Current redistribution and stability of superconducting triplex cable without electrical insulation carrying non-uniform current

N. Amemiya, H. Yonekawa*, E. Kobayashi, T. Ogitsu**, K. Sasaki***, N. Ohuchi**, K. Tsuchiya** and T. Shintomi**

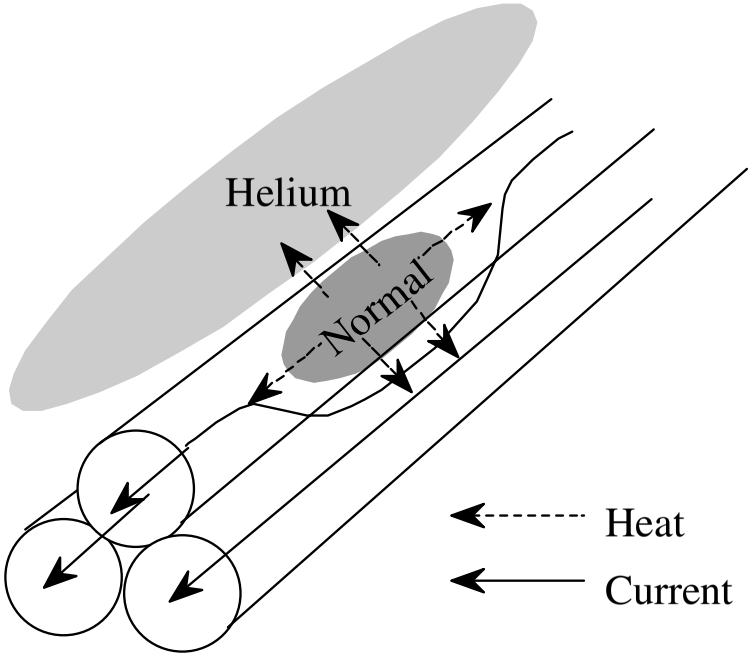
YNU, KBSI, KEK**, Hokkaido U.****

Background

-Two aspects of current distribution relating to the stability of superconducting cable-

- Steady or quasi-steady current distribution before quench initiation
  - Non-uniform current distribution possibly leads to quench initiation.
- Transient current redistribution during quench / recovery process
  - It might help recovery to improve stability against local disturbance.

Current redistribution during quench / recovery process



Normal zone is produced in one or a few strands in the cable ...

Their currents transfer to the other superconducting strands *through the contact resistance* between strands.

It can help the recovery of superconducting state.

Objective of this paper

- To study the Influence of the combination of
  - non-uniform initial current distribution
  - current redistribution during quench / recovery process

  on stability of superconducting cables against local disturbances.
  - If the current is very easy to transfer, the non-uniform current distribution does not affect the stability against local disturbances.
  - If not, …

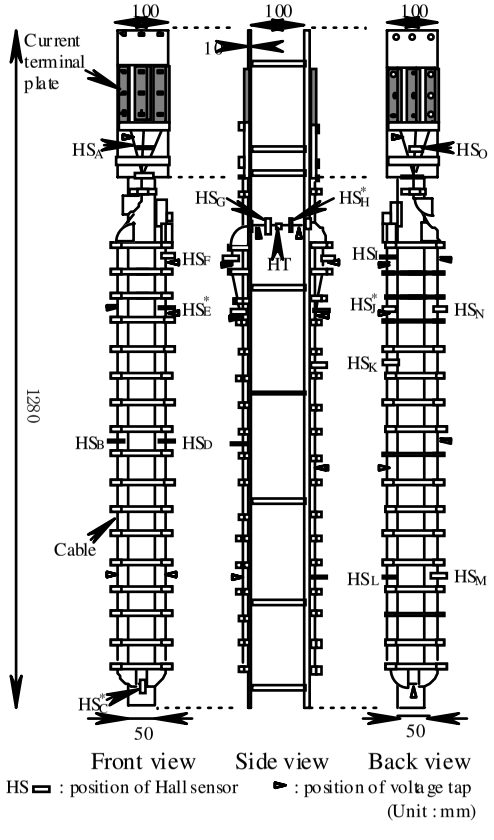
Procedure of experiments reported today …

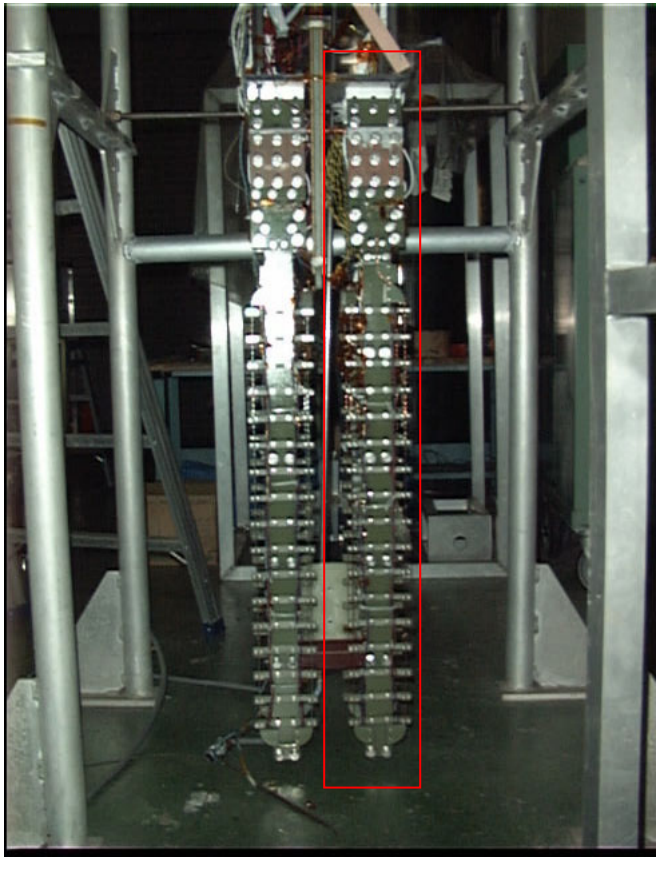
- Initial current distribution before quench initiation is controlled artificially.
- Stability test is made against a local disturbance to estimate the MQE.
- In the stability test, the local strand current and strand voltage are measured during quench or recovery process.

Specifications of sample triplex cable

Diameter of strand	0.81 mm
Cu/NbTi ratio	1.45
Critical current of strand at zero magnetic field	1680 A
Normal resistance of strand just above T_c	0.616 mΩ/m
Cabling pitch	30±2 mm
Strand surface	Bare copper

Overview of experimental set-up

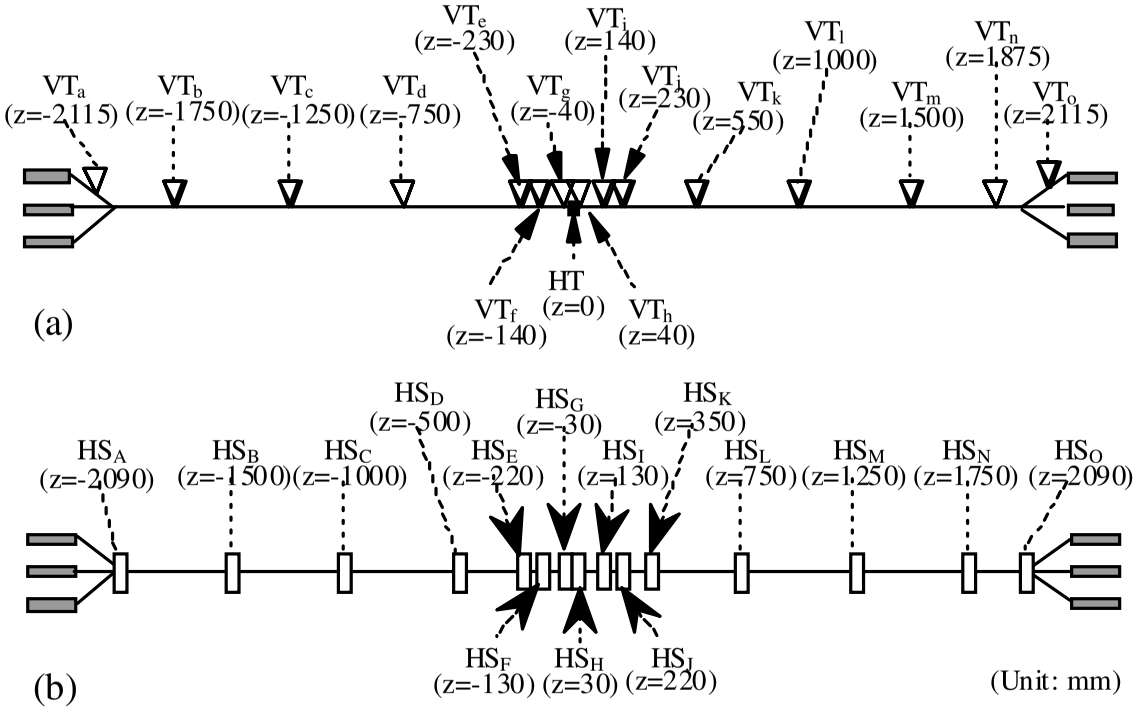




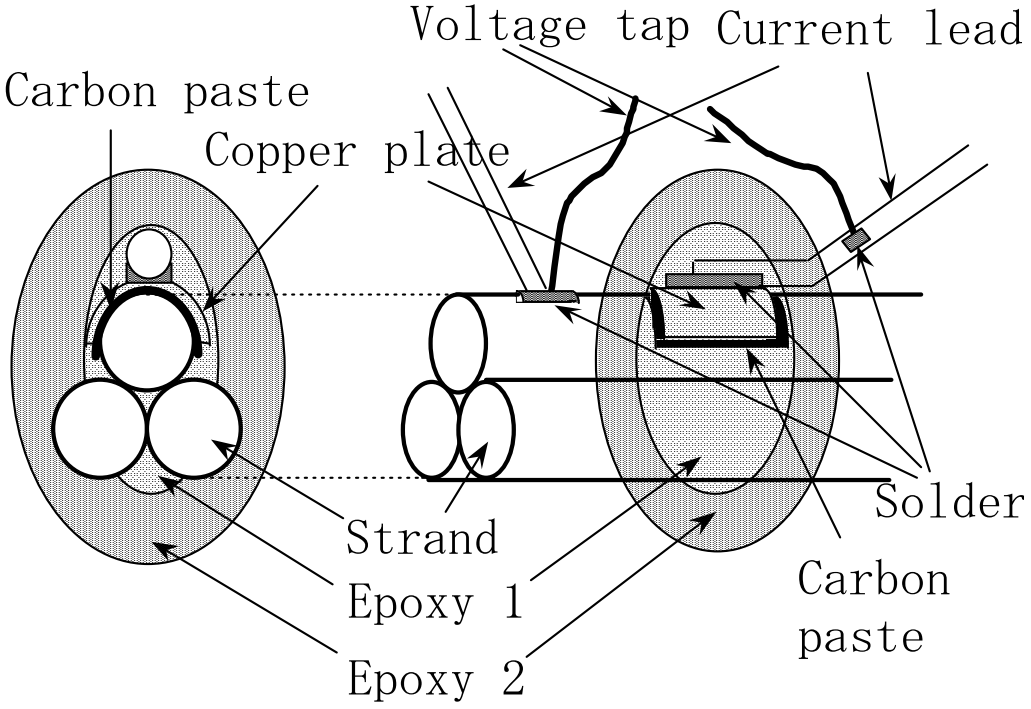
Locations of sensors

Instrumentation ;

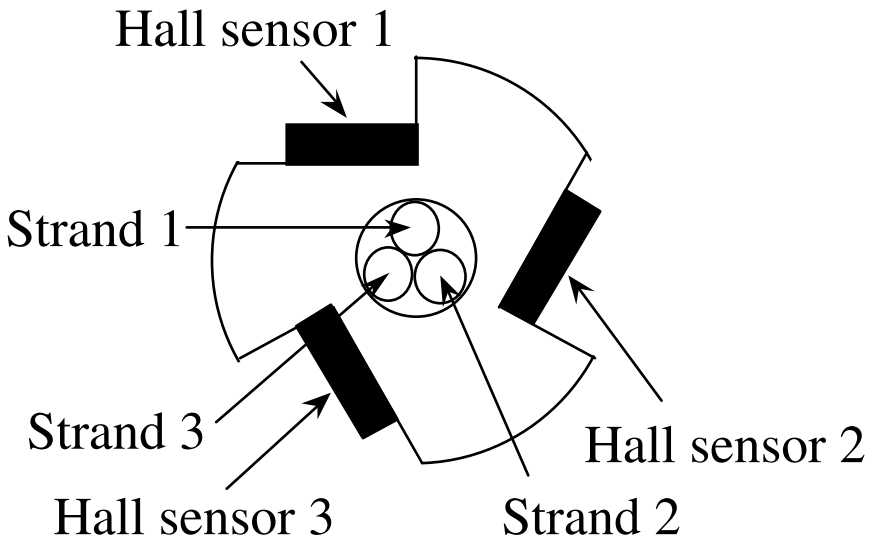
- Voltage taps attached to each strand
- Hall sensor triads to measure strand currents



Carbon paste heater



Hall sensor triad



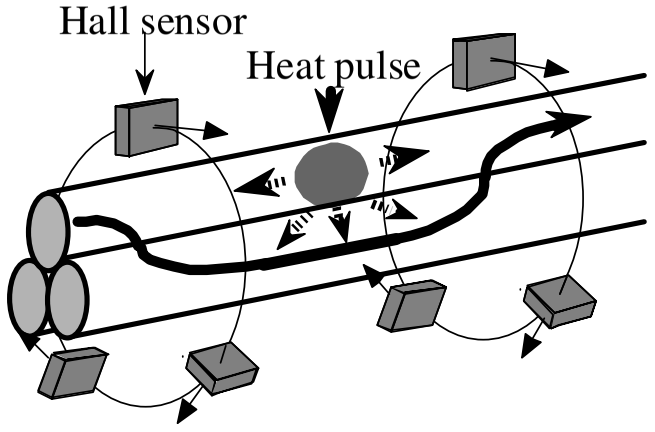
Three Hall sensors are placed around the triplex cable.

Three measured values; magnetic fields at three positions

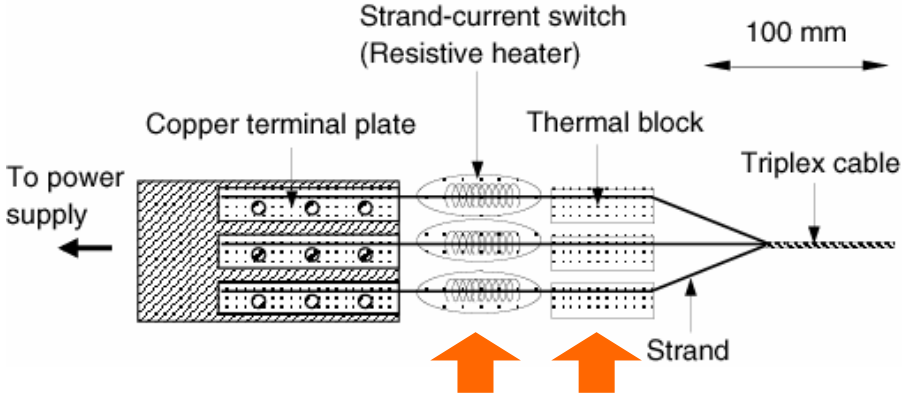
Three unknown values; three strand currents

Practical scheme of stability test and measurement

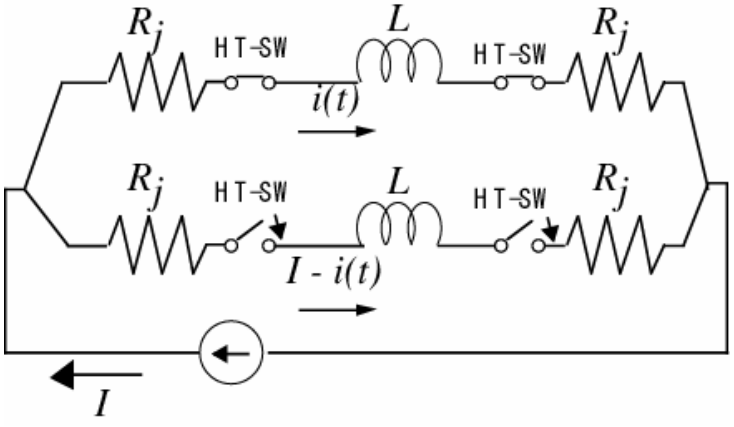
1) The initial current distribution is controlled artificially.
2) Heat pulse whose duration is 0.5ms is applied by carbon paste heater.
3) Temporal evolutions of strand currents and voltages are measured with Hall sensors and voltage taps.



Configuration near cable terminal with strand-current switches

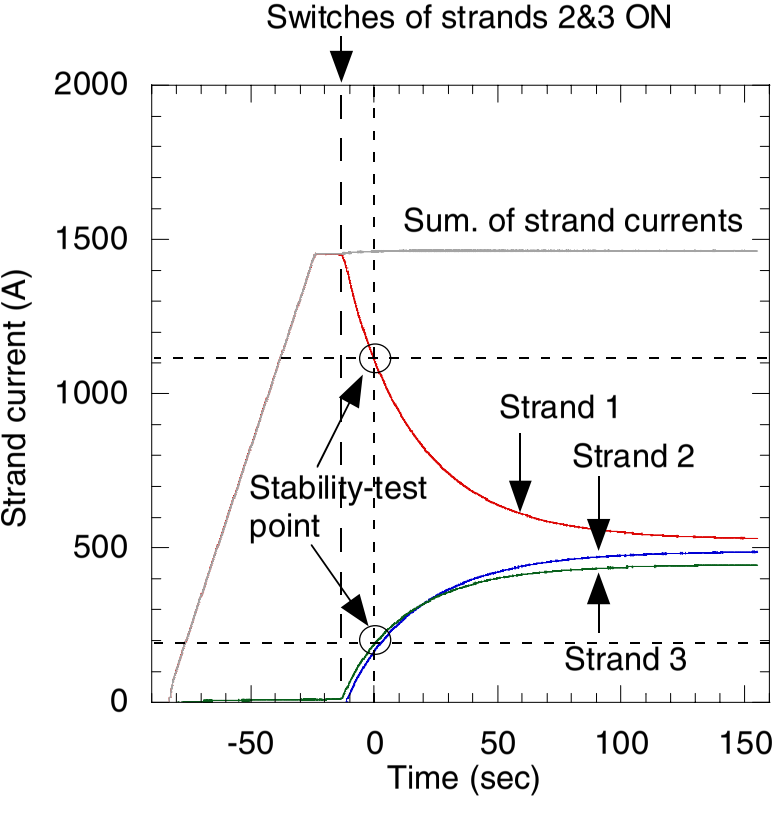


- Strand-current switch using resistive heater are installed at the end of the strands.
  - Static normal zone is produced to shut off the strand current.
- Thermal diffusion to the central part is blocked by the large copper blocks.

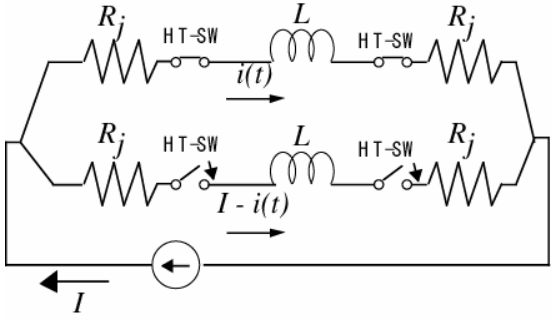


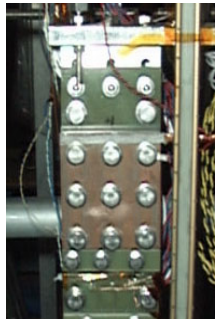
Electrical circuit representing two strands with switches

Control of initial current before quench initiation by strand-current switches

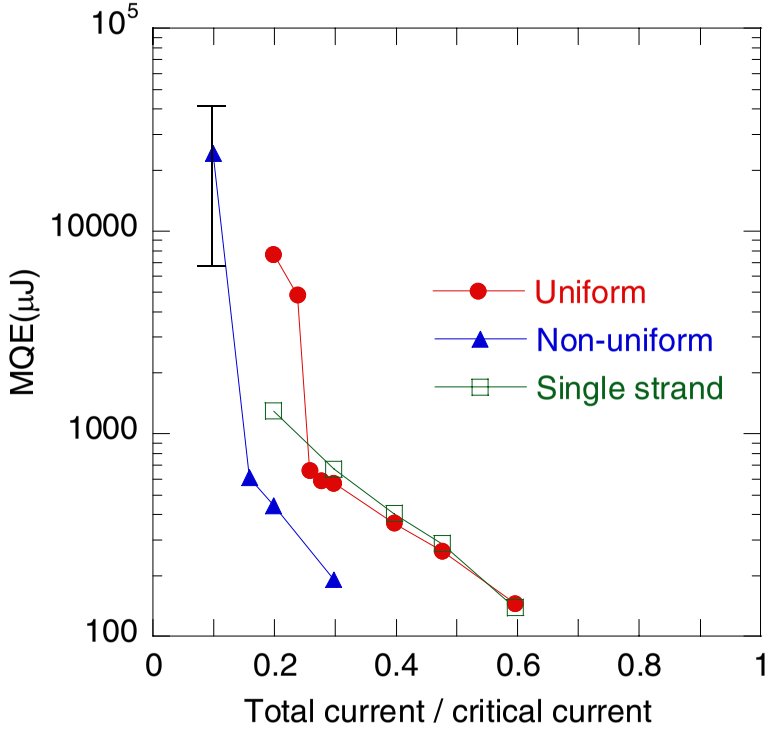


1) Switches of strands 2 &3 OFF
2) Ramp up the current. In this phase, whole current flows through strand 1.
3) Reach flat top
4) Switch ON strands 2&3
5) Current gradually transfer from strand 1 to strands 2&3
6) Stability test at intended current distribution



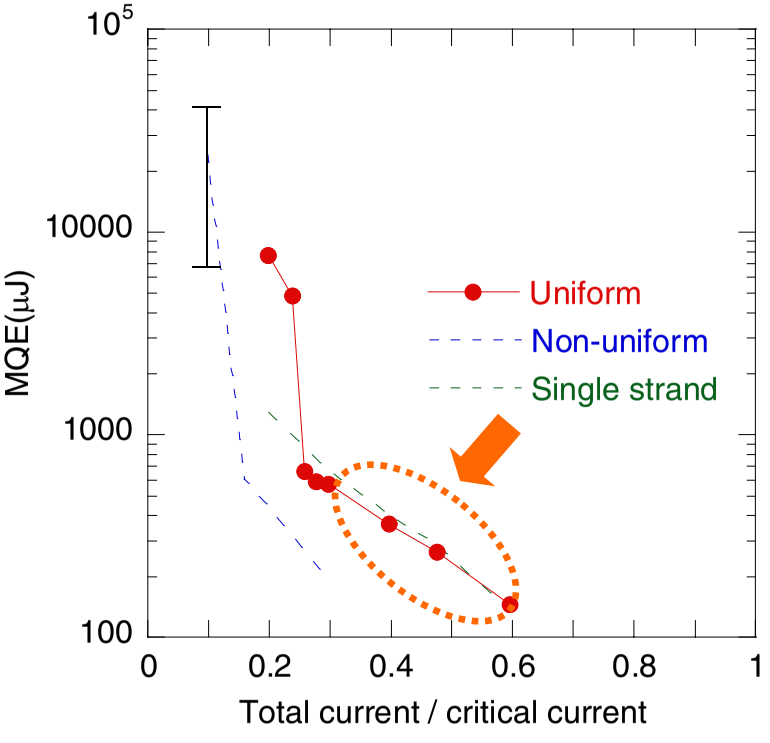


MQE vs. overall I_t / I_c

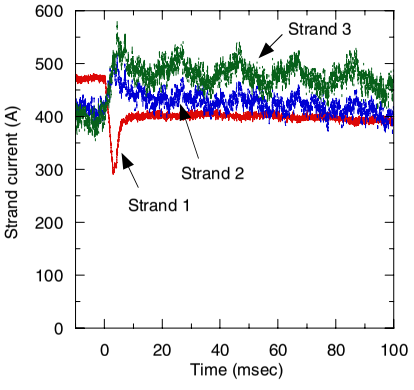


- Threshold, $I_t/I_c=I_1/I_c$
  - Bellow this threshold, MQE increases drastially.
- Relation between the MQE and current redistribution will given in the following view graphs.

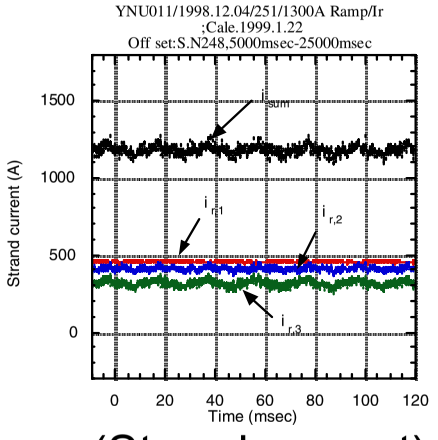
Uniform initial current distribution (1)



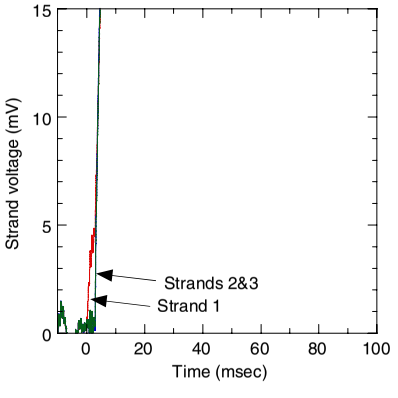
$I_t/I_c > I_1/I_c$



(Strand current)

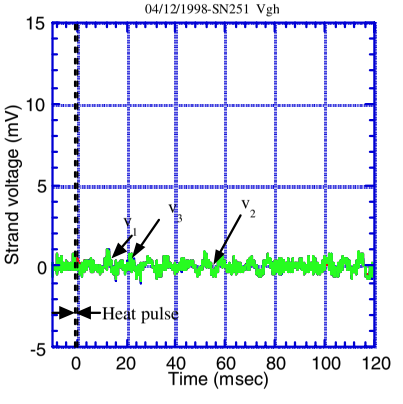


(Strand current)



(Strand voltage)

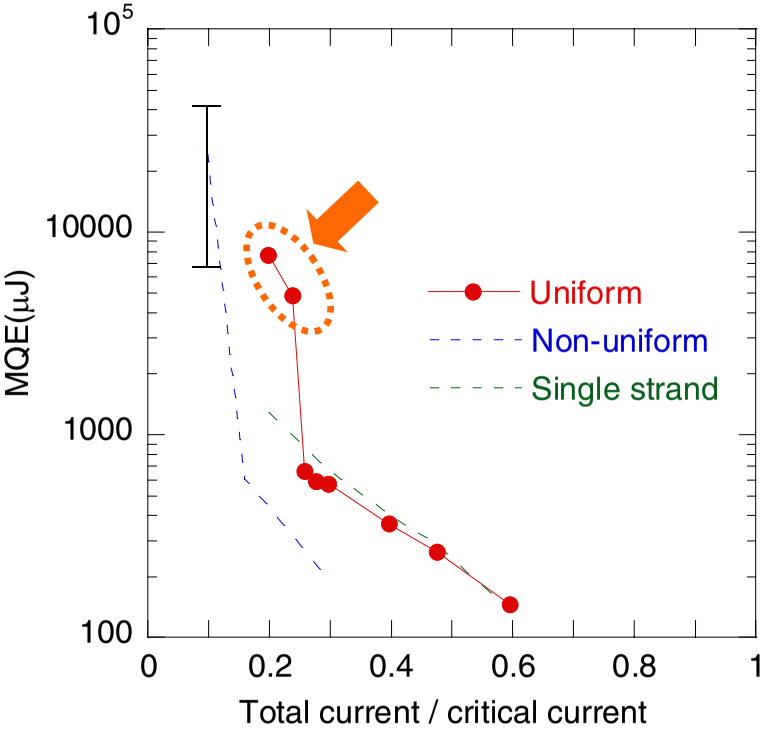
Quench



(Strand voltage)

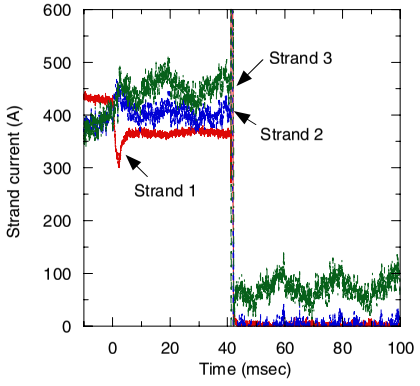
No normal

Uniform initial current distribution (2)

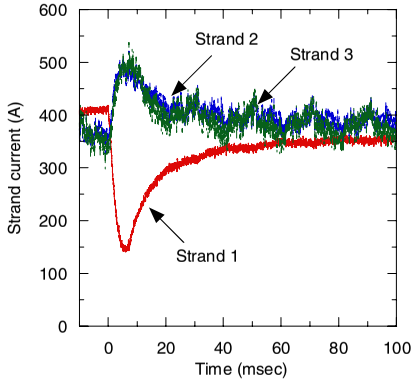


$I_t/I_c < I_1/I_c$

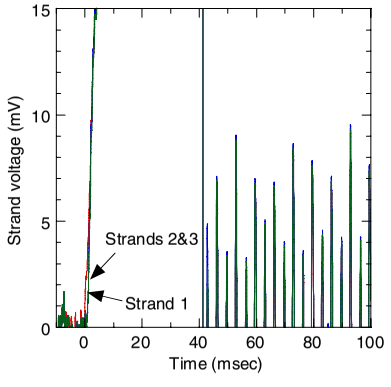
Current redistribution improves stability.



(Strand current)

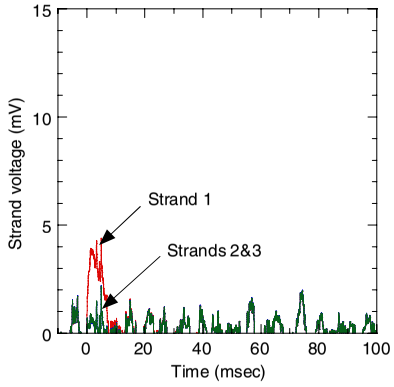


(Strand current)



(Strand voltage)

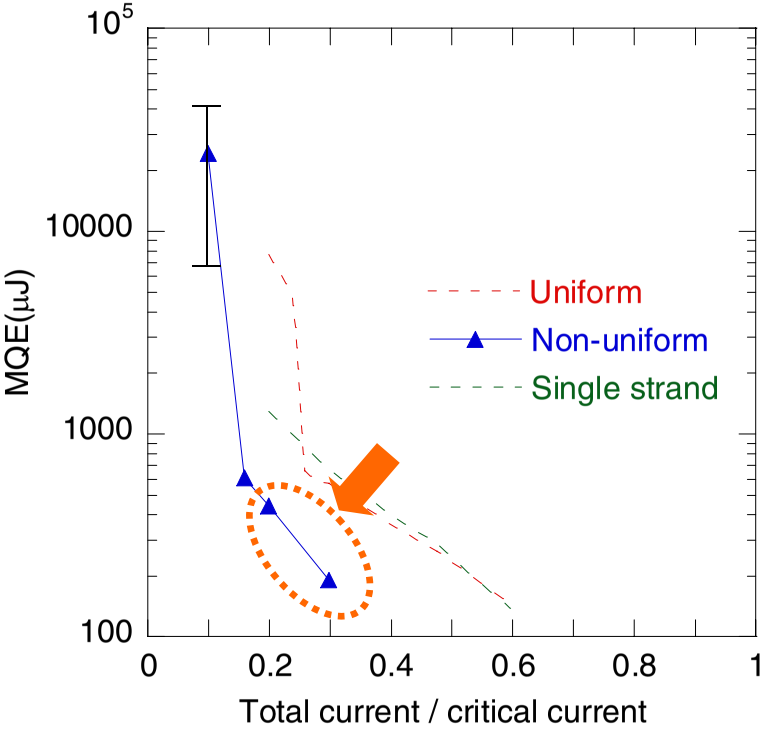
Quench



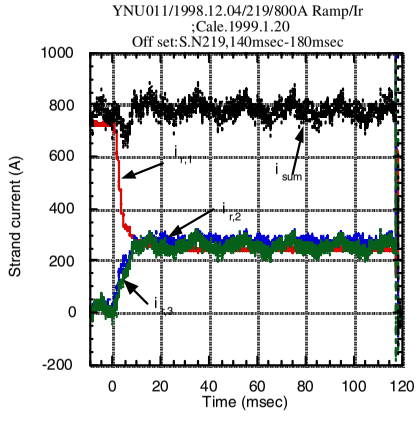
(Strand voltage)

Recover

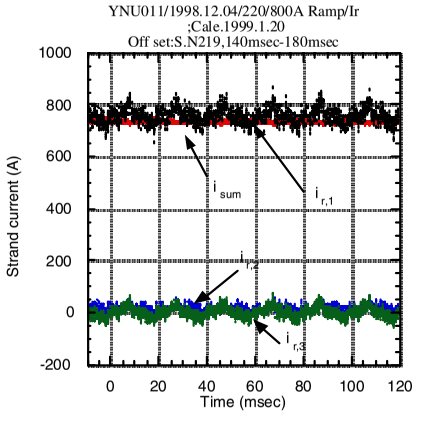
Non-uniform initial current distribution (1)



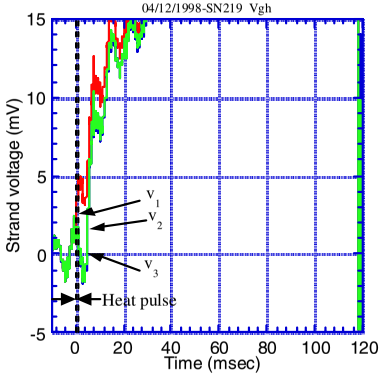
$I_t/I_c > I_1/I_c$



(Strand current)

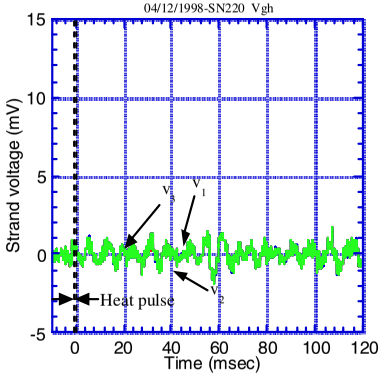


(Strand current)



(Strand voltage)

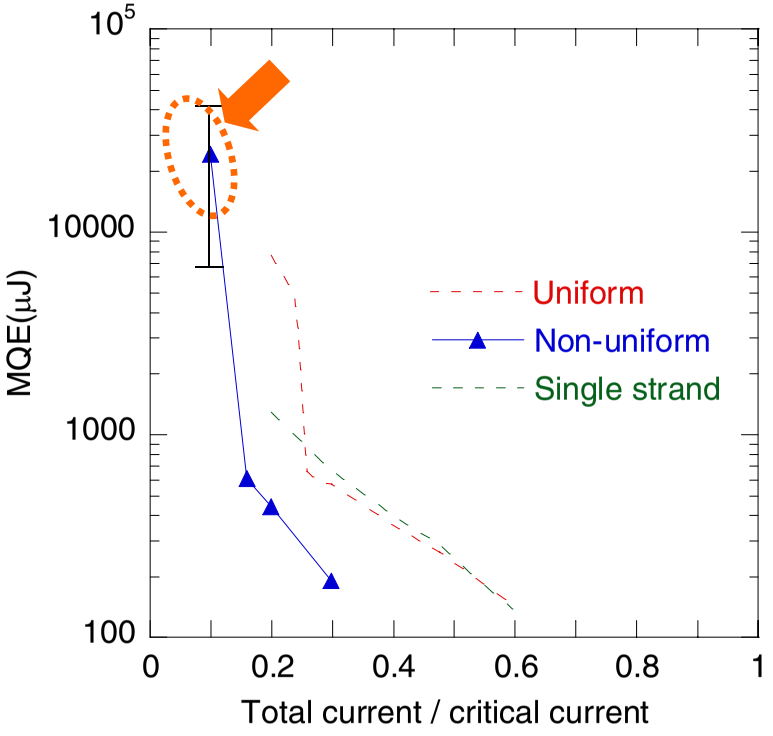
Quench



(Strand voltage)

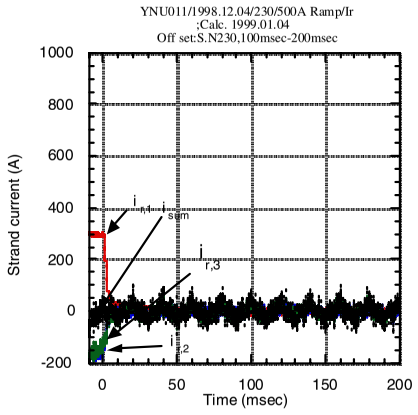
No normal

Non-uniform initial current distribution (2)

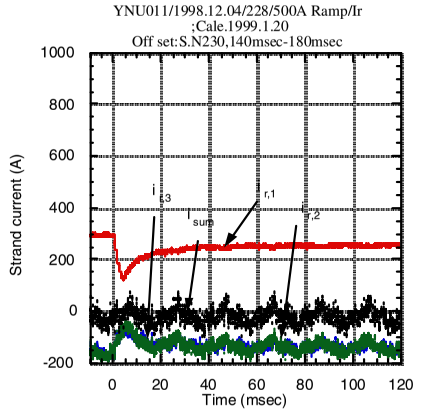


$I_t/I_c < I_1/I_c$

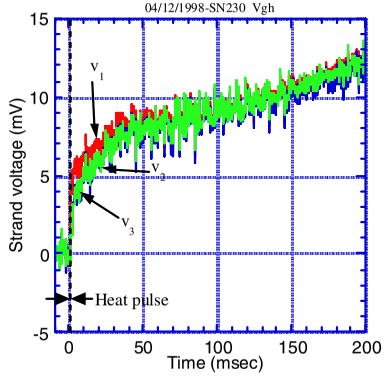
Current redistribution improves stability.



(Strand current)

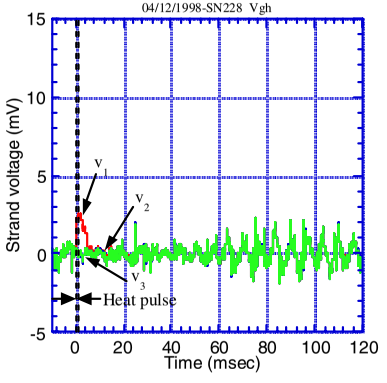


(Strand current)



(Strand voltage)

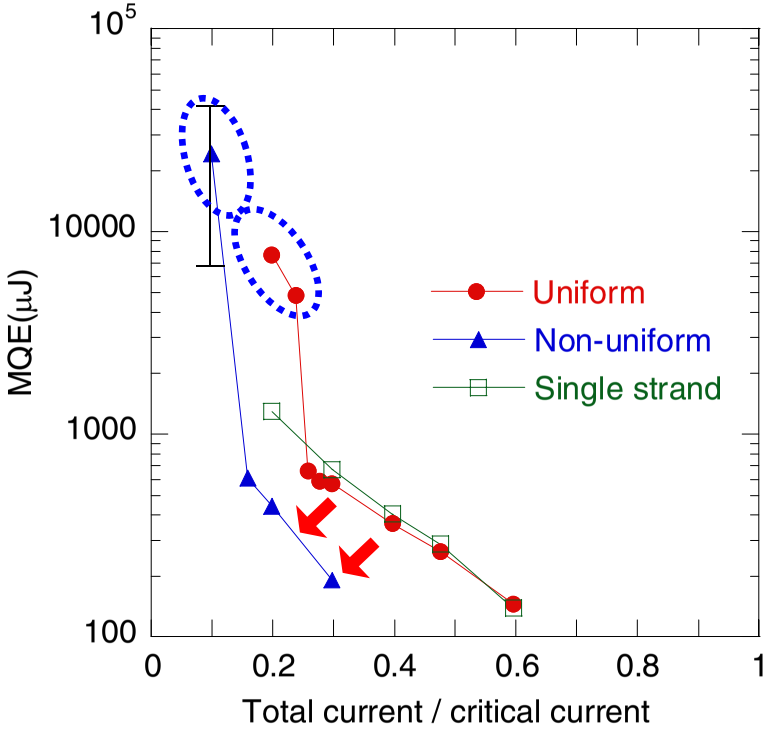
Quench



(Strand voltage)

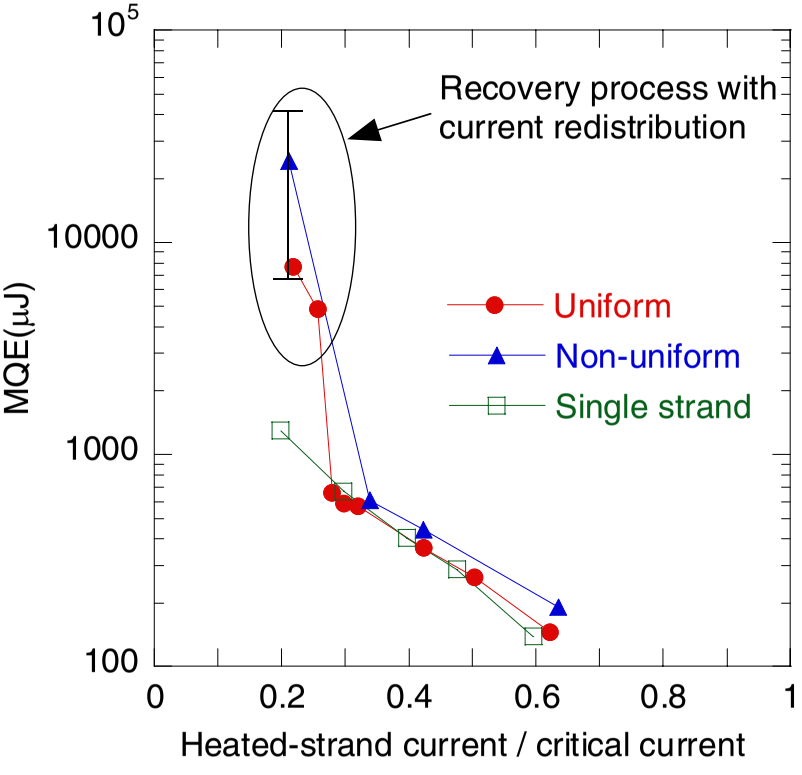
Recover

MQE vs. overall I_t / I_c



- Even if the initial current distribution is not uniform, the stability is improved by the current redistribution, when the transport current is less than some threshold value.
- In the region where the current redistribution is not effective to improve the stability, the non-uniform initial current distribution decreases the MQE against local disturbances.

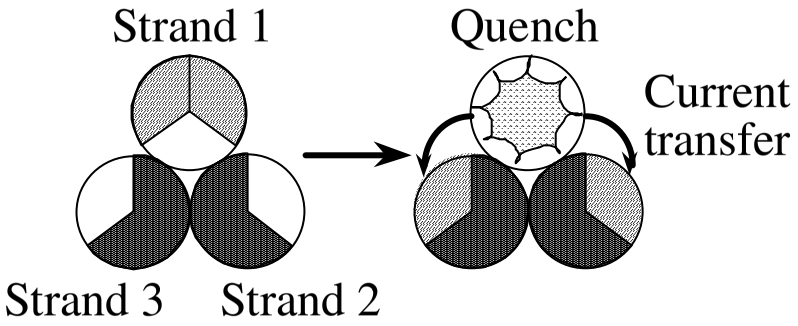
MQE vs. I_t / I_c of heated strand



- Above the threshold, the MQE of the triplex cables agree with the single-strand MQE, not depending on the initial current distribution.
  - The quench of one strand leads to the quench of whole cable.
  - Electrical and thermal interactions with other strands do not influence the stability of one strand in the cable.
- The threshold for the improving stability by current redistribution seems to relate to the I_t/I_c of the heated strand, rather than to the over all I_t/I_c.

In ideal situation where thermal conduction between strand is negligible …

A local disturbance is applied to a strand in triplex cable.

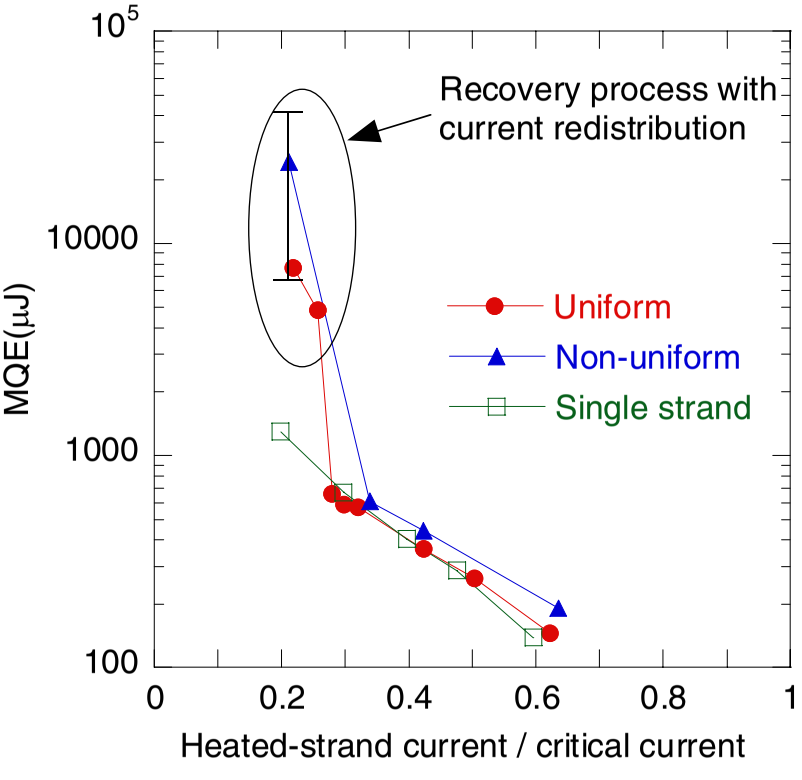


- If overall $I_t / I_c > 2/3$,
  - quench of one strand always leads to quench of whole cable.
  - MQE against local disturbances equals to the single-strand MQE, because no heat is absorbed by the other strands.
- $I_t / I_c < 2/3$; never quench; cryo-stable.

Comparison between experimental results and ideal situation

	Experimental results	Ideal situation
Threshold for stability improvement by current redistribution	Determined by heated strand current rather than total current, 0.3 **Thermal conduction is not negligible in quench / recovery process**	Determined by total current, 2/3 **Current transfers much more rapidly than heat**
Above threshold	MQE equals to single-strand MQE **No thermal interaction between strands in initiation phase of strand-quench**	MQE equals to single-strand MQE **No thermal interaction between strands in initiation phase of strand-quench**

Threshold for stability improvement by current redistribution



Why the threshold are determined by the heated-strand I_t / I_c?

- Effect of the current redistribution depends on
  - Rapidness of the current redistribution
  - Rapidness of thermal conduction between strands
- When the heated-strand current is decreased, the heat generation at the normal zone is decreased. It should reduce thermal conduction between strands, and the current can transfer before the other strands are heated up by the thermal conduction.

Conclusions

- *In small current region, the current redistribution can improve the stability against local disturbance, even if the initial current distribution is not uniform.*
- *In large current region where the current redistribution is not effective to improve the stability,*
  - the MQE of the cable against local disturbances equals to the single-strand MQE of the strand carrying the largest current that is most possible to initiate quench,
  - therefore, non-uniform current distribution before quench affect the stability against local disturbances.