Experimental Study on the Influence of Inter-strand Current Distribution on Current Redistribution and Stability of Superconducting Cables

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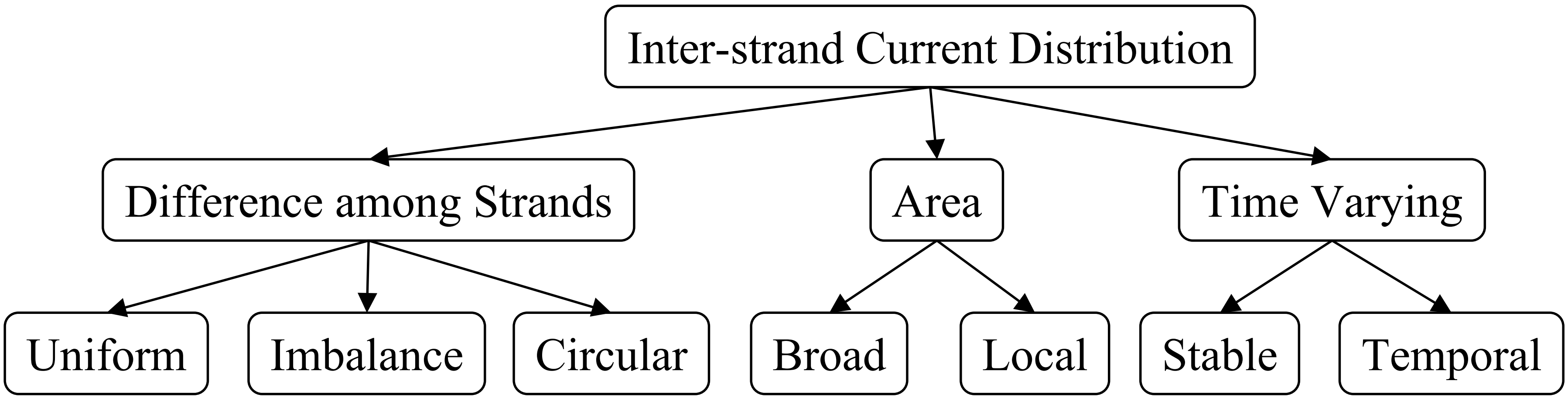
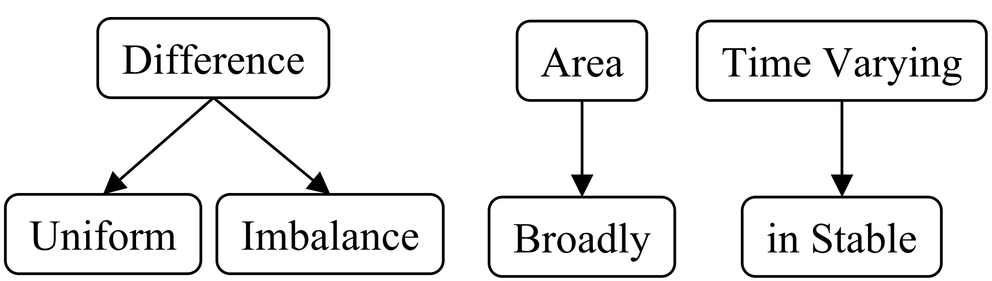
Introduction



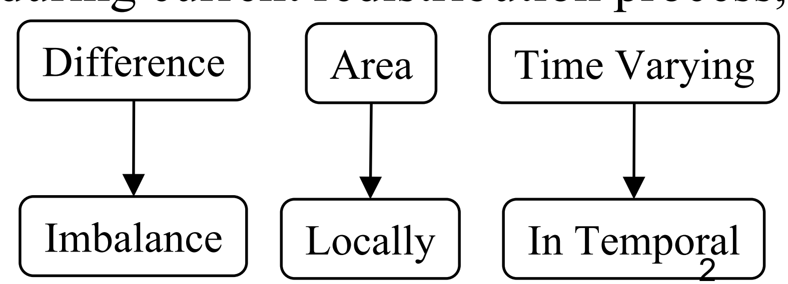
Inter-strand current distribution often affects the stability of superconducting cables with some phenomenon such as current redistribution.

Focus on the following case:

Initial :



After applying a disturbance :
during current redistribution process,



Objective

Problem :

Non-uniformity of inter-strand current distribution : often affects current redistribution and stability.

Larger cables (than triplex) : experimental researches are need.

Objective :

Experimental research on

influence of inter-strand current distribution on current redistribution and stability.

Method :

Sample : eight-strand Rutherford cables with different strand surface; for simplicity.

Inter-strand current distribution: artificially controlled.

Current distribution : measured by Hall sensor sets.

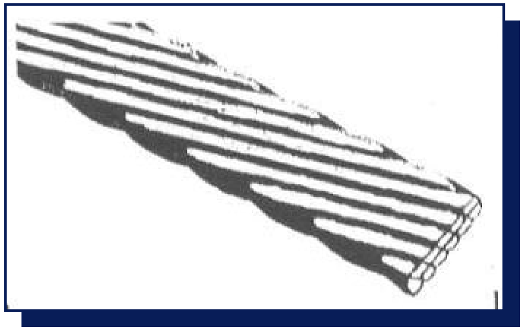
Measured data :

Strand current and voltage,

Minimum Quench Energy (MQE).

Specification of Samples

	Sample 1	Sample 2
Strand Surface	AgSn-plating	AgSn-Plating, Oxidized
Contact Resistance, side-by-side (μΩm)	0.04	4
Contact Resistance, one cross-over (μΩ)	4	400
Number of Strands	8	8
Diameter (mm)	0.81	0.81
Twist Pitch (mm)	31	31
Thickness x Width (mm)	1.5 x 3.3	1.5 x 3.3
Ic (A) at 4.2 K, 4 T	435	435



Contact between Strands :

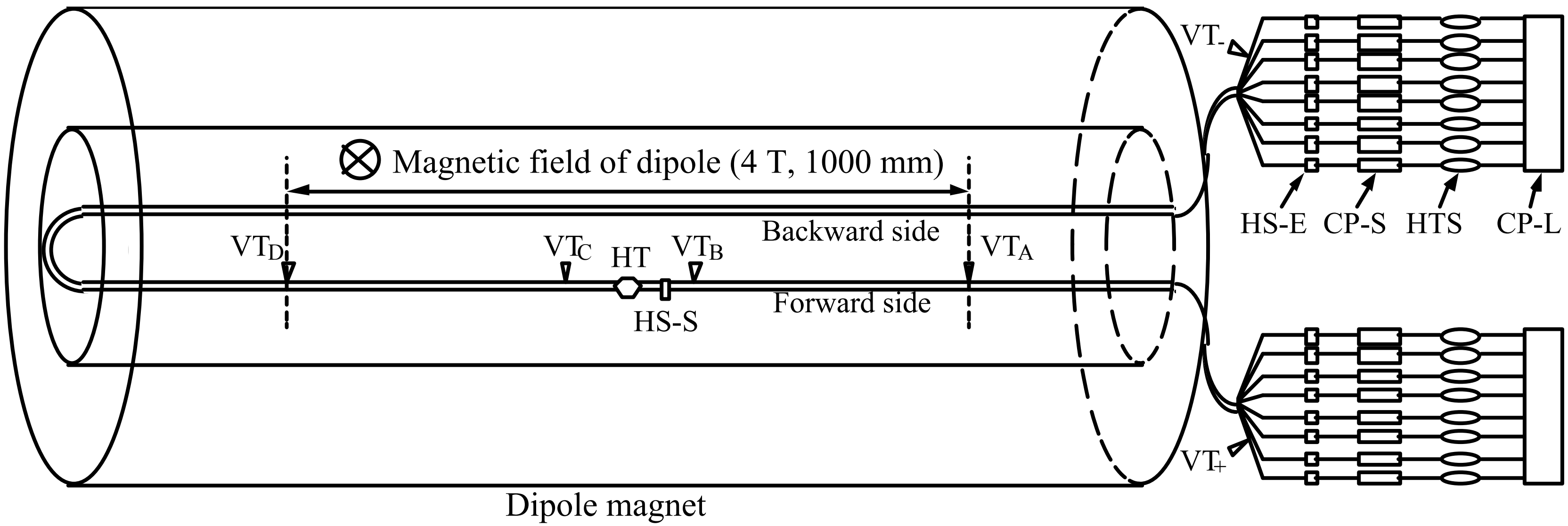
Sample 1 : Better .

Sample 2 : Worse.

The Other Characteristics :

Completely Same.

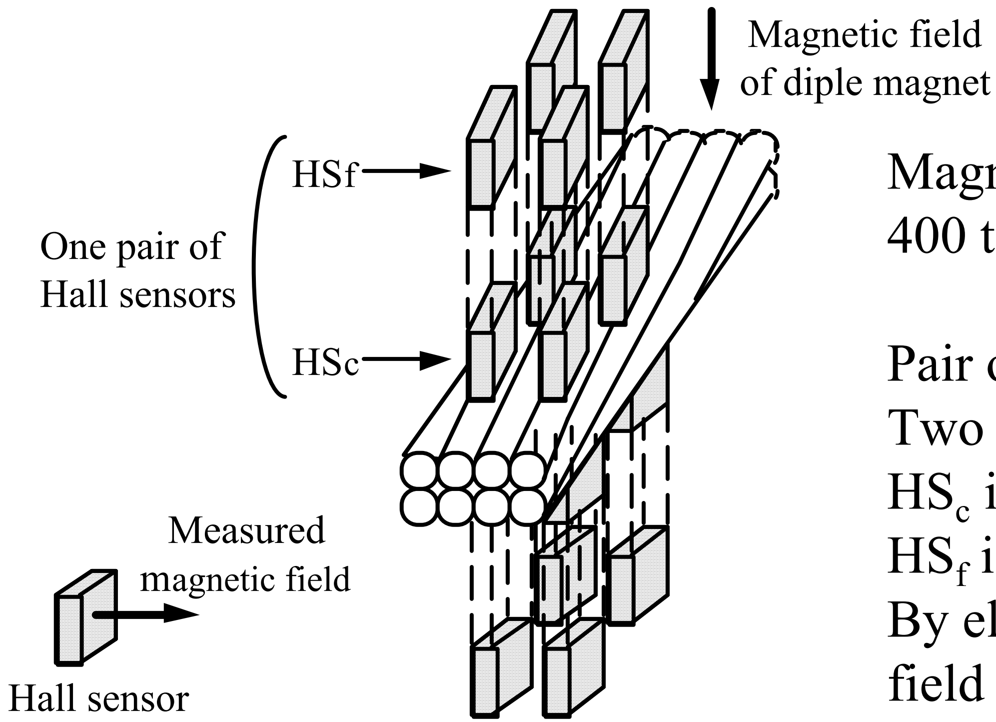
Arrangement : Sample, Heater, Hall Sensor, Voltage Tap, Copper Plate, and Magnet.



Sample :	3.6 m length, hairpin-shape (13 mm gap).
- Straight sections :	1m length, 4 T by a dipole magnet.
- Cable end :	All strands are separated.
Carbon Paste Heater, HT :	To input heat pulses to a strand.
Hall Sensor Sets :	Straight section (HS-S), both ends (HS-E).
Copper Plates :	Small one (CP-S) to each strand
	Large one (CP-L) to all strands.
Heater switches :	Resistive wire, between CP-S and CP-L (HTS).
	To control initial strand current distribution.

Hall Sensor Set

Hall Sensor Set at Straight Section, HS-S:



Magnetic Field of Dipole Magnet (4 T) :
400 times larger than that of Strand Current.

Pair of Hall Sensors:
Two sensors measure same dipole field.
HS_c is close to a strand.
HS_f is far from the strand.
By electrical subtraction (V_{HSc} - V_{HSf}), dipole field is suppressed.

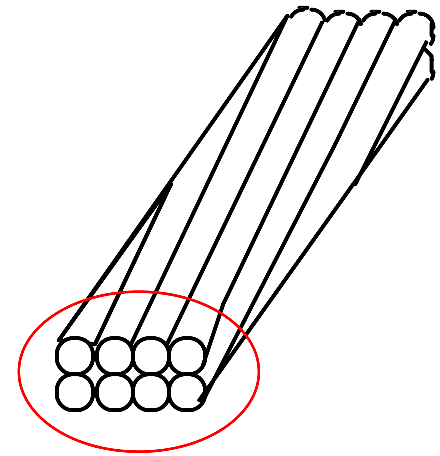
One set consists of eight pairs.

Hall Sensor Set at End of Cable, HS-E:

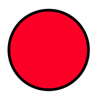
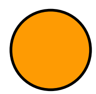
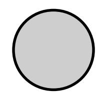
One Hall Sensor is attached on each strand.

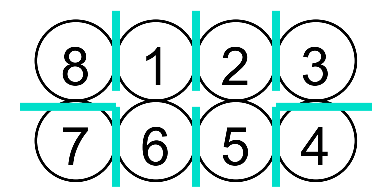
Conditions

Cooling: 4.2 K, pool boiling LHe.
External magnetic field: 4 T, dipole magnet.
Transport current: 540 A to 3100 A.
Heat pulse: 1ms width, to a strand.

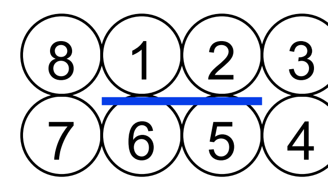


Initial strand current distributions before applying a heat pulse:

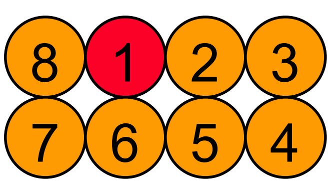
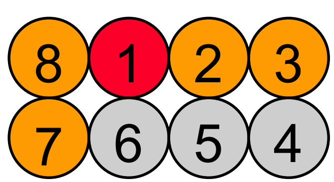
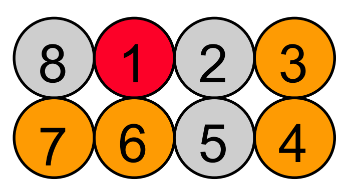
Strand			
Current	v	v	-
Heat pulse	v	-	-



Side-by-side contact

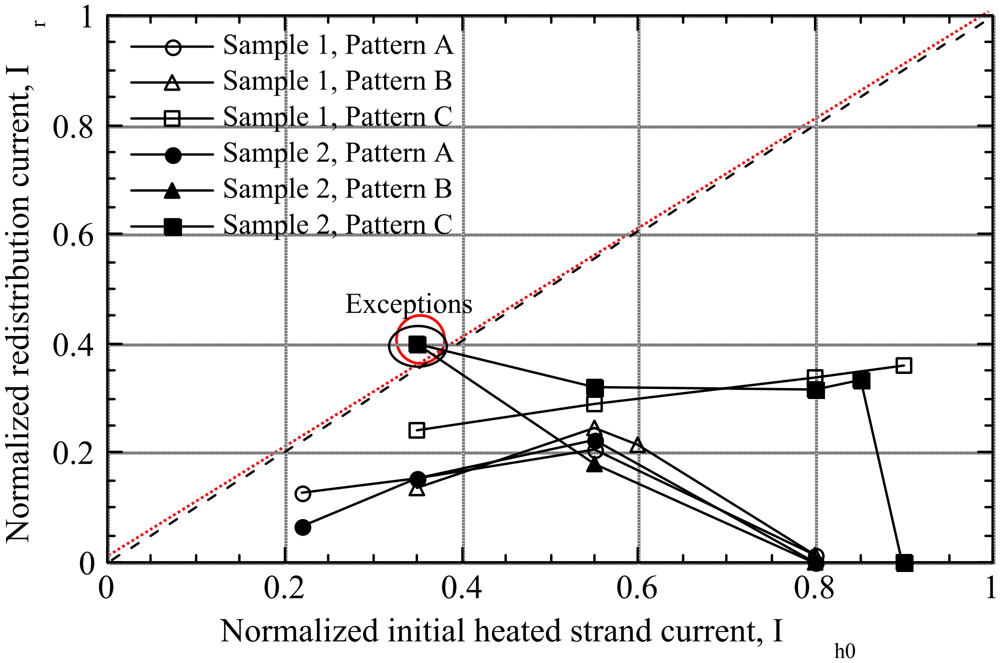


Cross-over contact

Pattern A (Uniform)	Pattern B (Intensive)	Pattern C (Sparse)
		

Neighbor : respect to side-by-side contact.

Measured values : Redistribution Current during Recovery Process



Definition :

Redistribution Current, I_r =

Peak Value of Change of Heated Strand Current during Recovery Process.

Dashed Line :

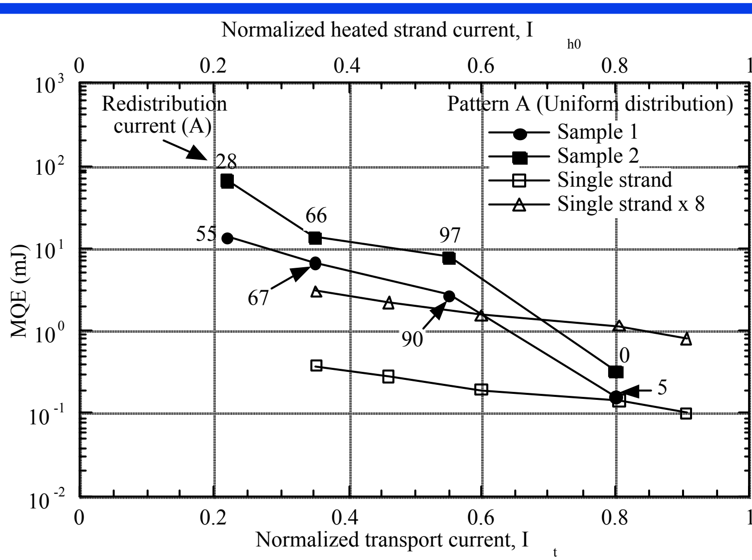
I_{h0}. I_r should =< I_{h0}.

Exception :

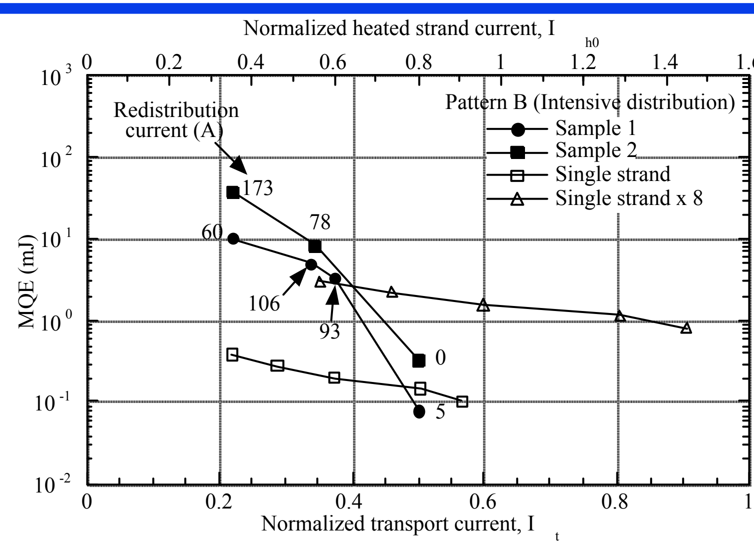
I_r of sample 2 where I_{h0} = 0.35 in the patter B and C.

Since they are on dashed line.

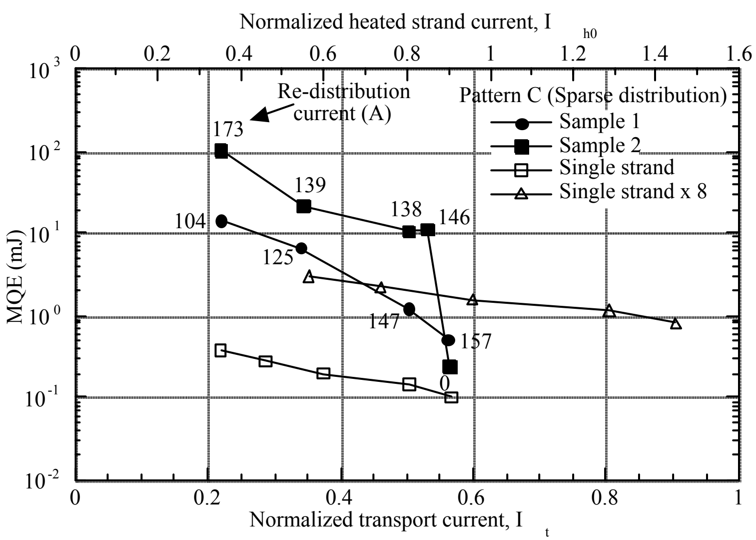
Measured values : MQE



Pattern A (Uniform)



Pattern B (Intensive)



Pattern C (Sparse)

Definition :

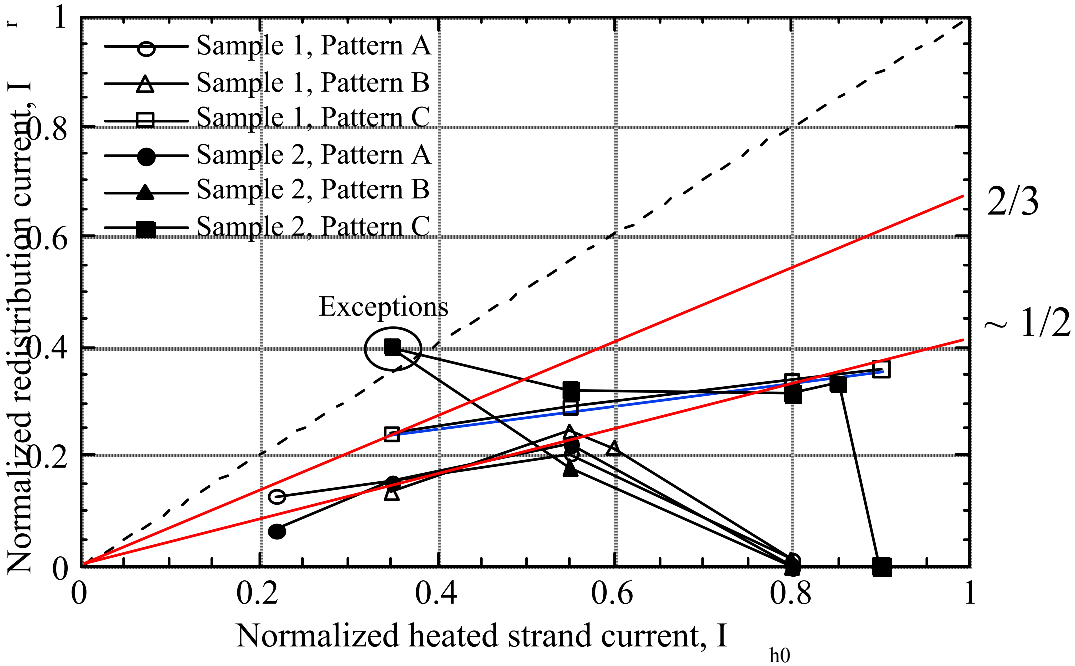
$$\text{MQE} = \frac{(\text{minimum heater energy for quench}) + (\text{maximum heater energy for recover})}{2}$$

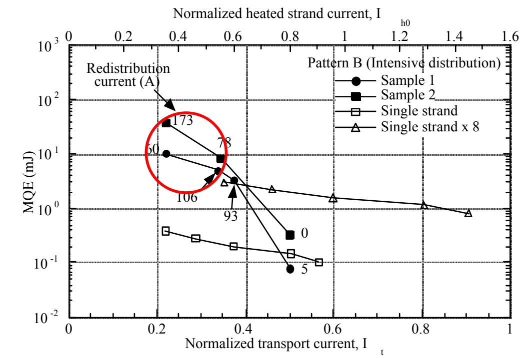
Efficiency to input heat pulses :

MQE of sample 2 was relatively larger, heater of sample 2 might have less efficiency.

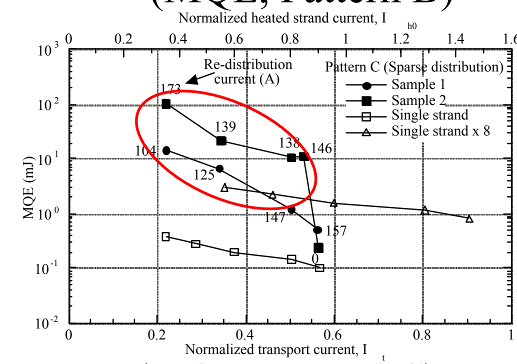
To watch tendency of profile is preferable.

Discussion:
Proportional Redistribution Current





(MQE, Pattern B)



(MQE, Pattern C)

Pattern A (Uniform distribution) :

Both samples had same profile.

When I_{h0} =< 0.55, I_r was proportional to I_{h0} with ratio of 1:2 at each point.

Pattern B (Intensive distribution) without exception:

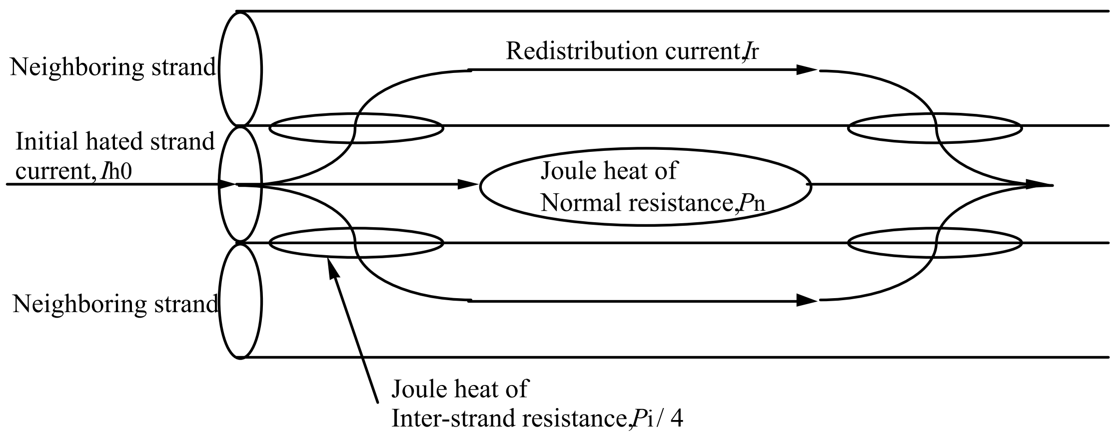
Both samples had almost same profiles as that of pattern A.

Pattern C (Sparse distribution) without exception :

Up to I_{h0} =< 0.8, I_r was proportional to I_{h0}, within 1:2 and 2/3 at each point.

MQE was improved in the corresponding region.

Discussion:
Proportional Redistribution Current



When MQE was improved, I_r and the I_{h0} balanced with some ratio.

Joule heat in strand that transports current is most directive factor for the stability of the strand.

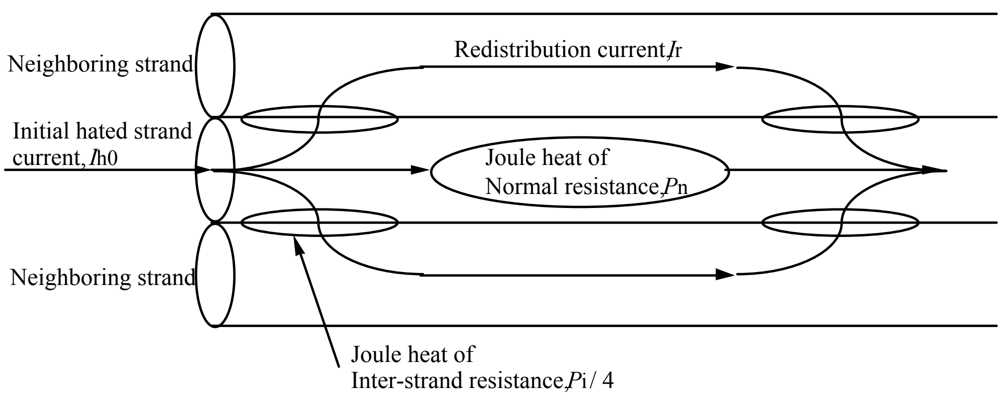
Pattern A and B:

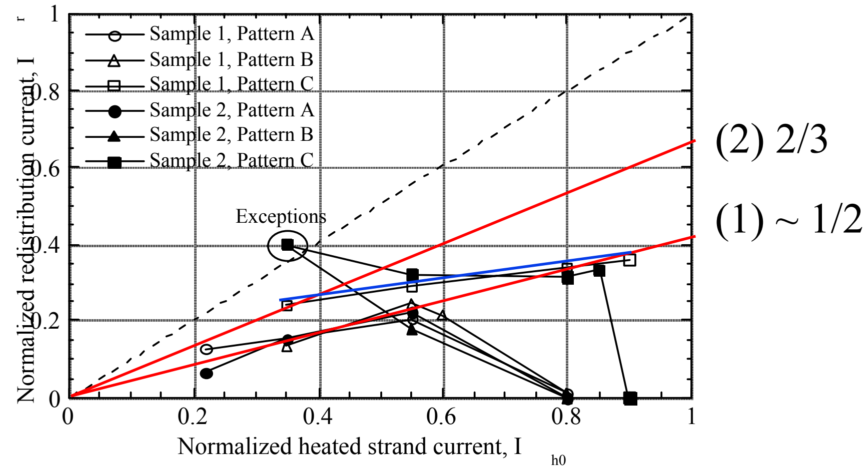
P_n and P_i are influential to stability.

Pattern C:

P_n and 1/2 of Pi are influential when heat transferring from neighboring strands to other strands is neglected.

Discussion:
Proportional Redistribution Current





Influential Joule heats of these strands may balance to be equal by increasing or decreasing of I_r, so that heating of these strands becomes in minimum.

Pattern A and B :

$P_n = P_i$;

$R_h\,(I_{h0} - I_r)^2 = R_i\,I_r^2$

Voltage Drop :

$R_h\,(I_{h0} - I_r) = R_i\,I_r$

Then, $I_r : I_{h0} = 1{:}2$ … (1)

Pattern C :

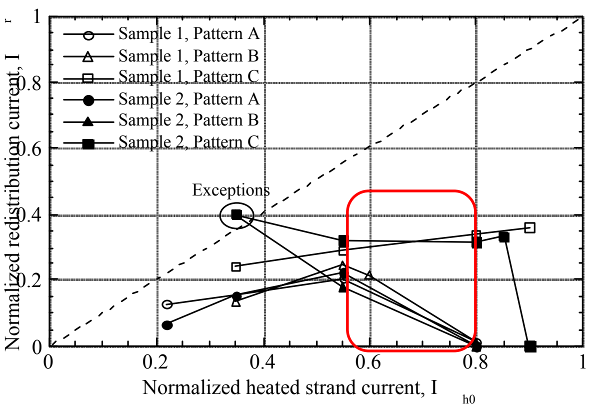
$P_n = P_i / 2$

$R_h\,(I_{h0} - I_r)^2 = R_i\,I_r^2 / 2$

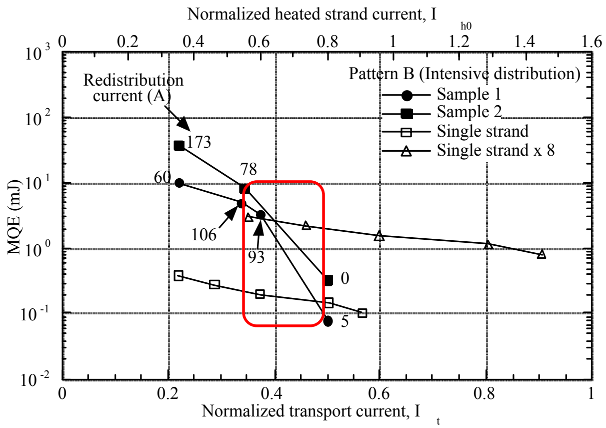
Then, $I_r : I_{h0} = 2{:}3$ … (2)

With increasing of I_{h0}, heat transferring from neighboring strands to others becomes influential.

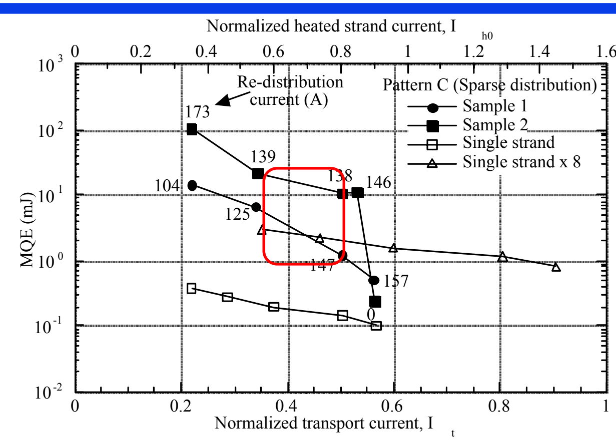
Discussion:
Decrease of Redistribution Current



Redistribution Current



MQE, Pattern B (Intensive)



MQE, Pattern C (Sparse)

When $I_{h0} > 0.55$,

Pattern A and B :

I_r decreased. MQE decreased to single strand stability region.

Pattern C :

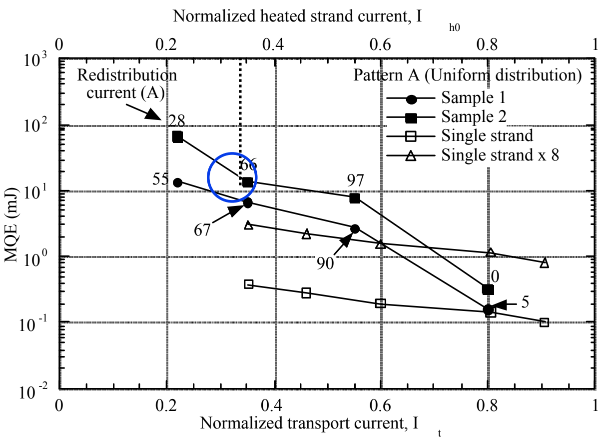
I_r was still proportional to I_{h0} up to $I_{h0} = 0.8$. MQE was still higher.

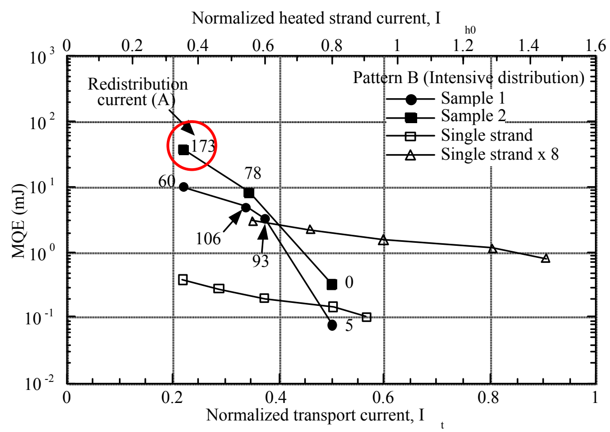
Strand stability region, a local heat pulse applying to a strand does not produce local normal zone in recovery process, or the cable quenches.

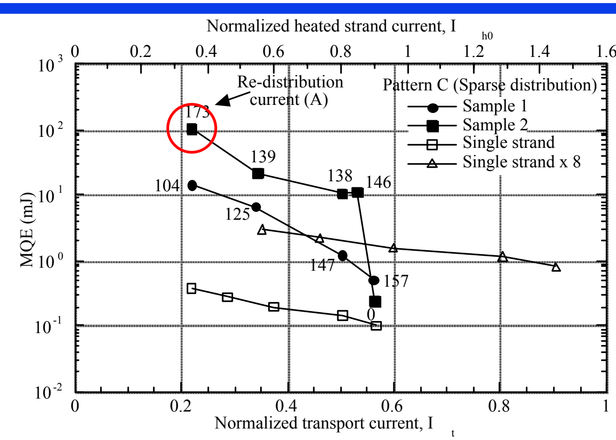
Initial condition: difference among pattern A, B and C : sparseness of distribution.

Chain reaction of changing to normal state is suppressed by sparse distribution.

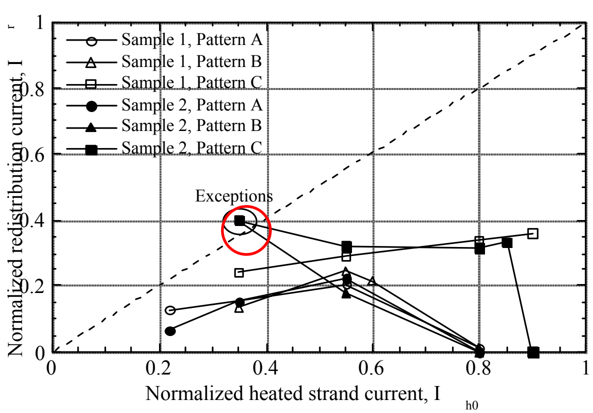
Discussion:
Exceptions of Redistribution Current







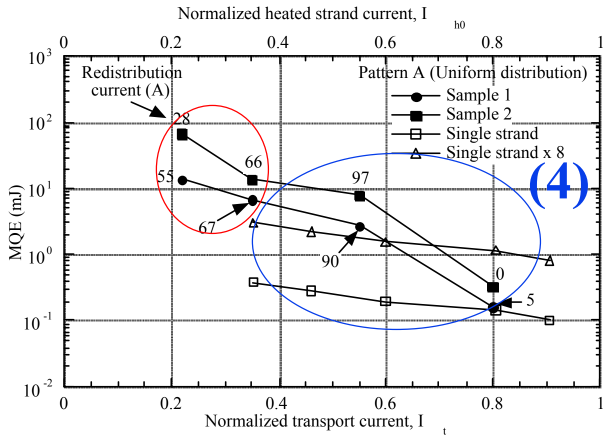
MQE, Pattern A (Uniform) MQE, Pattern B (Intensive) MQE, Pattern C (Sparse)



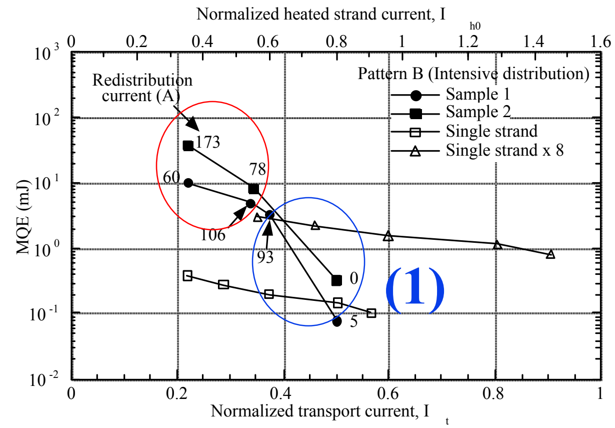
Exceptional Points:
I_r of sample 2 at I_{h0} = 0.35 in the patter B and C.
Corresponding MQE vs. I_{h0}:
The highest.

Applied heat pulse was largest, and possibly heated strand might quench locally even so sample recovered after a moment, so that full of heated strand current transferred to other strands.

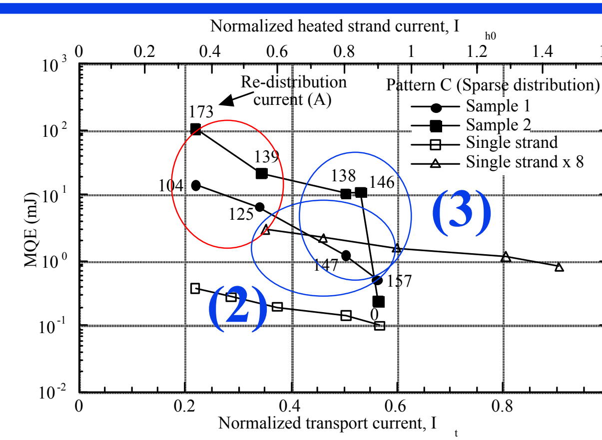
Discussion: Order of MQE



Pattern A (Uniform)



Pattern B (Intensive)



Pattern C (Sparse)

When I_t =< 0.35 : ○

Profiles of MQE were almost same.

Non-uniform current distribution didn't affect MQE in such transport current.

When I_t > 0.35 : ○

MQE was improved as the following in ascending order:

(1) Intensive (Worst)

(2) Sparse with Better Contact

(3) Sparse with Worse Contact

(4) Uniform (Best)

Discussion: Order of MQE

When $I_t > 0.35$:

MQE was improved as the following in ascending order:

(1) Intensive (Worst)
(2) Sparse with Better Contact
(3) Sparse with Worse Contact
(4) Uniform (Best)

Difference between (1) and (2) : Sparseness of distribution.

Sparse distribution might suppress chain reaction of changing to normal state.

Difference between (2) and (3) : Inter-strand contact.

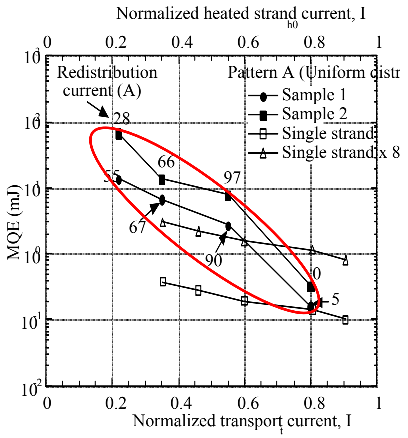
Larger inter-strand thermal conductivity might improve MQE.

Difference between (3) and (4) : Uniformity of distribution.

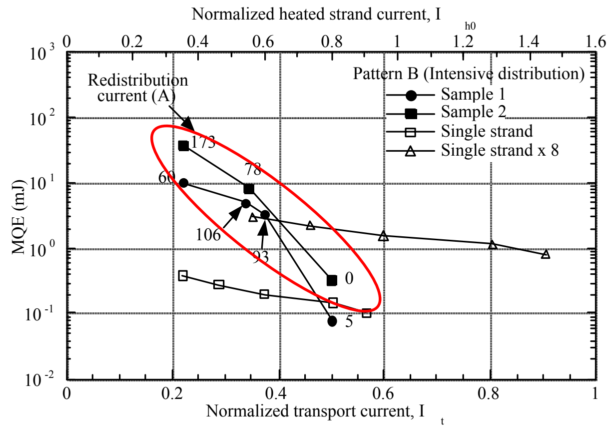
MQE of (3) did not decrease drastically when $I_t =< 0.55$, which is corresponding to $I_{h0} =< 0.8$.

Therefore when a cable has worse inter-strand contact and its inter-strand distribution is sparse by some reason, its MQE is significantly improved even so the inter-strand current distribution is not uniform.

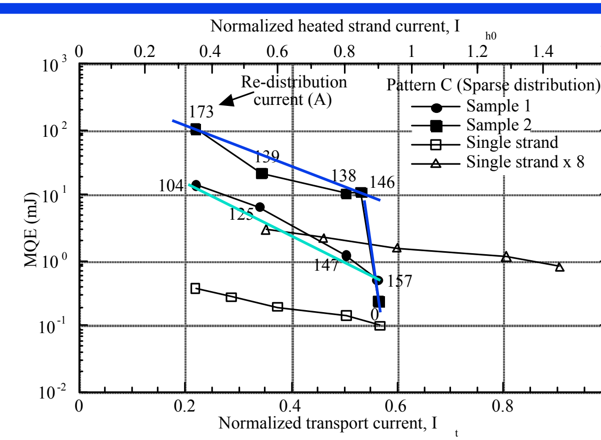
MQE vs. I_{h0}



Pattern A (Uniform)



Pattern B (Intensive)



Pattern C (Sparse)

In Unform and Intensive Distribution:

Profiles of MQE vs I_{h0} were nearly same.

Strand without current didn't improve MQE much in intensive distribution.

In Sparse Distribution:

MQE vs. I_{h0} was better especially in the worse contact sample.

Sparse distribution improved MQE, even so some strands transported much current than the others.

Conclusion

To examine the influence of inter-strand current distribution on current redistribution and MQE,
Two types of eight-strand Rutherford cables with different strand surfaces ware tested.

Current Redistribution :

In uniform and intensive distribution:

Peak value of redistribution current during recovery process was proportional to heated strand current when cable transported smaller current.

In sparse distribution :

Proportional redistribution current was observed up to larger transport current.

Possible reasons :

Sparseness of initial strand current distribution
and Balance of Joule heat in strands that transports current.

MQE

In sparse current distribution:

Worse contact cable was significantly improved , even so sparse distribution is one of non-uniform distributions.