscillations on the strains measured had been detected due to wire motion or structure deformation. The maxmium amplitude of the oscillations can be achieved as 400με. But the current and tempeture signals are still stable.

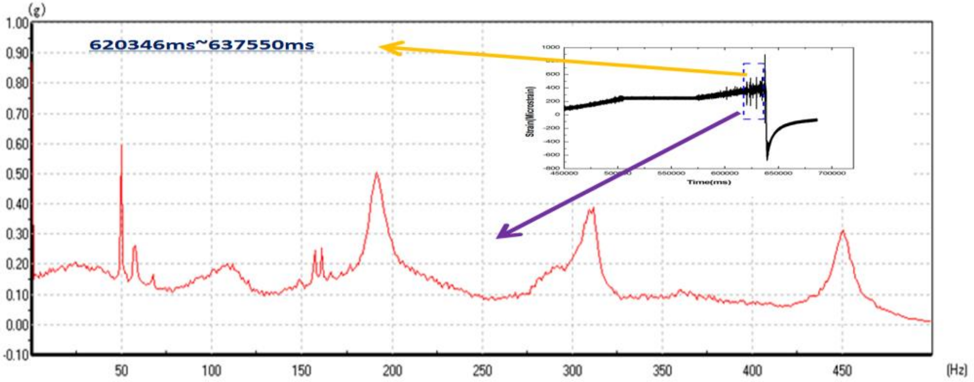
To better understand the **dynamic strain histories** in the SC magnet during the excitation, pre and post quench , **a spectrum analysis** of the measured strain signals is conducted.



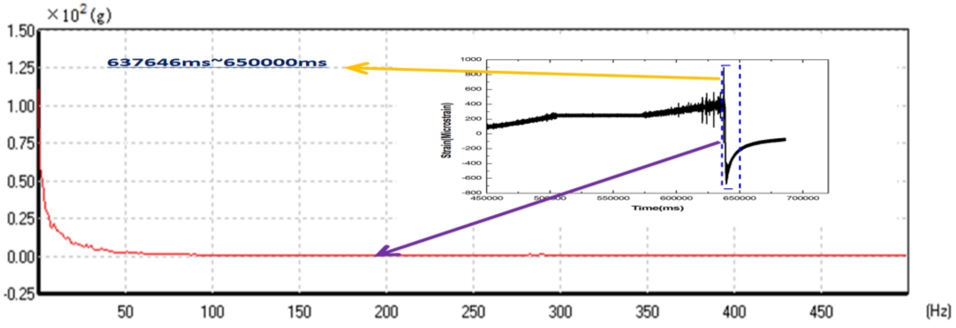
Excitation of the coil

At a stable excitation or post-quench, only little spectral peak with low frequency (work or natural frequency)were obeserved;

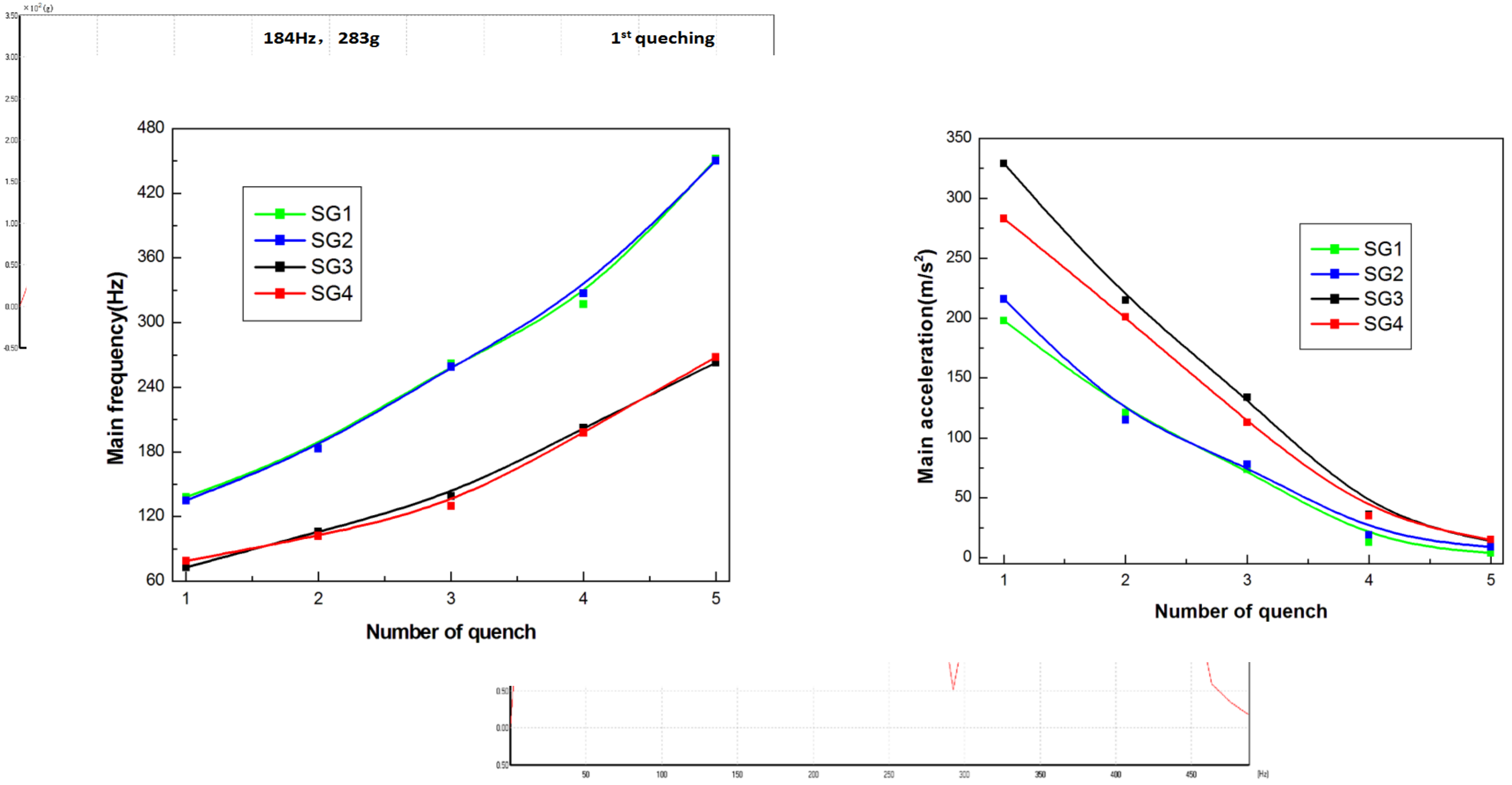
During the pre-quench processes, we can detect several equivalent spectral peaks, which can indicate that the vibrations of wires at multiple frequencies, that may be important signals for warning a quenching.



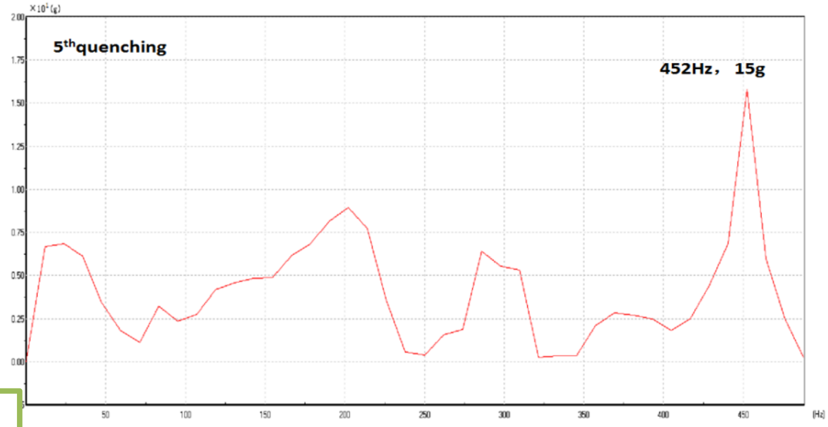
Pre-quench of the coil



Post quench of the coil



The **strain spectrums** in the case of **quench trainings** for 1.5s before a quench, in the same manner, it is intersting that the **main frequency** will **be improved** with increasing of quenching current(NO.). And vibration amplitude will be decreased.



This phenomenon can be explained **by increasing training current** allowing wires to **be constrained.**

Sources of Disturbance

$$C_{cd}(T)\frac{\partial T}{\partial t}=\nabla\cdot[k_{cd}(T)\nabla T]+\rho_{cd}(T)J^2_{cd_\circ}(t)+g_d(t)-\left(\frac{f_p\mathcal{P}_D}{A_{cd}}\right)g_q(T)$$

Storage Conduction Joule heating Disturbance Cooling

- Mechanical
  — Lorentz force; thermal contraction
  - Wire motion / "micro-slip"
  - Structure deformation
  - Cracking epoxy; debonding

$$\left\{\begin{array}{l} e_{11}=\mu_d F_N\int_{t_0}^{t_1} vdt \\ e_{12}=\gamma\iint\sigma\dot{\varepsilon}dtdv \end{array}\right.$$

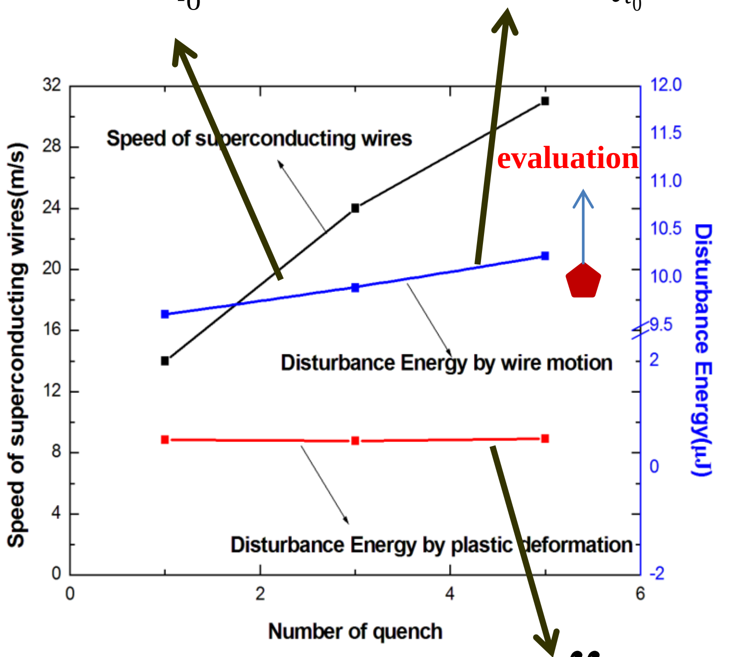
$$q_f(z)=\mu_d\bar{\sigma}_r(z)u_z(z)$$

$$e_{expxy}\approx\frac{1}{2}V_f E_{epoxy}\left[\frac{\sigma_{hoop}}{E_t}+\int_{293}^{42}\alpha_t dT-\int_{293}^{42}\alpha_{expxy}dT\right]^2$$

- Electrical/Magnetic
  —Time-varying current/field
  - Current transients, includes AC current
  - Flux motion, e.g., flux jump
  - Field transients, includes AC field
- Thermal
  - Conduction, through leads
  - Cooling blockage (poor ventilation)
- Nuclear radiation
  - Neutron flux in fusion machines

$$v=\int_{l_0}^{l_1}\dot{\varepsilon}dl$$

$$e_{11}=\mu_d F_N\int_{t_0}^{t_1} vdt$$



$$e_{12}=\gamma\iint\sigma\dot{\varepsilon}dtdv$$

According to our dynamic strain measurements and energy equation with mechanical events, we can calculated the speed of wires and its disturbance energy during a quench, which is fall to the same order of magnitude as other evaluation methods for low-temperature superconducting magnet .

Conclusion

◆A dynamic strain measurment technique appears useful for detection of LTS magnet. The strong turbulence of measured strains are always detected in advance compared to the current, and temperature signals during a quench;

◆We also come to the quantitative relation between the main frequency of dynamic strain spectra and quenching currents;

◆The speed of wires and its disturbance energy during a quench are evaluated from dynamic strain measurements .

Thanks for Your Attention !