CHATS
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Effect of combination of twist pitches on distribution of strands appearing on cable surface in CICC

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Outline

1. Background and Objective
2. Experiment of a resistance distribution between strands and a copper sleeve at LHe temperature
3. Calculation of a resistance distribution between strands and a copper sleeve using computed strand paths
4. Influence of a combination of twist pitches on a distribution of strands appearing on cable surface
5. Summary

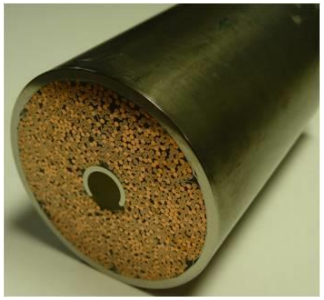
Background and Objective

Superconducting coils used for fusion reactors and SMES are formed from a Cable-in-Conduit-Conductor (CICC).

i. Cable-in-Conduit Conductor (CICC)

✓Composed of many superconducting strands twisted in multiple stages (usually 4~5 stages) for large current capacity.

✓Strands are compacted into a metallic conduit for high mechanical strength.



CICC

However, ………

✓ Critical current of a CICC is lower than the expected.

➡ partly explained by filament fracture and unbalanced current.

Background and Objective

One of the reasons is unbalanced current distribution caused by inhomogeneous contact resistances between a copper sleeve and strands at joint called "wrap joint".

ii. CICC Joint (Wrap Joint)

✓Two cables without conduit are inserted into a copper sleeve to join each other.

✓Strands are in contact with a copper sleeve on the cable surface.

✓Current flow between two CICCs through a copper sleeve.

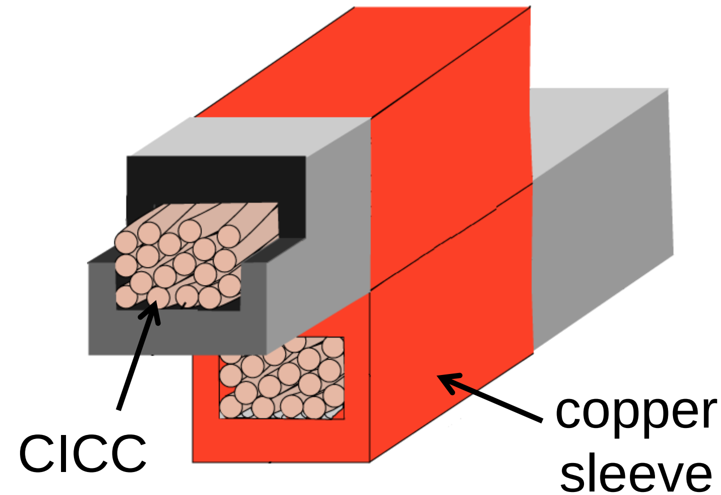


Fig. Schematic view of a CICC wrap joint.

✓Contact condition between a strand and a copper sleeve was estimated to be inhomogeneous by our calculation.

➡ It has been unclear that the resistance distribution between strands and a copper sleeve is inhomogeneous actually.

Objective of this study

✓The resistance distribution **becomes inhomogeneous**?

⇨ ✓**We measured resistances** between each strand and a copper sleeve.

✓The resistance distribution **relates to contact condition**?

⇨ ✓**We calculated the resistance** distribution using the calculated **strand paths.**

We examined the influence of a combination of twist pitches on a distribution of strands appearing on cable surface using the calculated strand paths.

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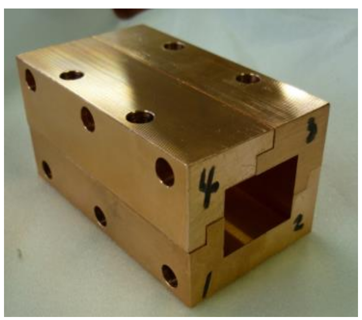
Specifications of Measurement Sample

CICC (LHD OV coil)

number of strands	486
material of strand	NbTi / Cu
strand diameter [mm]	0.89
cable size [mm]	20.5 × 24.8
cable twist pitch [mm]	70/120/170/250/400



Copper Sleeve

length [mm]	75
size [mm]	18.8 × 23.0

The inner shape of the sleeve was designed such that **the void fraction of the CICC changed from 38% to 30%.**

Indium Sheet

thickness [mm]	50

(Simulates the solder coating)

Simple model "Wrap Joint"

1. A conduit and a stainless wrap were removed at one end of a sample.
2. The conduit and the stainless wrap were removed within 75mm in length.
3. A thin indium sheet was wrapped around the cable.
   The wrap of indium sheet simulated the solder coating in a real wrap joint.
4. The copper sleeve was installed on the cable with the indium sheet.

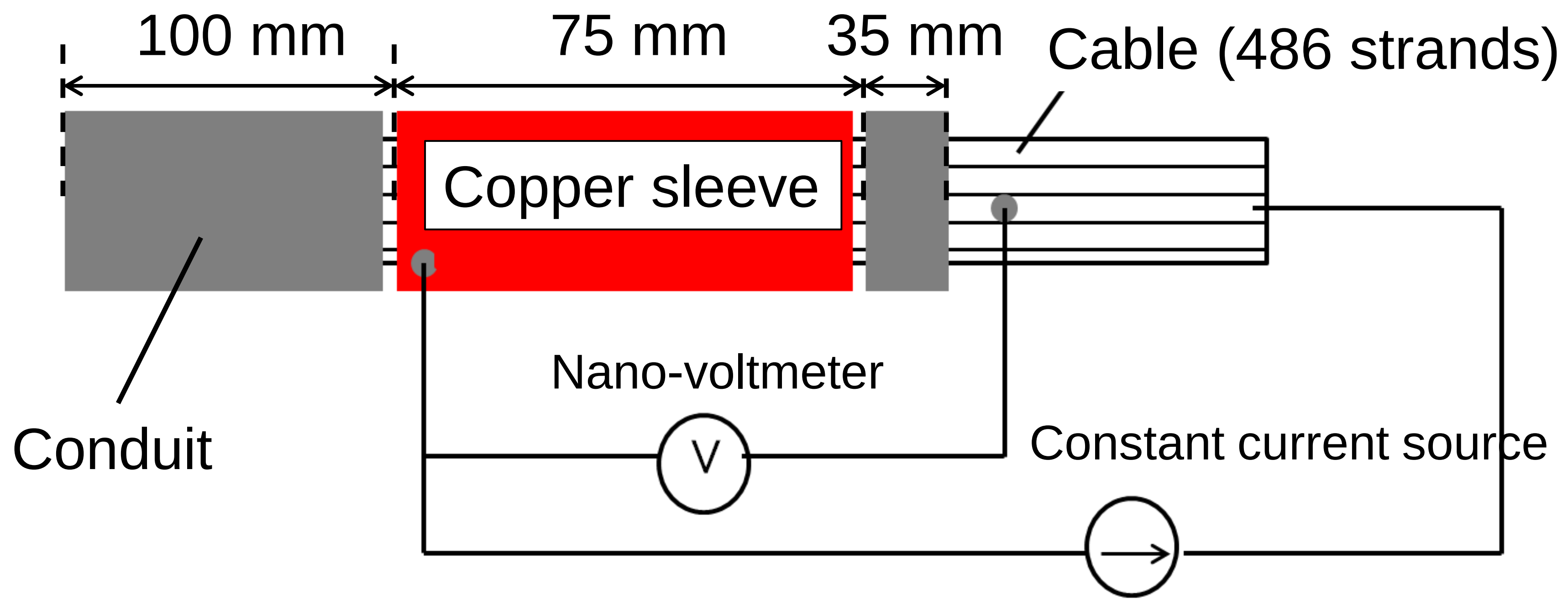


Fig. Schematic view of a measurement sample arrangement.

Simple model "Wrap Joint"

We measured the contact resistance between the copper sleeve and each strand using the four-terminal method at the LHe temperature (4.2K).

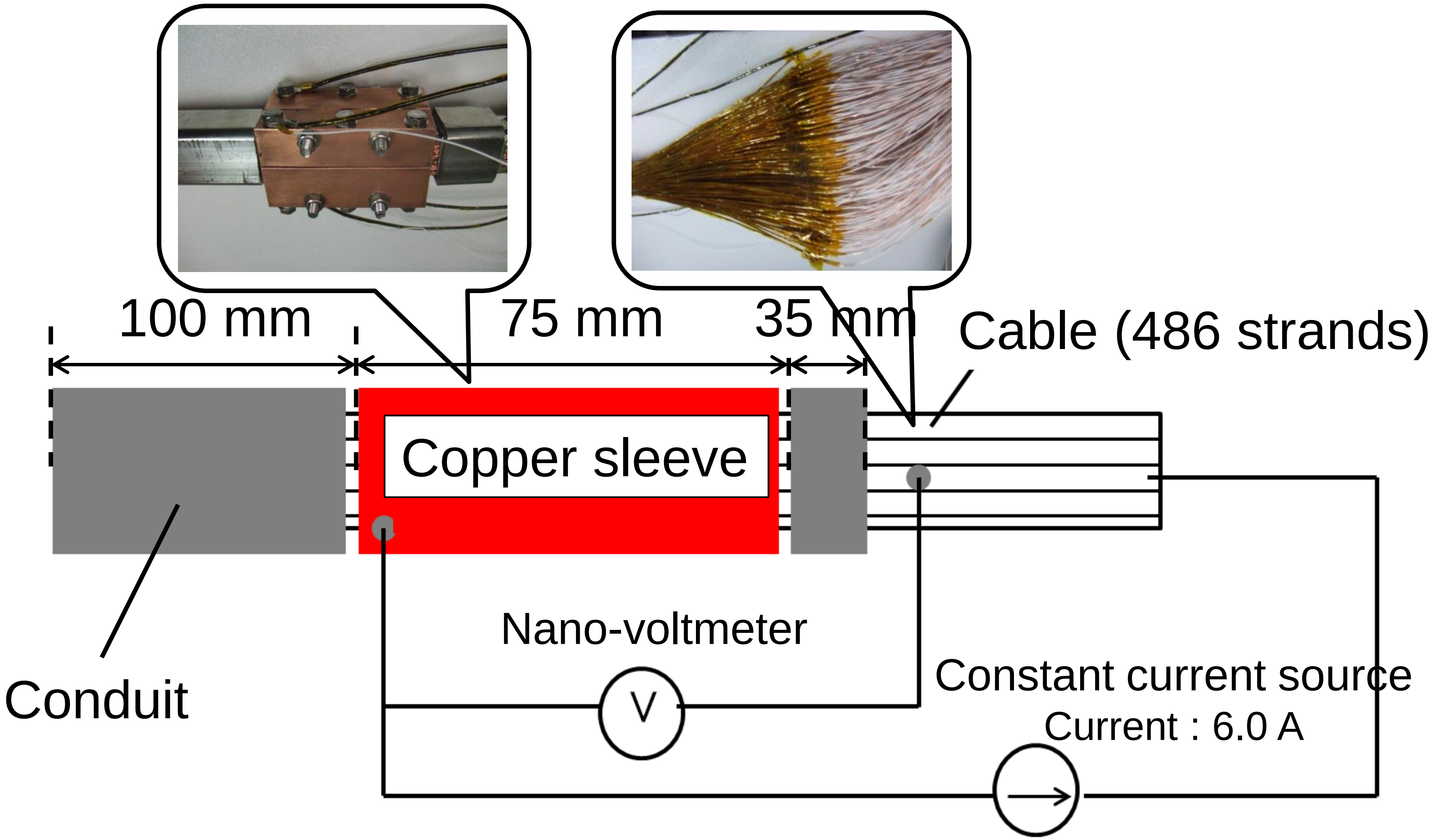


Fig. Schematic view of a measurement sample.

Measurement Results

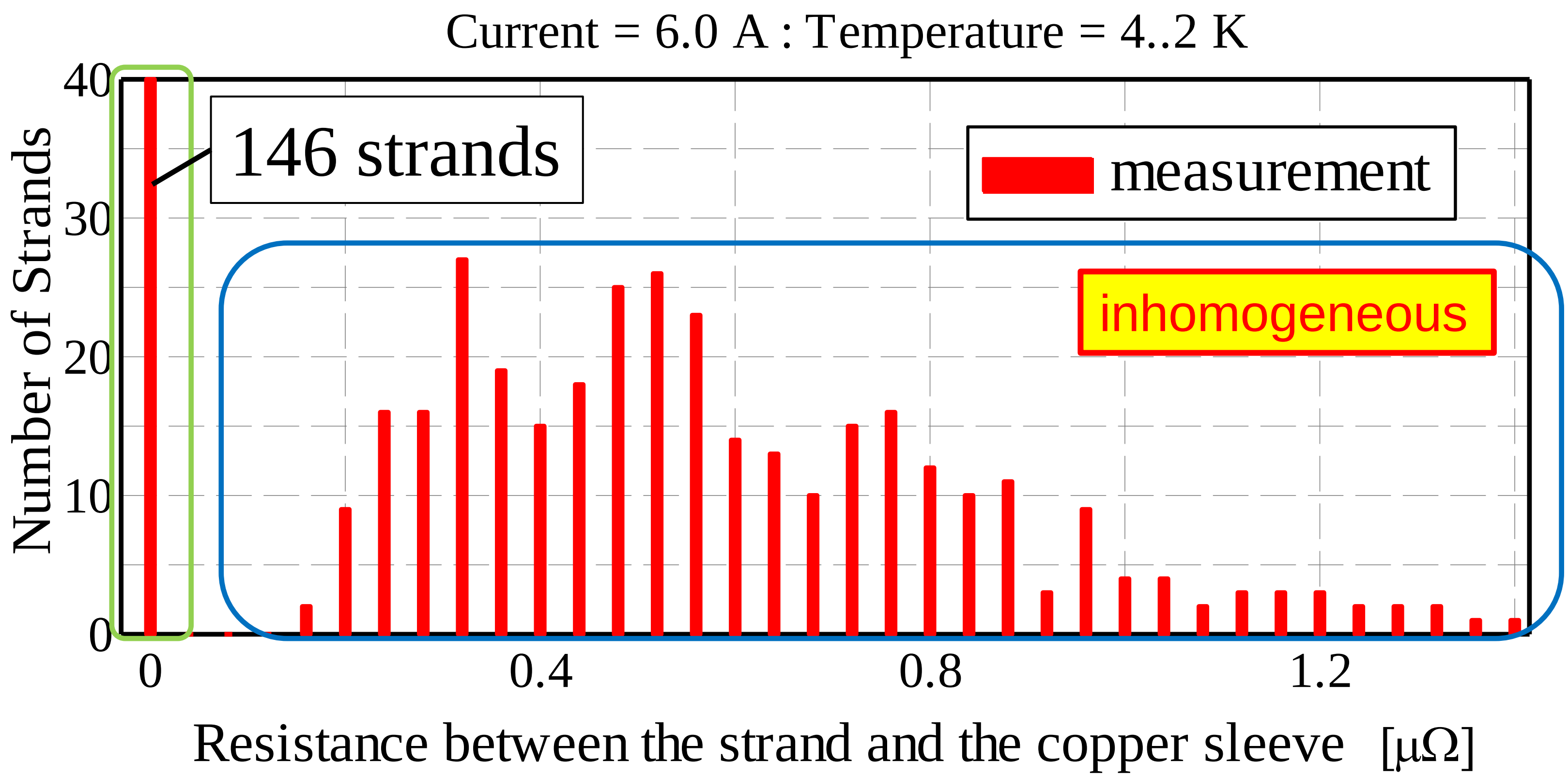
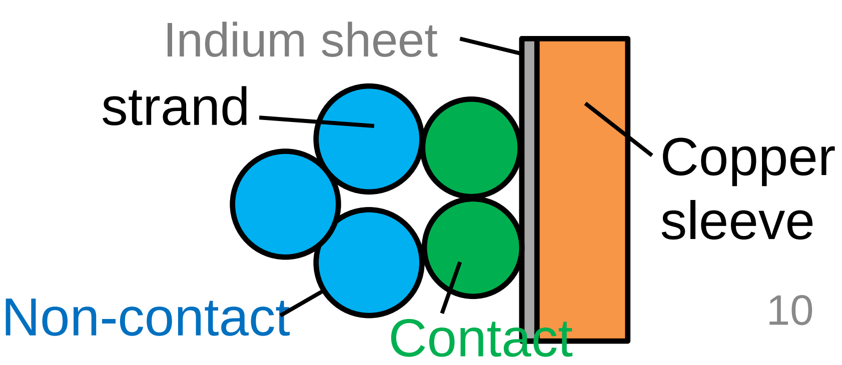


Fig. Measurement resistance distribution between the strands and the copper sleeve.

The 0 ohm strands are considered to be in direct contact with the copper sleeve through the indium sheet .



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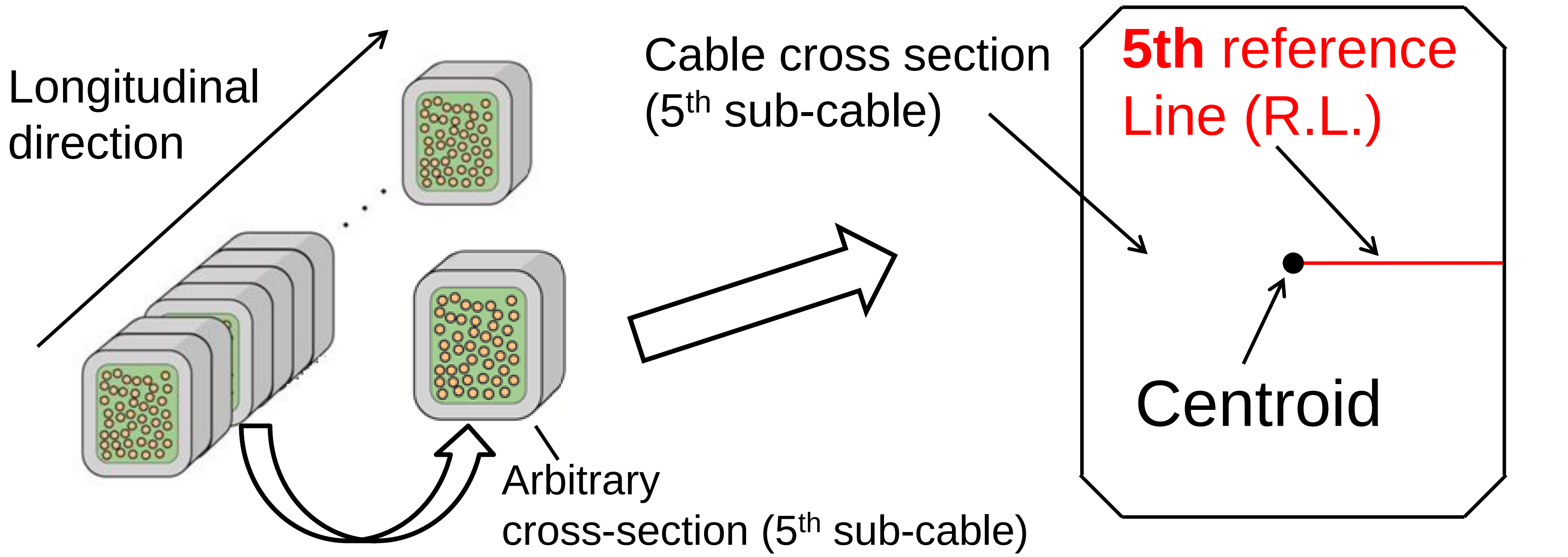
Evaluation of the Strand Path

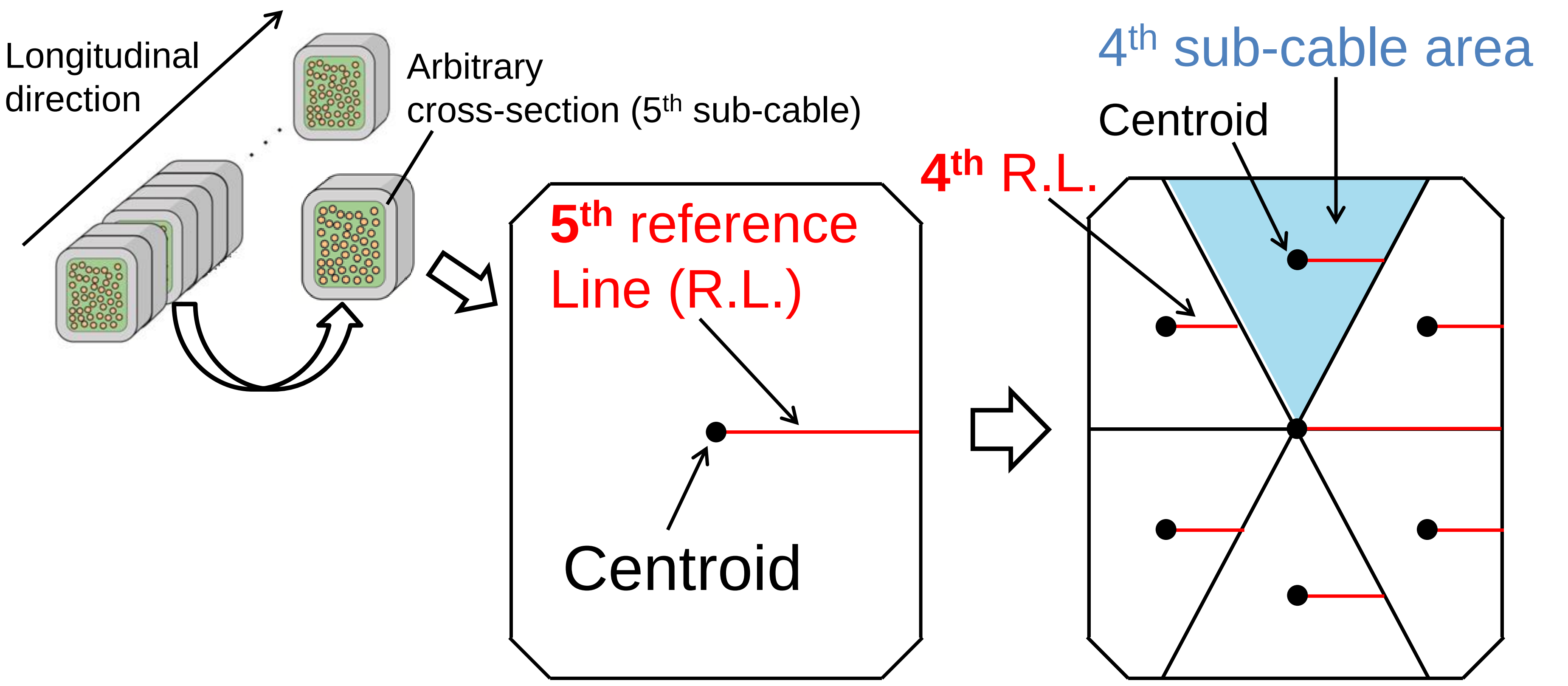
In order to calculate the resistance distribution between the strands and the copper sleeve, we evaluated all strand paths by numerical approach considering the manufacturing process of the CICC. ➡ **Equal-area method**

We evaluated all strand positions at each cross-section every 10mm .



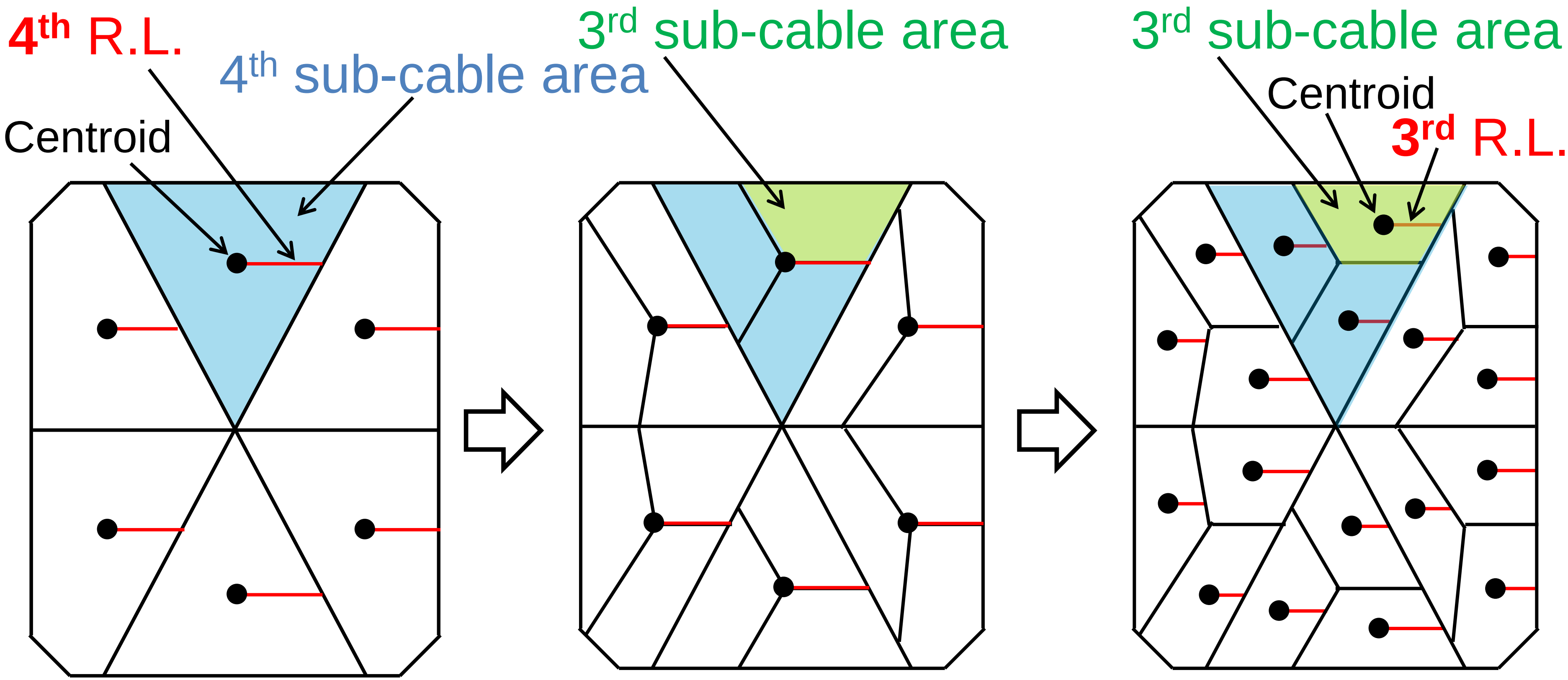
1. Draw the outer shape of the 5th sub-cable in the cross section of a sample CICC.
2. Draw a “reference line” from the 5th sub-cable centroid to the outer shape.

Evaluation of the Strand Path



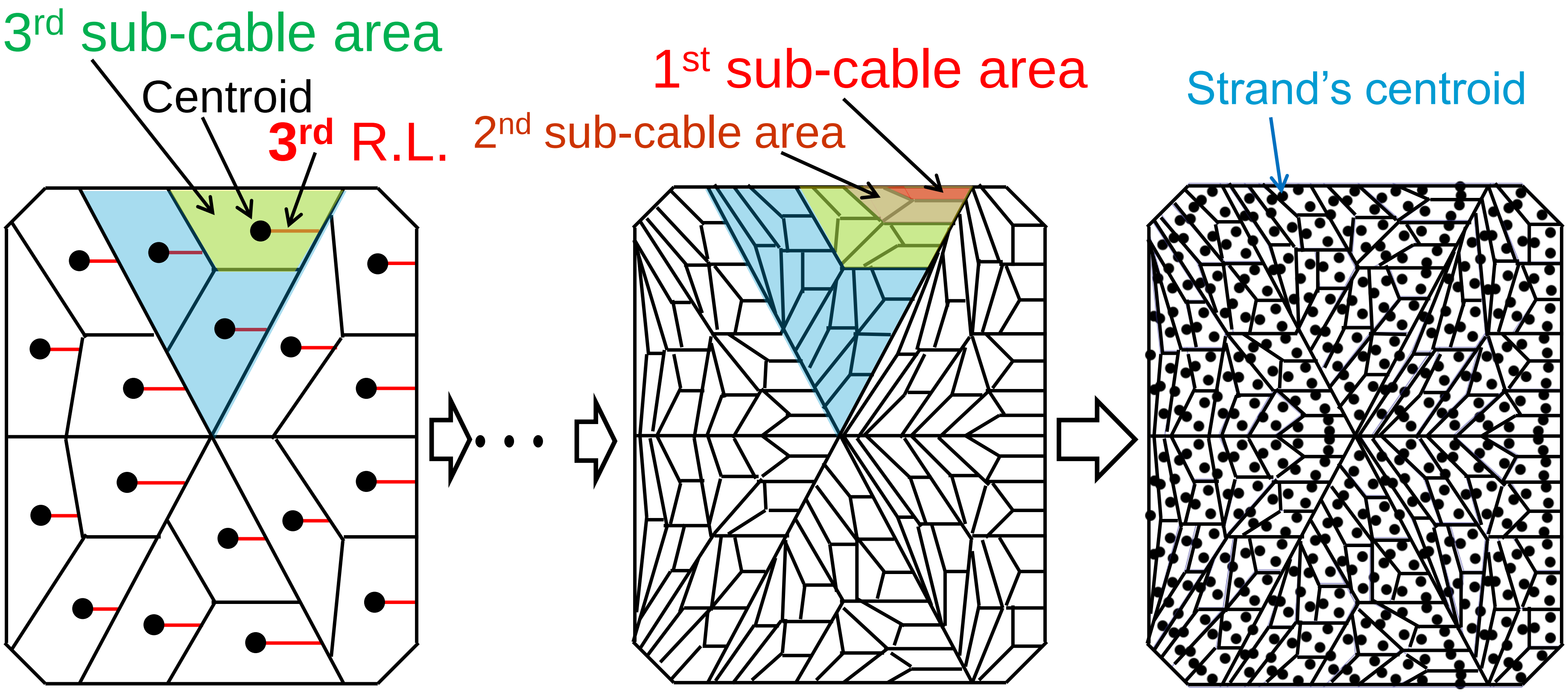
3. Divide the cross section (5th sub-cable) into six 4th sub-cables with same area on the basis of the 5th reference line. Because the same order sub-cables consist of the same number of strands.
4. Draw a "4th reference line" from the 4th sub-cable centroid to the outer shape of the 4th sub-cable in each 4th sub-cable area.

Evaluation of the Strand Path



5. Divide each 4th sub-cable area into three 3rd sub-cables with same area on the basis of the 4th reference line.
6. Draw a "3rd reference line" from the 3rd sub-cable centroid to the outer shape of the 3rd sub-cable in each 3rd sub-cable area.

Evaluation of the Strand Path



7. Divide each 3rd sub-cable area into three 2nd sub-cables with same area.
8. Similarly, divide each 2nd sub-cable area into three 1st sub-cables with same area.
9. divide each 1st sub-cable area into three strands and obtain all strands' centroid's position at the cross-section of the cable.

Evaluation of the Strand Path

10. Rotate each sub-cable about its centroid. The rotation angle depends on the longitudinal position (*z*). The rotating angle θ_n of *n*-th order sub-cable is given as follows:

$$\theta_n = \theta_{n0} + \frac{2\pi}{p_n} z$$

n : R.L. order (1~5)

θ_n : rotation angle of *n*-th R.L.

θ_{n0} : initial rotation angle of *n*-th R.L.

P_n : twist pitch of *n*-th sub-cable

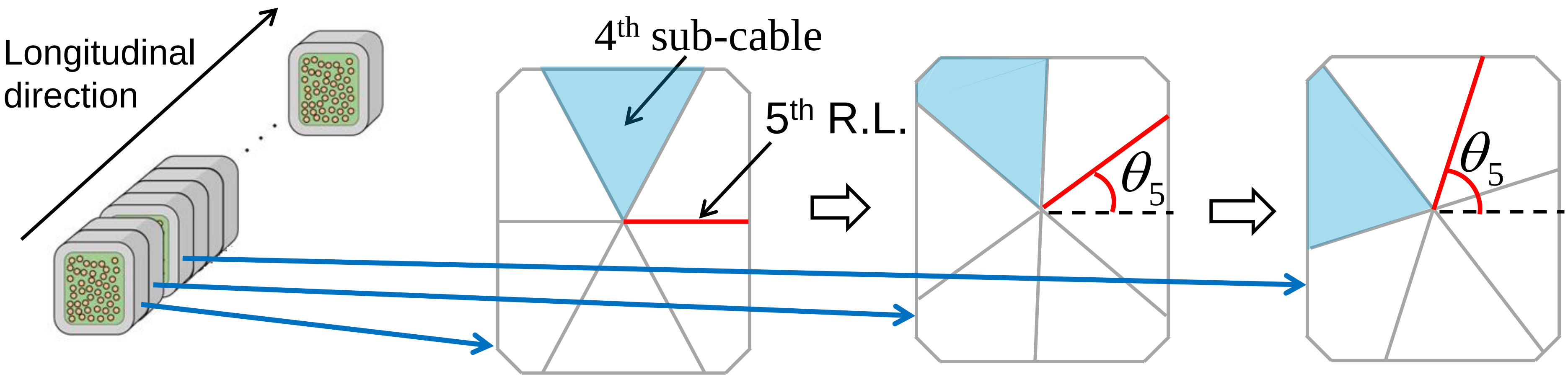


Fig. Schematic view of 5th reference line and 4th sub-cables' rotation at a cross-section.

The cable contraction due to refrigerant cooling was not considered in this method.

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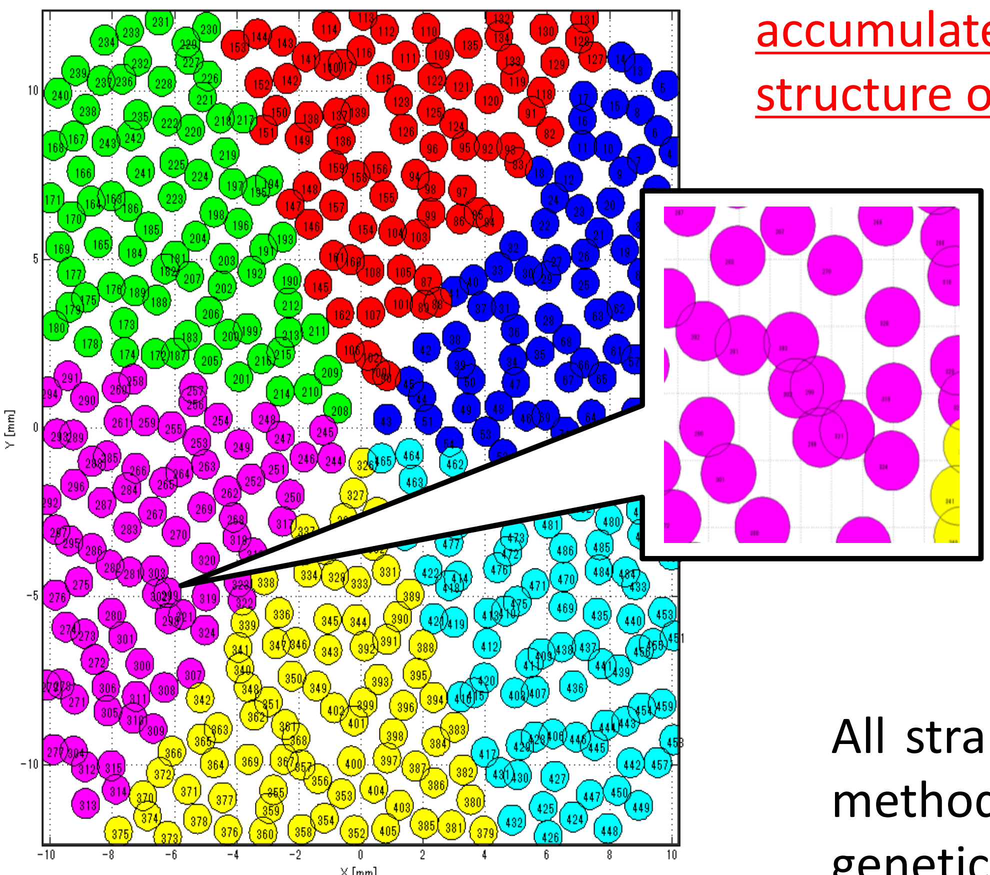
Evaluation of the Strand Path

Our technique "equal-area method" to evaluate strand's positions ignores the overlap among strands. However, **actual strands do not overlap**, and **each strand's contact region is pressurized**. In this situation, the elastic potential energy is accumulated in the strands. In addition, the elastic potential energy is also accumulated by the deformation of the twist structure of strands.



Evaluated strands' positions at a cross section by "equal-area method".

We introduce the elastic potential energy into our method.

We search strand's positions with the minimum elastic potential energy.

All strand's positions evaluated by "equal-area method" are iteratively perturbed using a genetic algorithm until the elastic potential energy in the cross section is minimized.

Evaluation of the Strand Path

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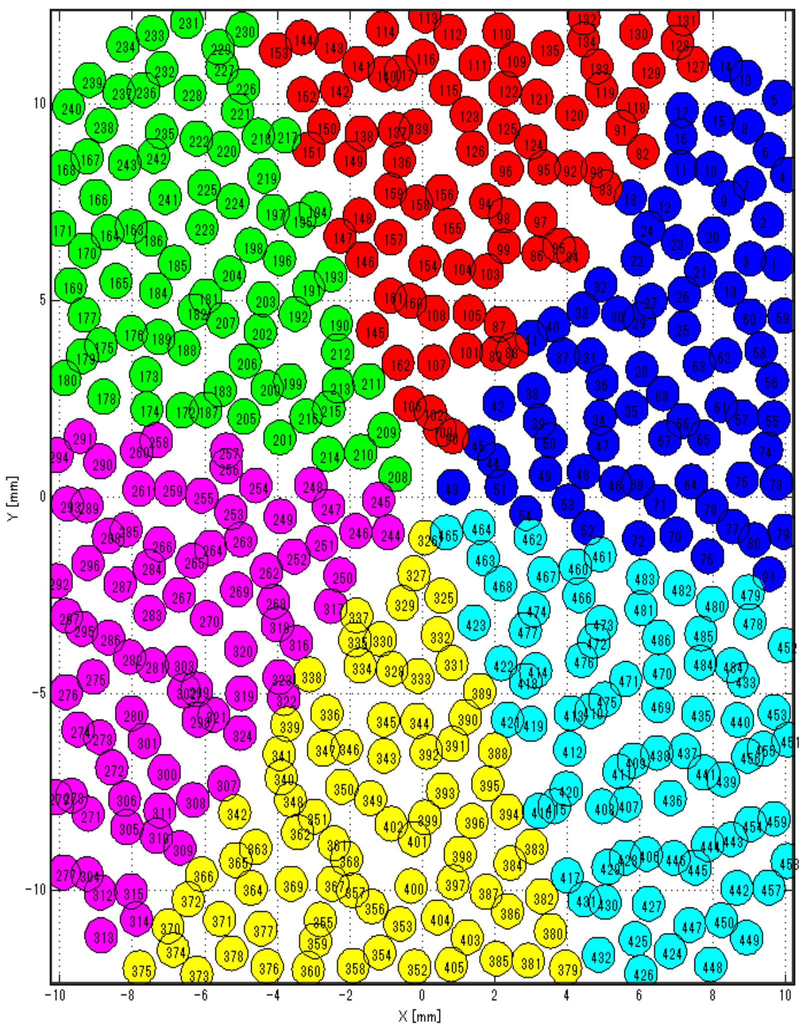
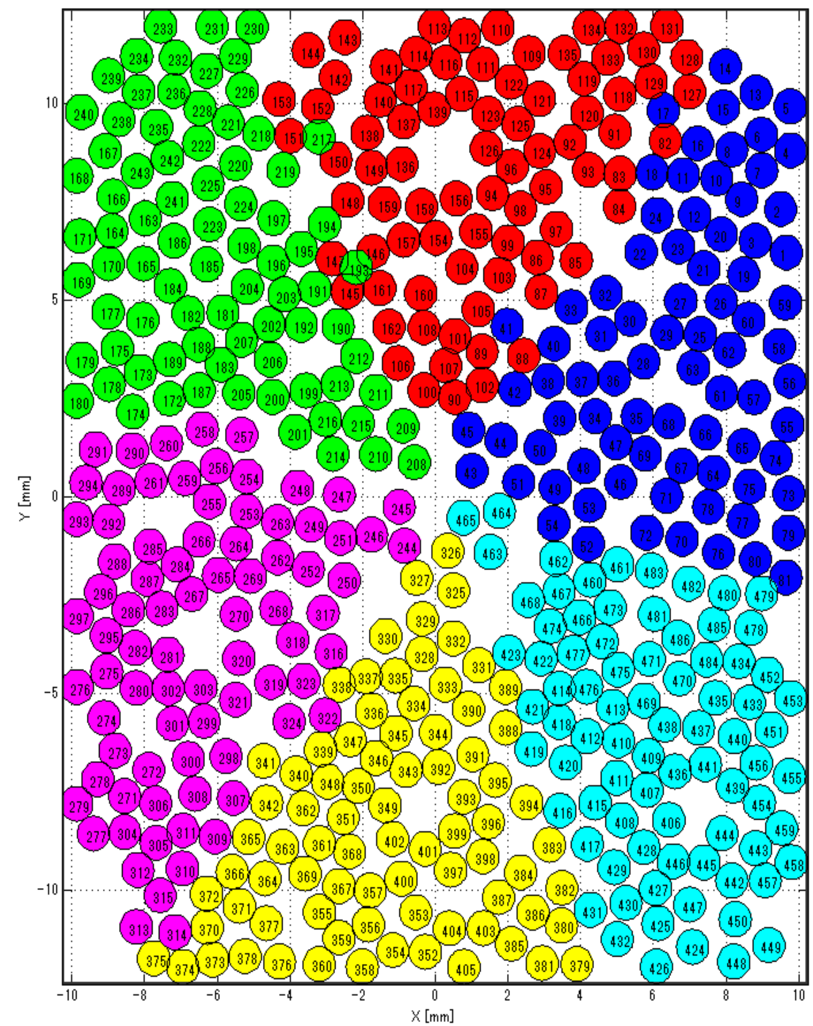


Evaluated strand's positions at a cross section by only "equal-area method".



Evaluated strand's positions at a cross section **in consideration of the elastic potential energy minimization**.

Calculation of the Contact Resistance

- We assumed **the contact resistance** **between a strand and a copper sleeve** **to be 0 Ω** according to our experimental results.
- We assumed that **the contact resistance "R_c"** **between strands** only **depends on the contact length**.

➢ The contact length "l_c" between two strands was considered as the sum total of partial contact length.

➢ The contact conductance between the strands "G_c" was obtained by

$$G_c = G_a \times l_c$$

G_c: contact conductance [S]

G_a: constant value [S/m]

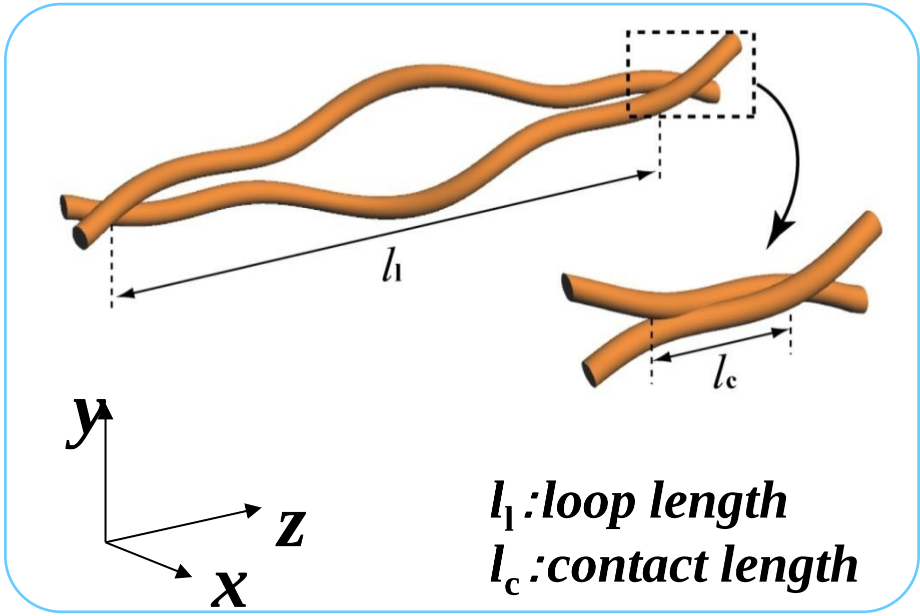


Fig. Schematic view of two strands contacting each other.

Resemblance between the resistance distribution

The calculated resistance distribution between the strands and the copper sleeve depends on the value “Ga” and contact length.

We analyzed the similarity between the calculated resistance distribution and the measured one using “cosine similarity” as a function of “G_a”.

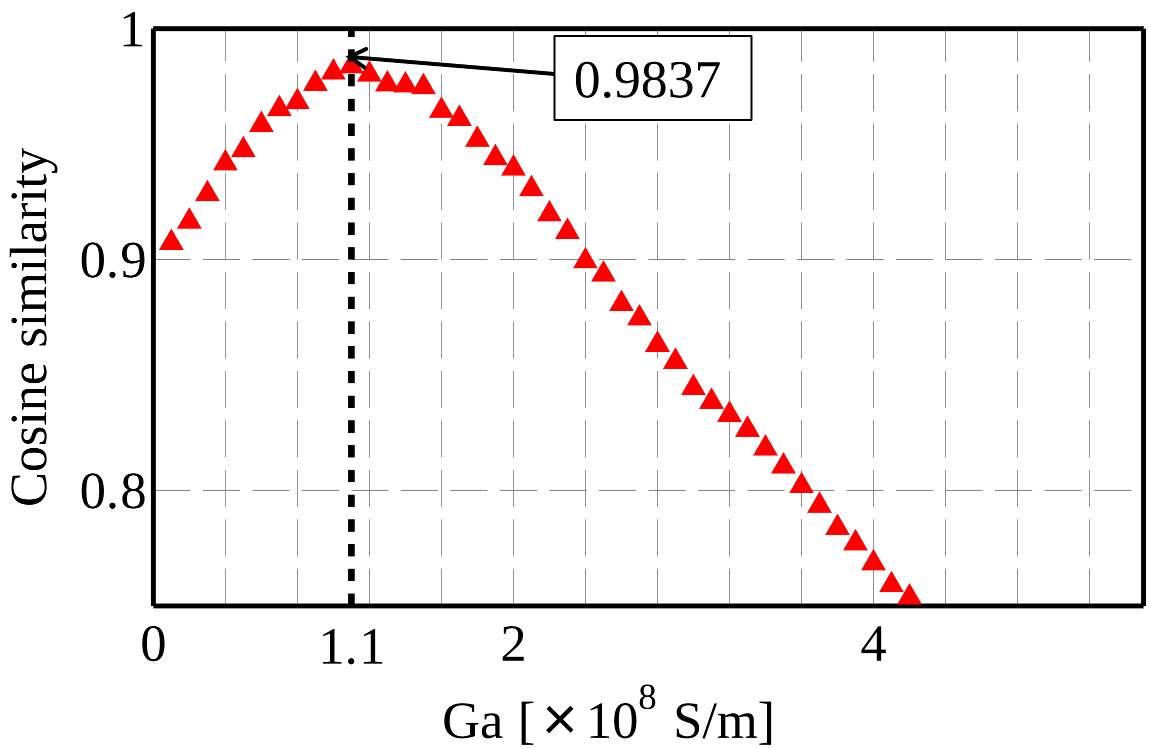


Fig. The relation between the cosine similarity and “Ga” contact conductance per meter between strands.

Comparison of Resistance Distribution

Tab. Characteristics of measured and calculated resistance distribution.

/	Mea.	Cal.
number of 0 Ω strands	146	148
average [μΩ]	0.4006	0.3890
standard deviation [μΩ]	0.3558	0.3465

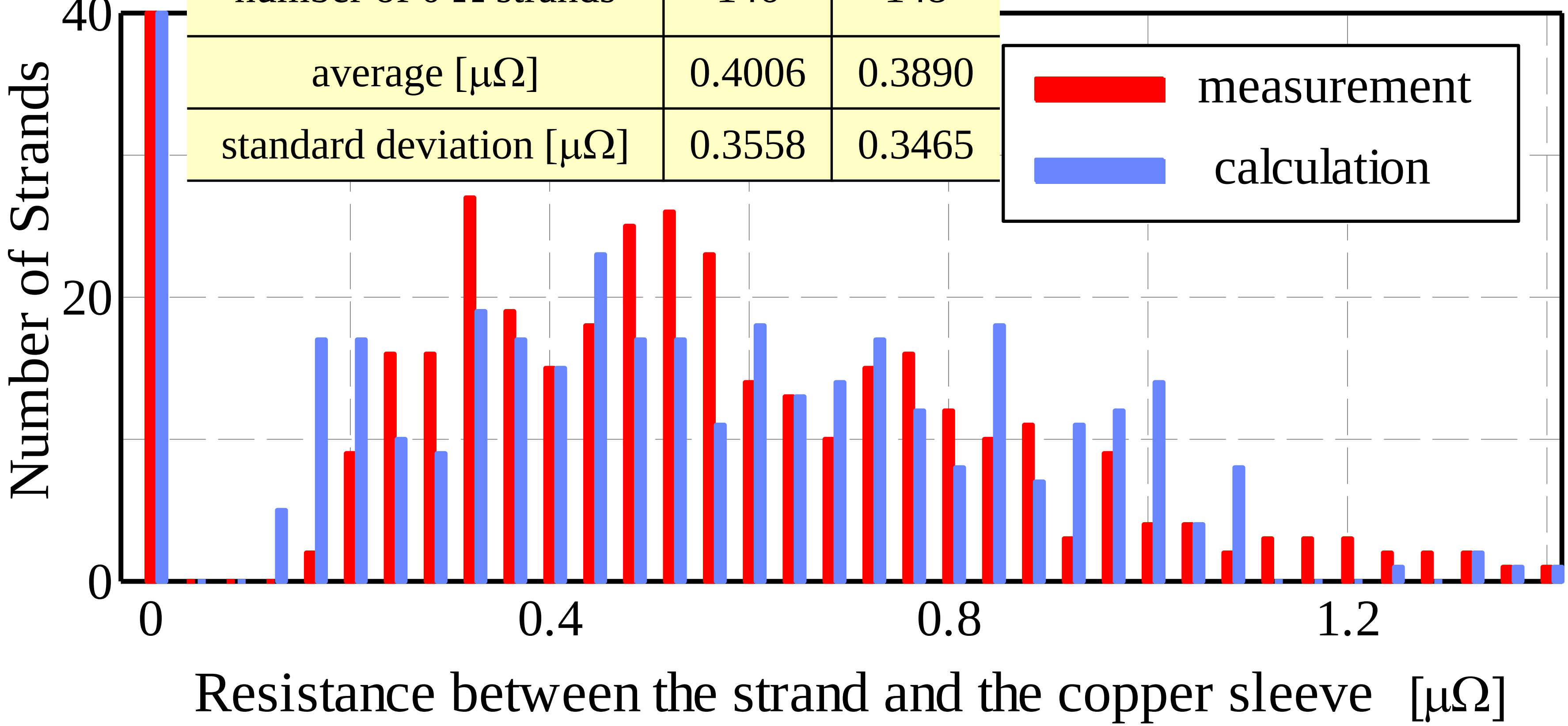


Fig. The comparison of the calculated resistance distribution with the measured resistance distribution between the strand and the copper sleeve.

Comparison of Resistance Distribution

The homogeneity of the resistance distribution between the copper sleeve and strands is strongly dependent on whether the strand is in direct contact with the copper sleeve or not.

The CICC structure should be arranged such that all strands are in direct contact with the copper sleeve.

Since the strand paths depend on the combination of twist pitches, it is important to choose the suitable twist pitches for realizing homogeneous resistance distribution at joint.

Fig. The comparison of the calculated resistance distribution with the measured resistance distribution between the strand and the copper sleeve.

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Influence of Twist Pitch on Contact Situation

Tab. Specifications of analyzed model of a CICC.

number of strands	486
strand diameter [mm]	0.89
cable size [mm]	20.5×24.8
Cable length [mm]	400
Actual model :cable twist pitch [mm]	70/120/170/250/400
Analyzed model :cable twist pitch [mm]	**40**/**60**/**100**/**<u>160~280</u>**/400
Copper sleeve length [mm]	400
Copper sleeve inner size [mm]	18.8×23.0

- It has been reported that a contact situation is improved between a strand and a copper sleeve when twist pitches have been shorter.
- The strand has the degradation of the critical current when twist pitches of 1st and 2nd sub-cable are shortened too much.

We investigated the influence of the combination of twist pitches of each sub-cable on contact length between the strand and the copper sleeve **by varying the twist pitch of the 4th sub-cable from 160 to 280 mm**.

Influence of Twist Pitch on Contact Situation

Cable twist pitches : 40/60/100/160~280/400

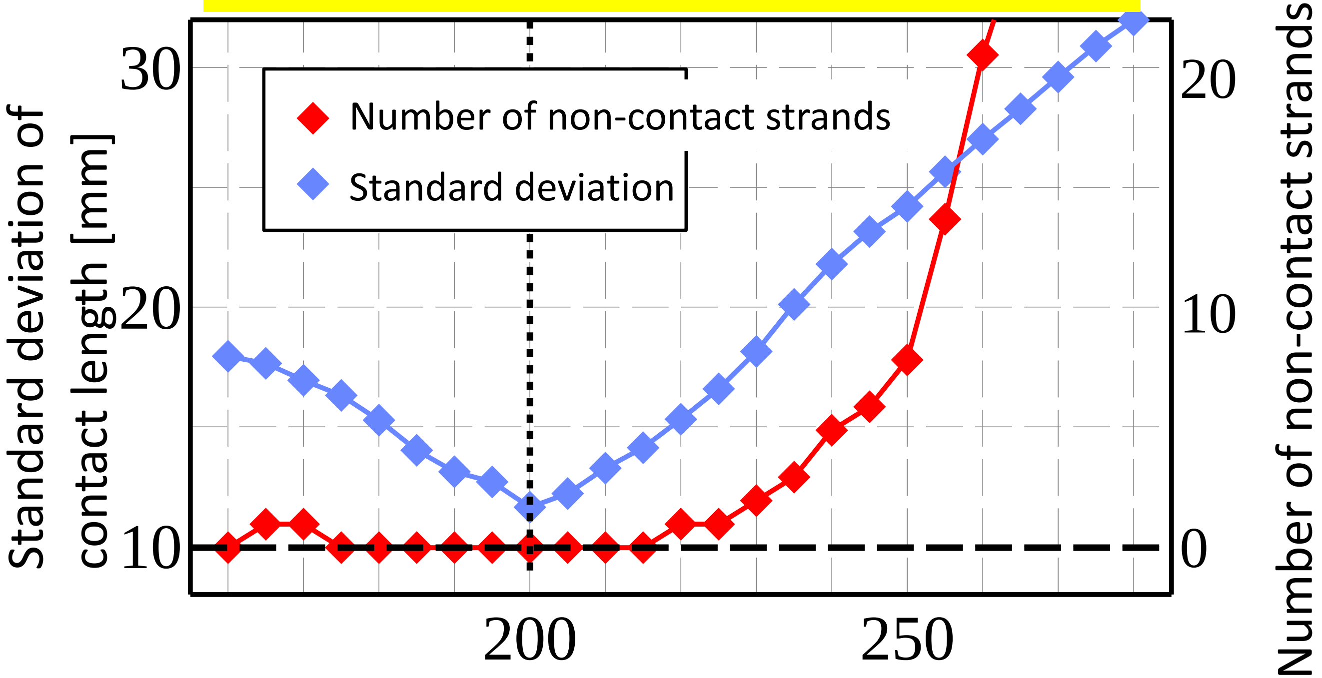


Fig. Influence of the twist pitch of the 4th sub-cable on contact situation between strands and the copper sleeve.

<Actual model>

Number of non-contact strands : 66

Standard deviation of contact length : 32.54 mm

All strands are in contact with the copper sleeve and standard deviation of contact length between strands and the copper sleeve becomes the minimum, <u>when twist pitches of 3rd and 4th sub-cables are aliquot part of a twist pitch of a 5th sub-cable</u>.

Cable twist pitches : 40/60/100/200/400

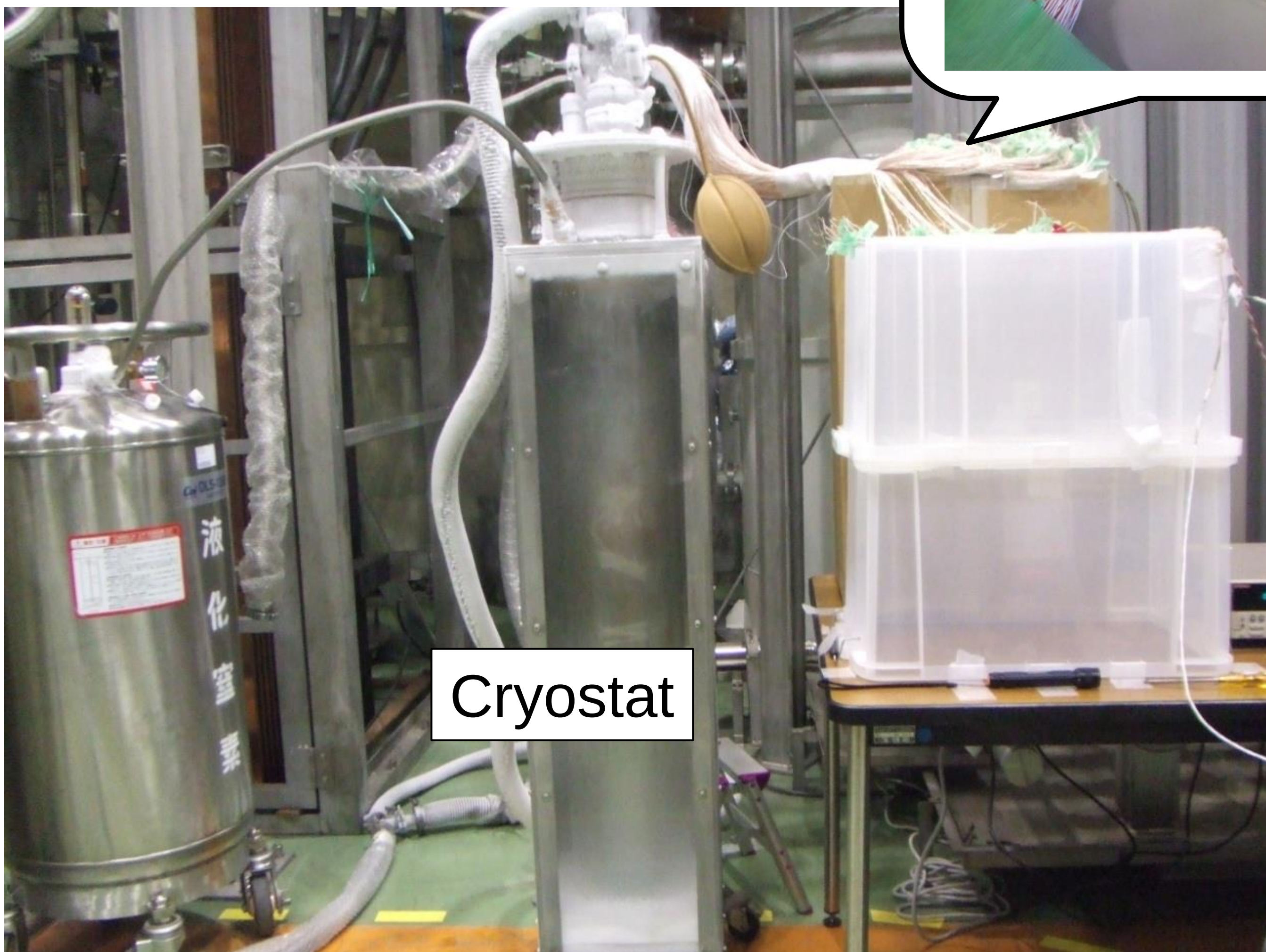
Summary

- We measured the contact resistance between the copper sleeve and each strand at a joint which simulated the wrap joint.
  - The non-uniformity of contact resistances between the copper sleeve and the strands was observed.
  - The homogeneity of the resistance distribution between the copper sleeve and strands is strongly dependent on whether the strand is in direct contact with the copper sleeve or not.
- The CICC structure should be arranged such that all strands are in directly contact with a copper sleeve at a joint.
  - It is expected that the resistance distribution between the strand and the copper sleeve is homogeneous, when twist pitches of 3rd and 4th sub-cables are aliquot part of a twist pitch of a 5th sub-cable.

Thank you for your attention.

Measurement system

We measured the resistance distribution
and the copper sleeve at LHe temperatu



Calculation of Elastic Potential Energy

calculate following component in each section

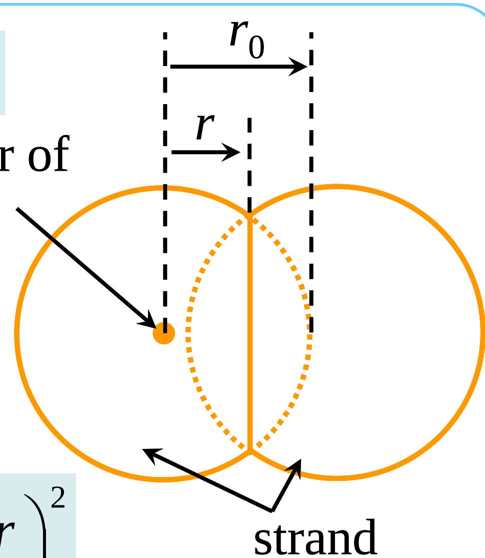
- ☑ w_{strand} , $w_{conduit}$

  energy of strand deformation by strand and conduit

- ☑ w_n

  energy of *n* stage sub-cable's deformation

w_{strand}, w_{conduit}

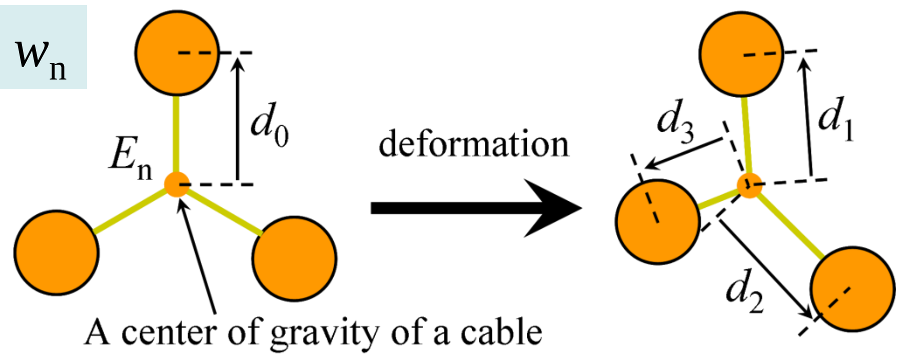


$$\Delta r = r - r_0$$

$$w = \frac{1}{2} E_{\mathrm{strand}} \left(\frac{\Delta r}{r_0} \right)^2$$

E_{strand}: Young's modulus of strand

w_{n}



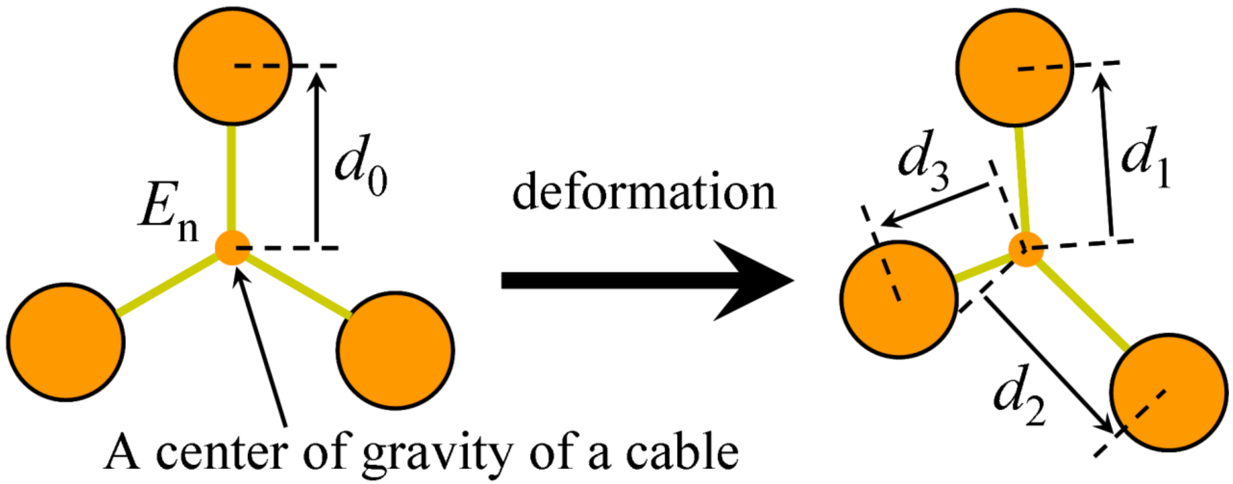
$$w_{\mathrm{n}} = \frac{1}{2} E_{\mathrm{n}} \left\{ \left(\frac{\Delta d_1}{d_0} \right)^2 + \left(\frac{\Delta d_2}{d_0} \right)^2 + \left(\frac{\Delta d_3}{d_0} \right)^2 \right\}$$

E_{n}: hypothetical elastic modulus
(simulate twist under 3D component)

Evaluation of strands' positions

Evaluate all strands' positions in each section by

- ☑ *1st Sub-Cable (triplet) Deformation*
- ☑ *Loop Length between strands*
- ☑ *Contact Length between strands*



$$\textbf{Cable Deformation} = \sqrt{\left(\frac{d_1 - d_0}{d_0}\right)^2 + \left(\frac{d_2 - d_0}{d_0}\right)^2 + \left(\frac{d_3 - d_0}{d_0}\right)^2}$$

Schematic view of deformation of a triplet at a cross section.