Module assembly R&D of the Dual-Readout Calorimeter for future e+e- colliders

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On behalf of the Korea Dual-Readout Calorimeter Team

Saga-Yonsei Joint Workshop XVIII
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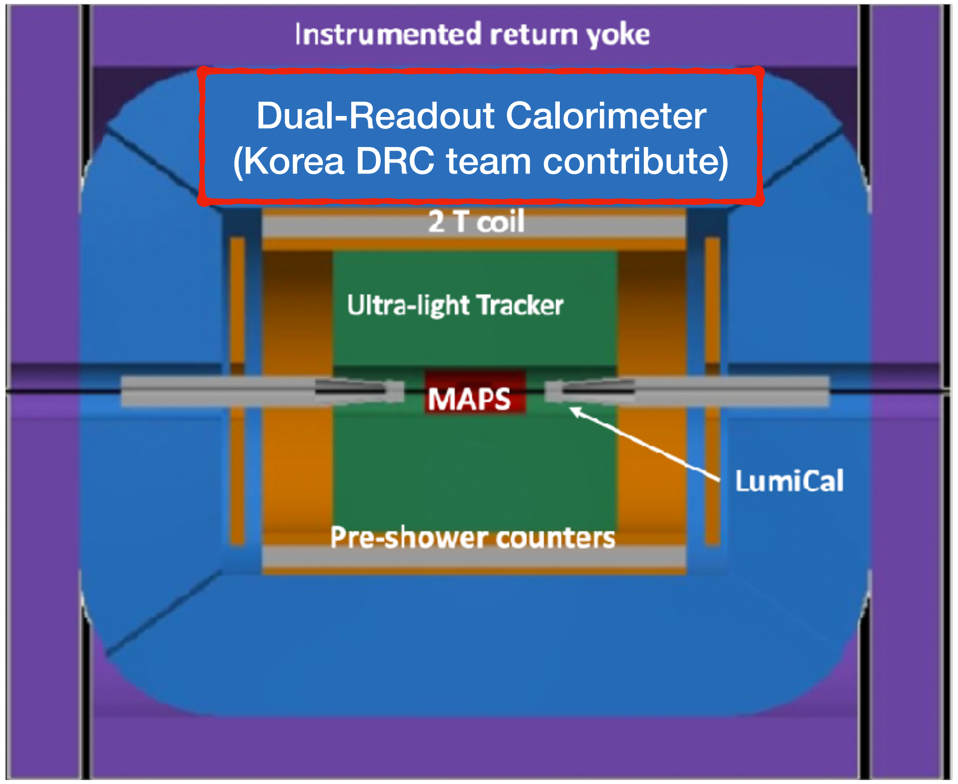
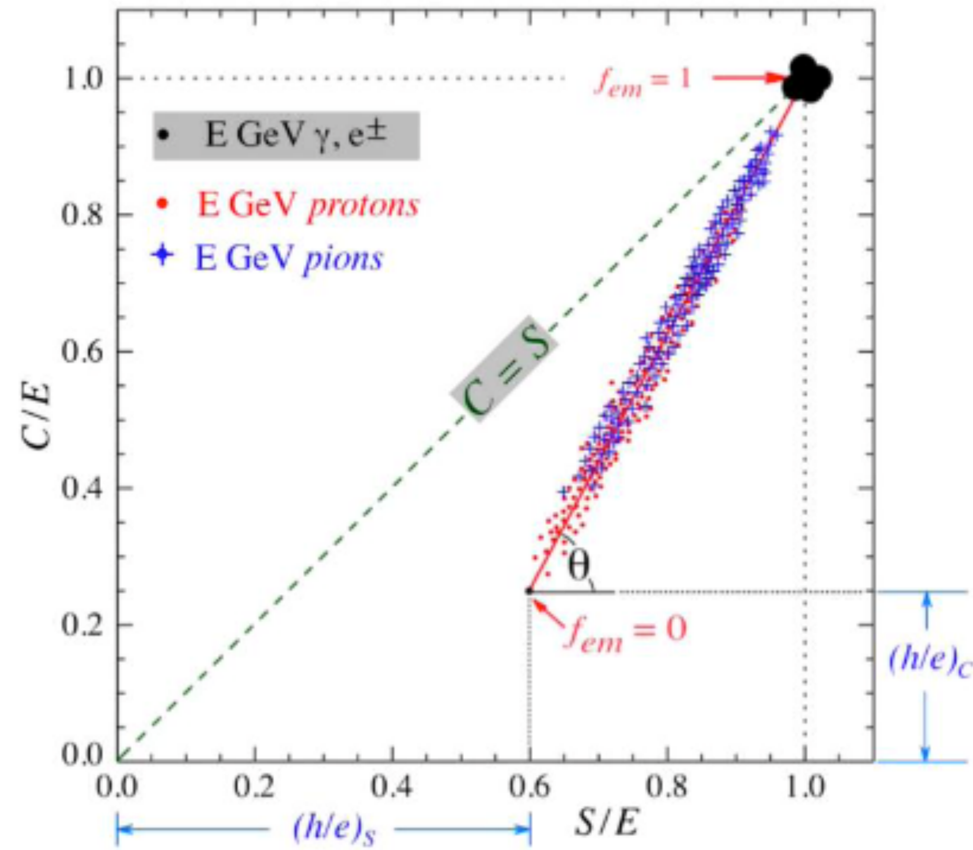
Outline

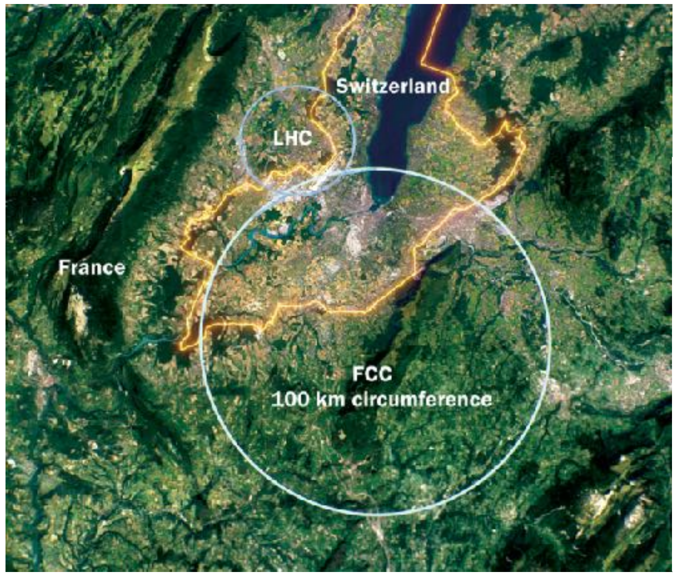
1. Introduction
2. Configuration
3. Process of Assembly
4. Readout System
5. Summary

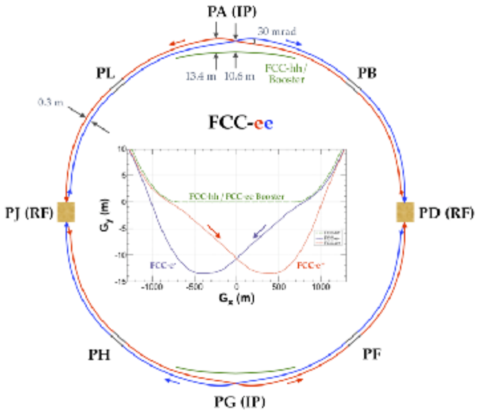
1. Introduction

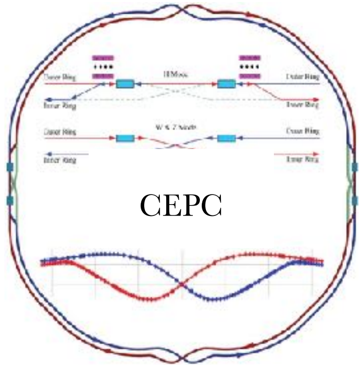
- **Dual-Readout Calorimeter**
  - I) The dual-readout calorimeter has been included in the conceptual design report of both **FCC-ee** and **CEPC**
  - II) **Non-gaussian electromagnetic fluctuations** are a major factor that makes it difficult to measure the energy of hadron shower
  - III) The dual-readout calorimeter offer **high-quality energy measurement** for both EM particles and hadrons simultaneously
  - IV) Outstanding energy resolution can be achieved by **measuring EM component** and **correcting hadron energy event by event**











2. Goal of Test Beam

1) Measurement Goal

Module 1	Module 2
Shower depth	Position resolution
Time resolution (MCP-PMT)	Time resolution (SiPM)
Longitudinal shower profile	Lateral shower profile
Light attenuation length	EM energy resolution
	Uniformity study

North area at CERN

2) R&D Goal

- Readout test (MCP-PMT vs. SiPM)
- Fiber type test (Shape/Cladding)
- Time resolution (< 50ps)

3) Training goal

- Training next-generation experts for DRC HW

- Timeline (*Preliminary*)

● Today

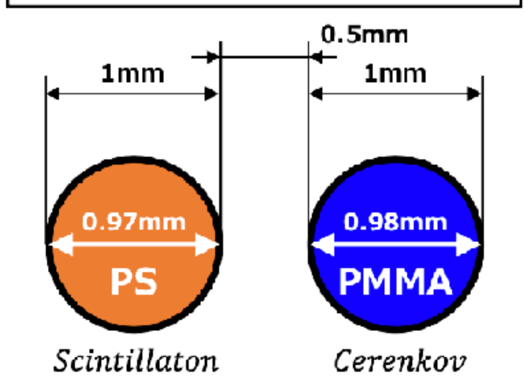
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Module	Rebuilding (fiber+Cu)		Attach readout / Test	Commissioning	Shipping to CERN	Test Beam		Analysis				

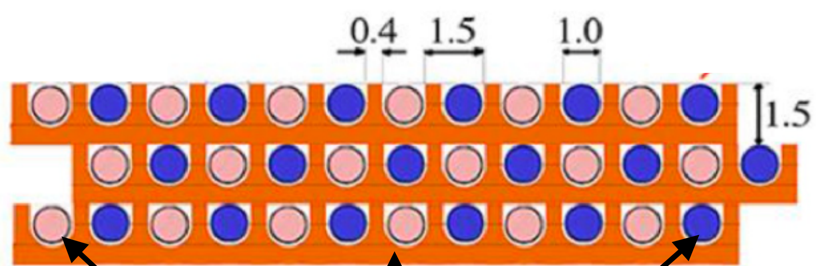
2. Configuration

- The dual-readout calorimeter can be divided by 2 parts in building process
  - i) Copper plate
    - **61 plates** are used to build a module
  - ii) Optical fibers
    - Čerenkov fibers: round shape and single cladding
      - Made by Mitsubishi, Japan
    - Scintillating fibers: **round** and **square** shape & **single** and **double** cladding
      - Made by Kuraray, Japan

- **Module 1**
  - 4 towers
  - Different shape & cladding for scintillating fibers
  - PMT & **MCP-PMT**
- **Module 2**
  - 9 towers
  - PMT & **SiPM**

Implemented Optical Fibers



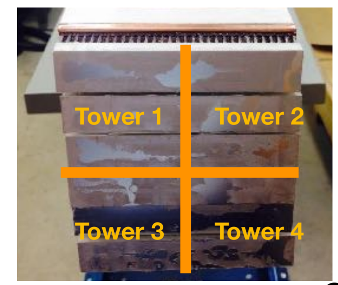


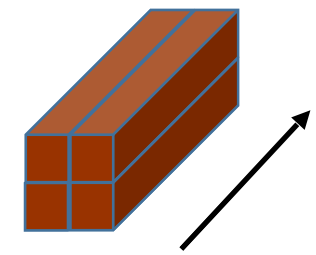
Scintillation (S)

Čerenkov (Č)

Cu:Te(Cu260,tellurium 0.35%)

Module #1 (2x2)





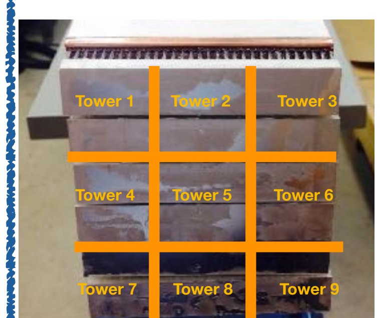
Module#1

Tower#1	Tower#2
Tower#3	Tower#4

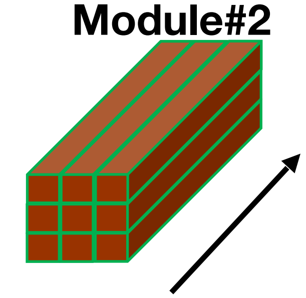
Combination of fibers for Module#1

	Tower #1	Tower #2	Tower #3	Tower #4
Scintillation fibers	Round / Single cladding	Round / Double cladding	Round / Single cladding	Square / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding	Round / Single cladding	Round / Single cladding
Readout detector (2*4 ch)	2 PMTs	2 PMTs	2 MCP-PMTs	2 PMTs

Module #2 (3x3)



Module#2



Module#2

Tower#1	Tower#2	Tower#3
Tower#4	Tower#5	Tower#6
Tower#7	Tower#8	Tower#9

Combination of fibers for Module#2

	Tower #1~4 and #6~9	Tower #5
Scintillation fibers	Round / Single cladding	Round / Single cladding
Cherenkov fibers	Round / Single cladding	Round / Single cladding
Readout detector (400+16 ch)	16 PMTs	400 SiPMs

3. Process of Assembly

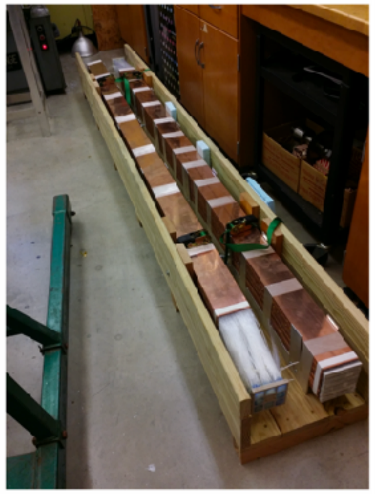
3-1. Preparation
3-2. Assembly
3-3. Reflector

3-1. Preparation

1) Clean up copper plates

- To build calorimeter, we have to disassemble and clean up all plates because they were used in 2016

US in 2016

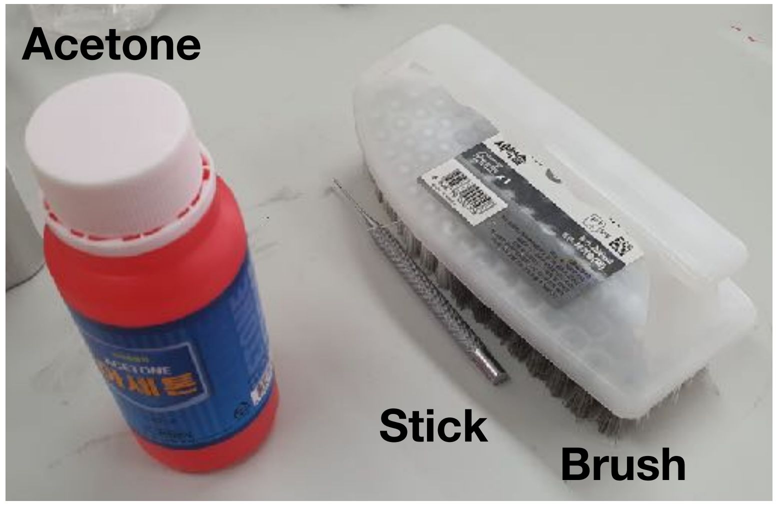


YU in 2020

- We tried to remove residual epoxy and dust using brush and acetone

Remove & classify the fibers

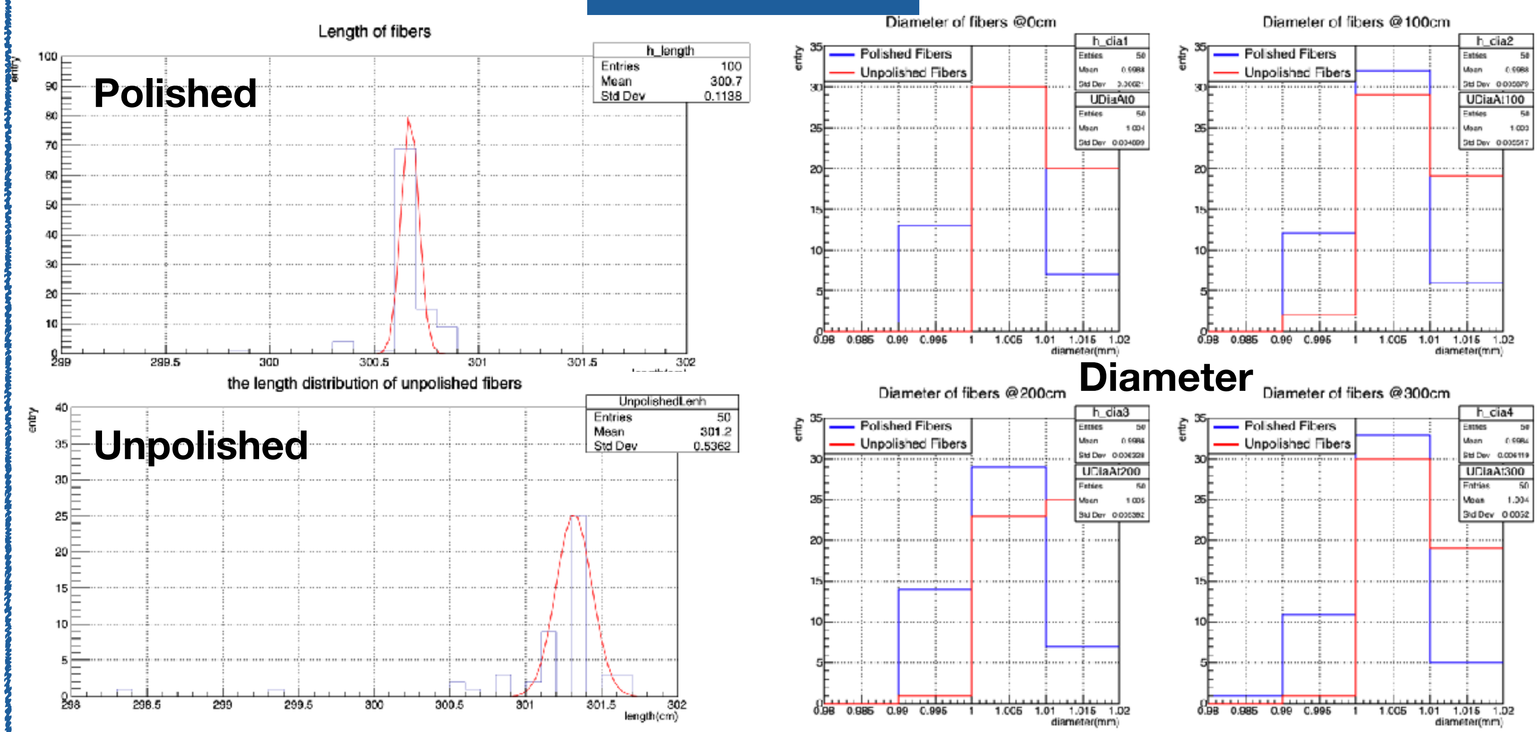
Clean up copper plates



2) Optical Fiber Treatment

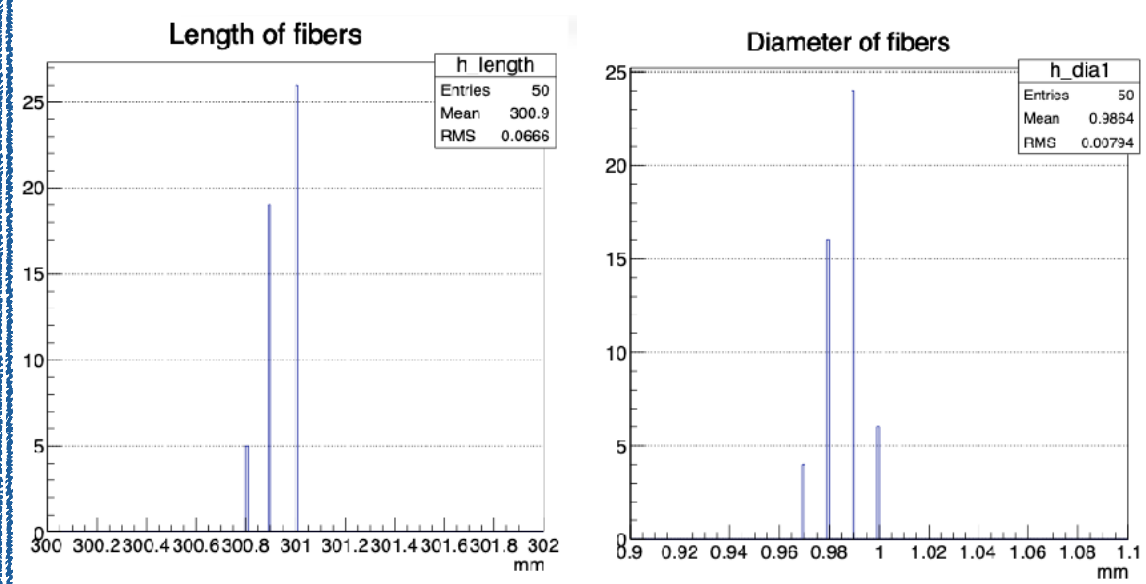
- First, we measured 50 optical fibers that are randomly picked: polished, unpolished čerenkov and scintillating fibers respectively

Čerenkov fiber



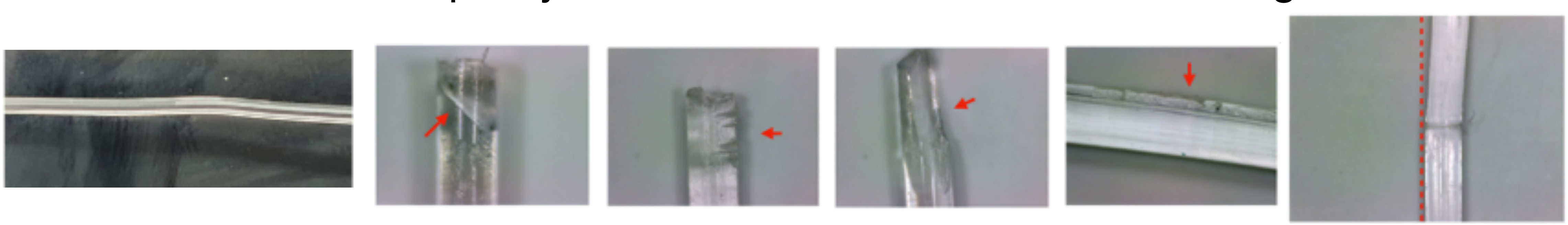
- **Length: polished 300.7cm, unpolished 301.2cm**
- **Diameter: 1mm**
- **Note: some fibers have cracked or been curved**

Scintillating fiber

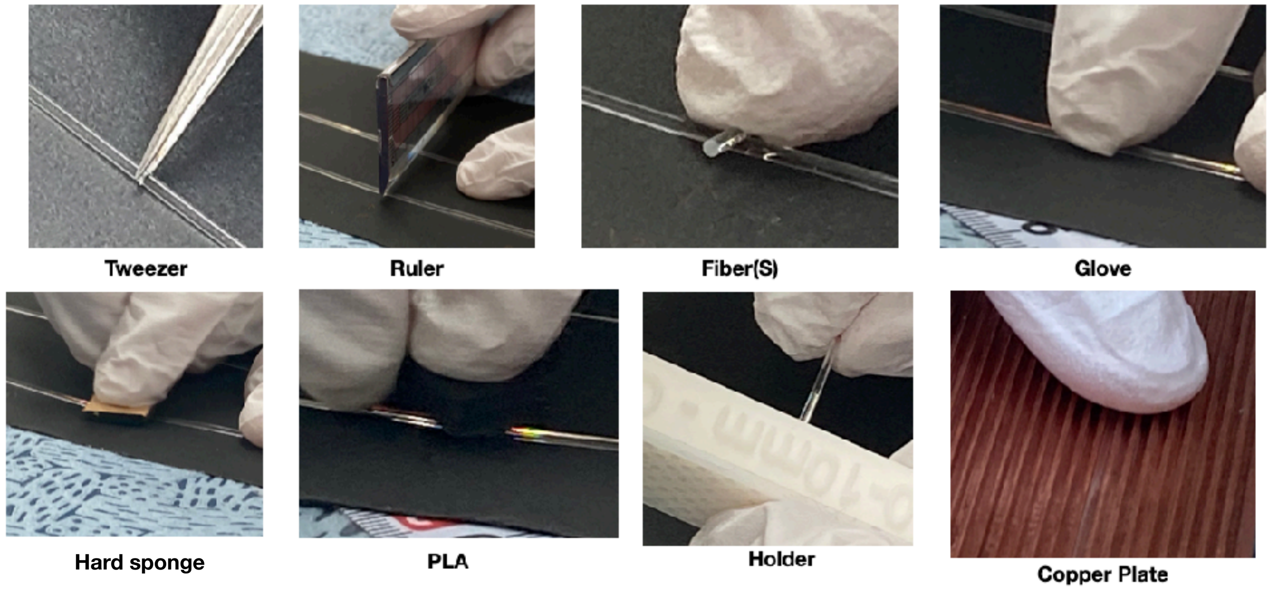


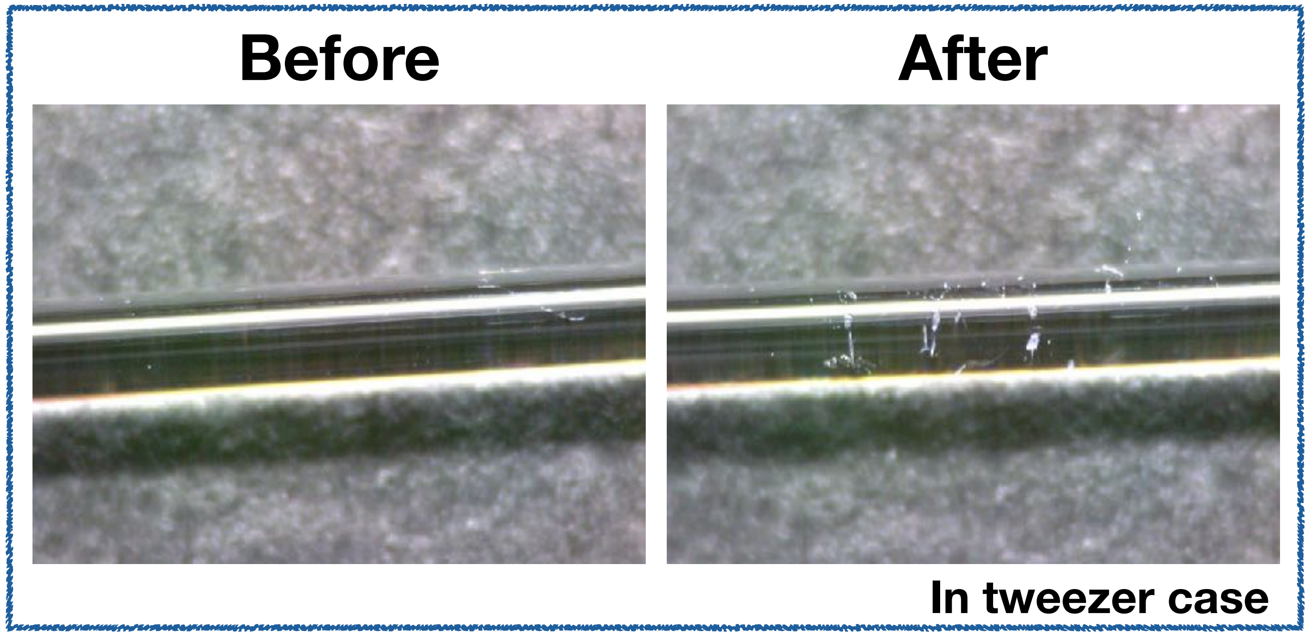
- **Length: 300.9cm**
- **Diameter: 1mm**
- **Note: most fibers have good quality**

- We also checked the quality of fibers and discriminated them to good or bad

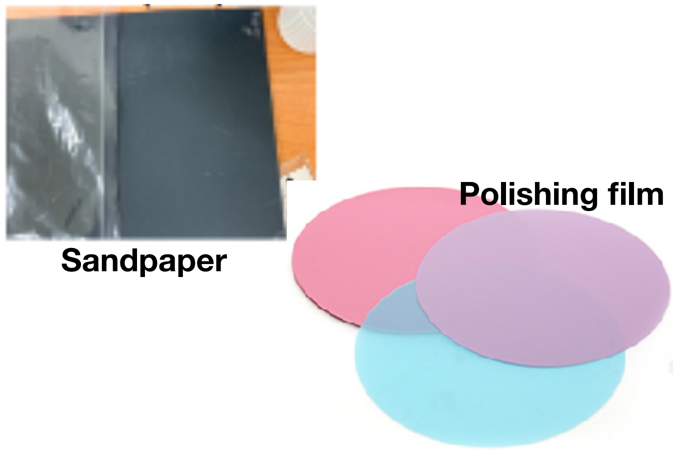


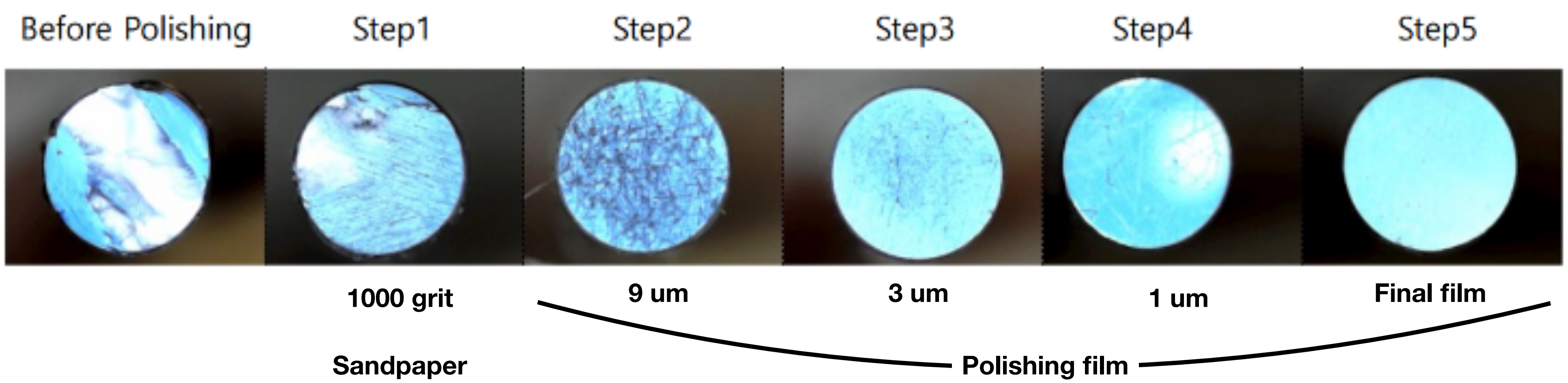
- **Damage Test**
  - Then, we tested the damage when dealing with the fiber's surface using various materials: tweezer, ruler, fiber(Scint.), glove, sponge, PLA, 3D-printed holder, copper plate





- **Polishing Test**
  - Also performed polishing fibers using sandpapers & polishing film

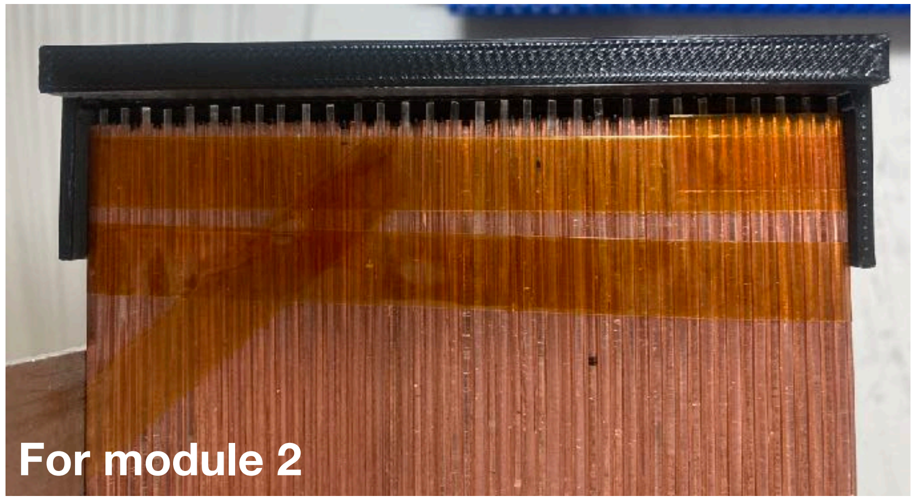




3-1. Preparation

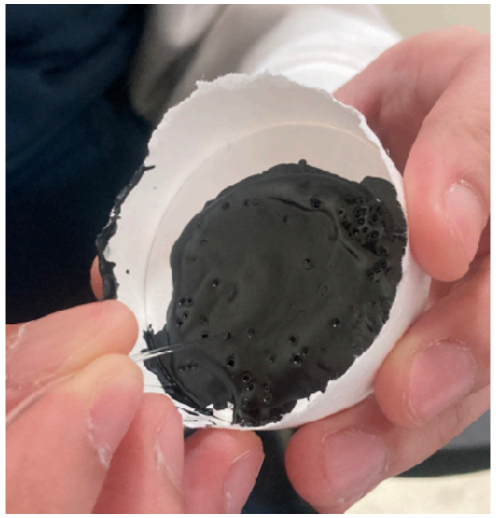
3) 3D-printed Tools

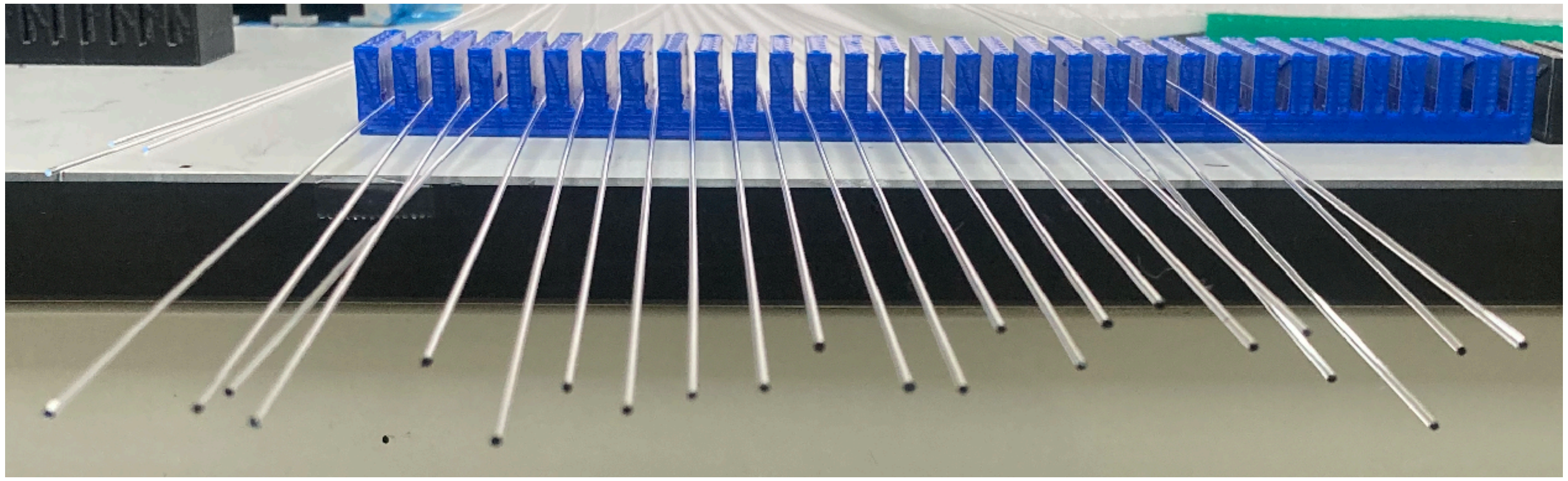
- **The alignment supporters**
  - We prepared tools to **align fibers** when assembling



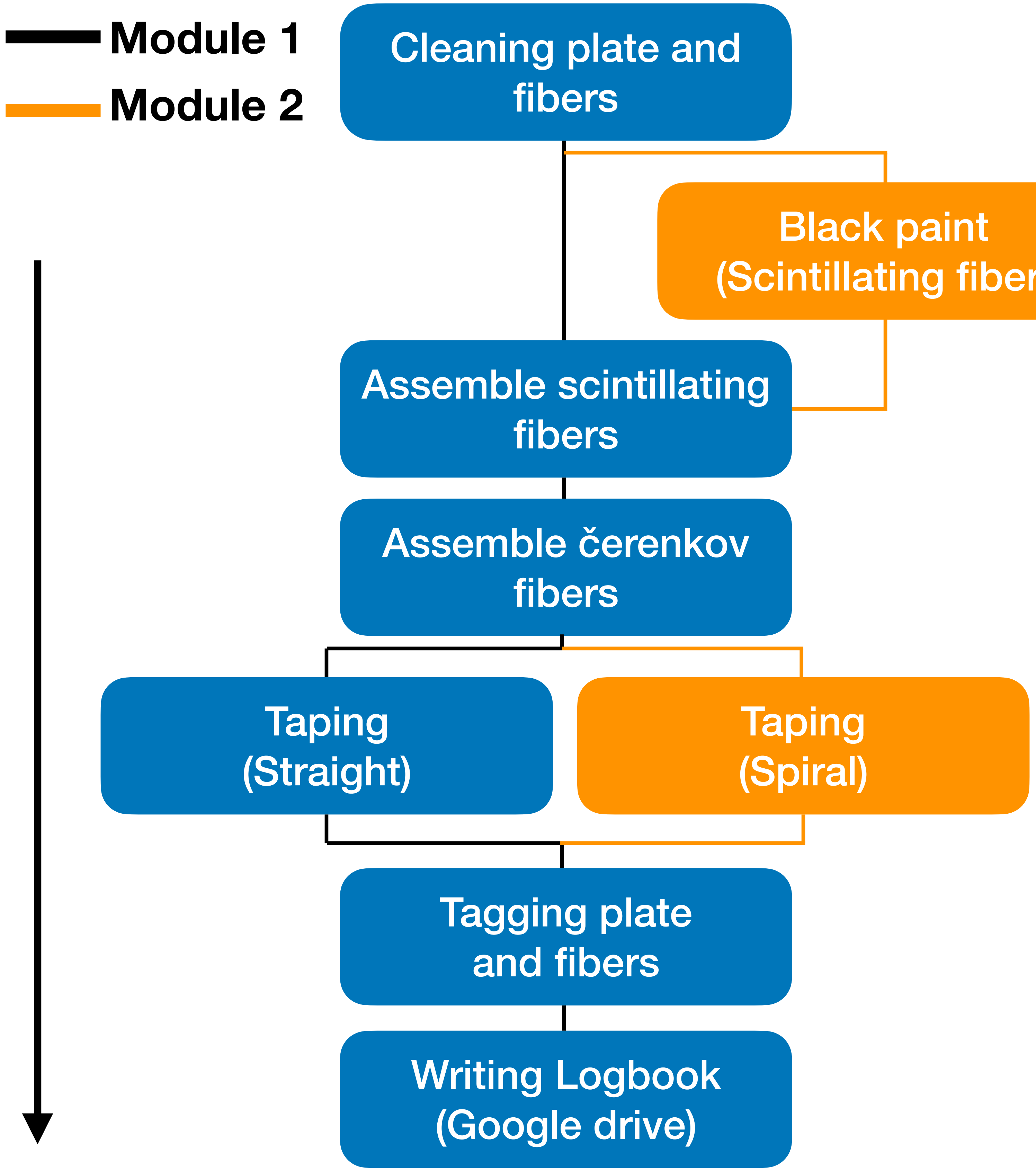
- Because we changed the way to align fibers in module 2 assembly, the different-shaped supporter is used

- **Painting supporter**
  - It helps to paint the edge of scintillating fiber





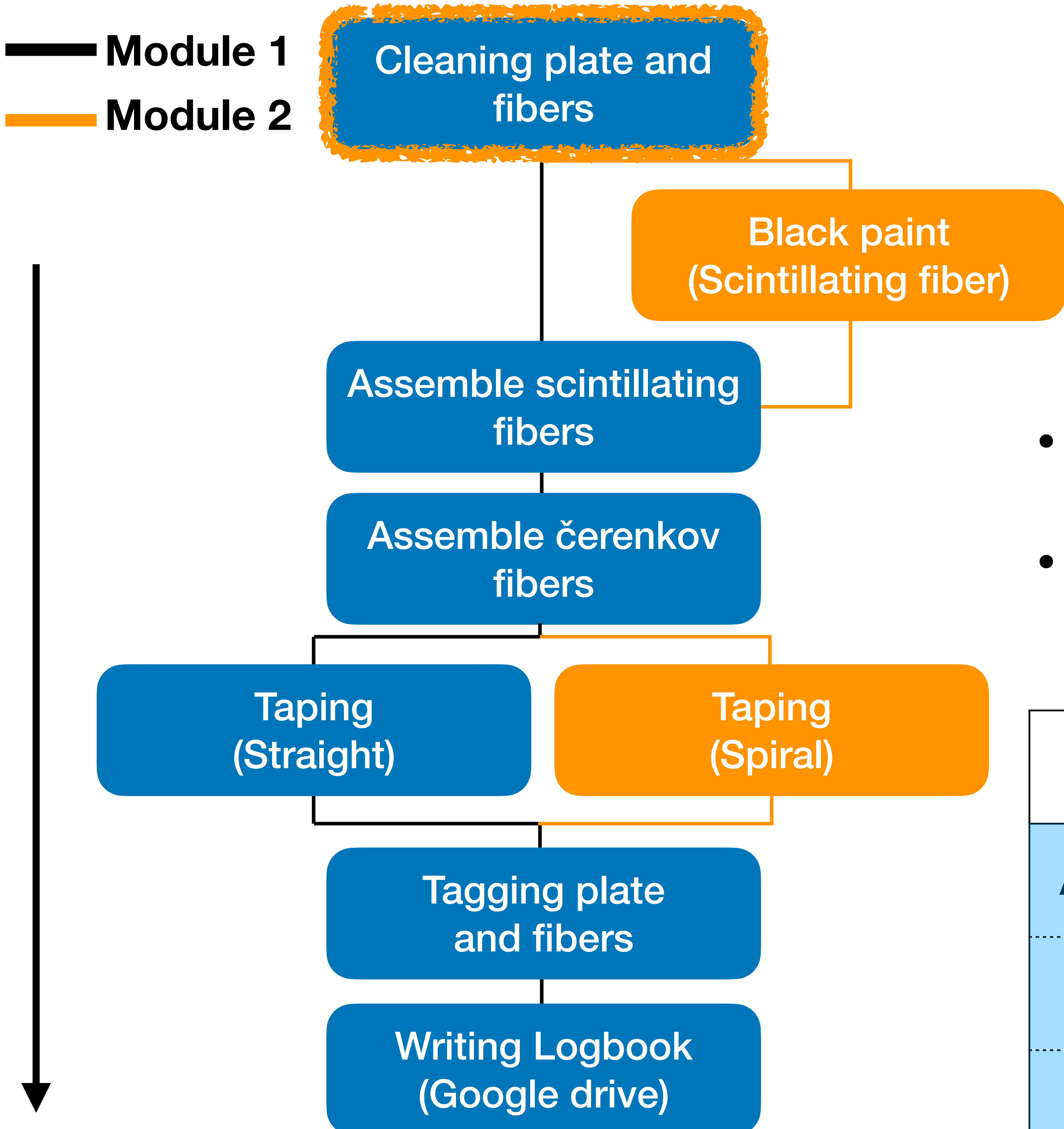
3-2. Assembly

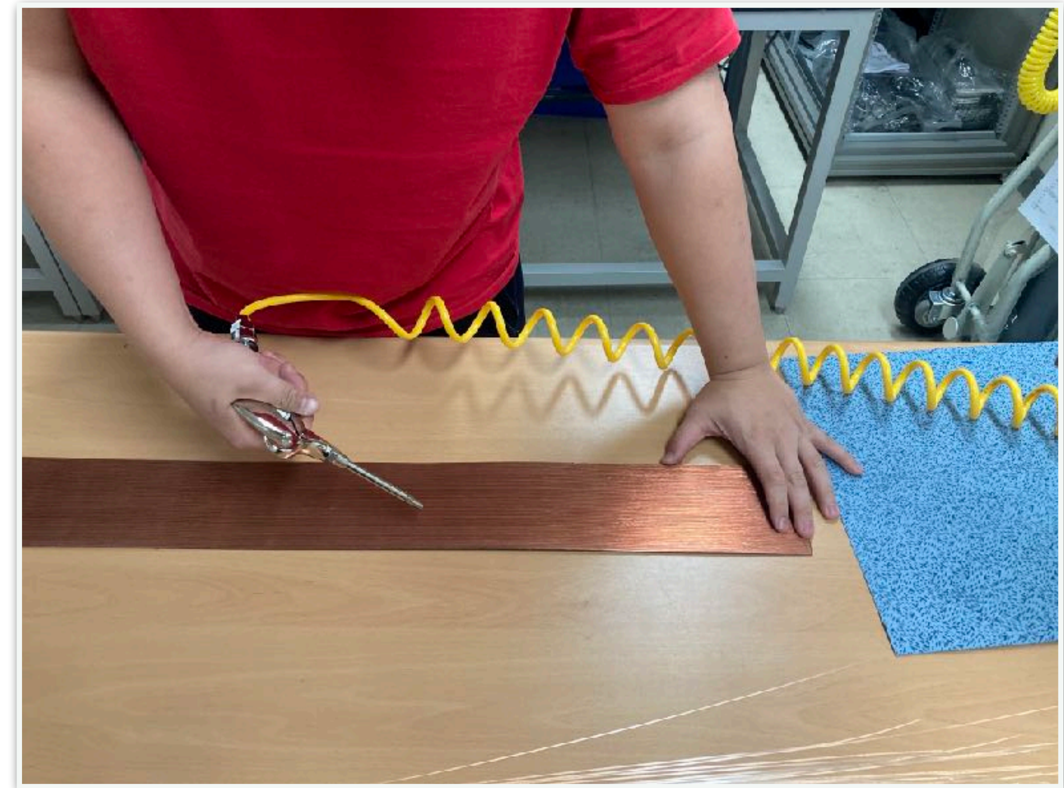


- The process of assembly for module 1&2 is the same
- However, there are differences in **alignment**, **taping**, and **painting scintillating fibers**

	Module 1	**Module 2**
Alignment	C: 30mm S: 2mm	C: **2mm** S: **0mm**
Taping	Straight	**Spiral**
painting	After inserting fibers	Before inserting fibers

3-2. Assembly





- However, there are differences in **alignment**, **taping**, and **painting scintillating fibers**

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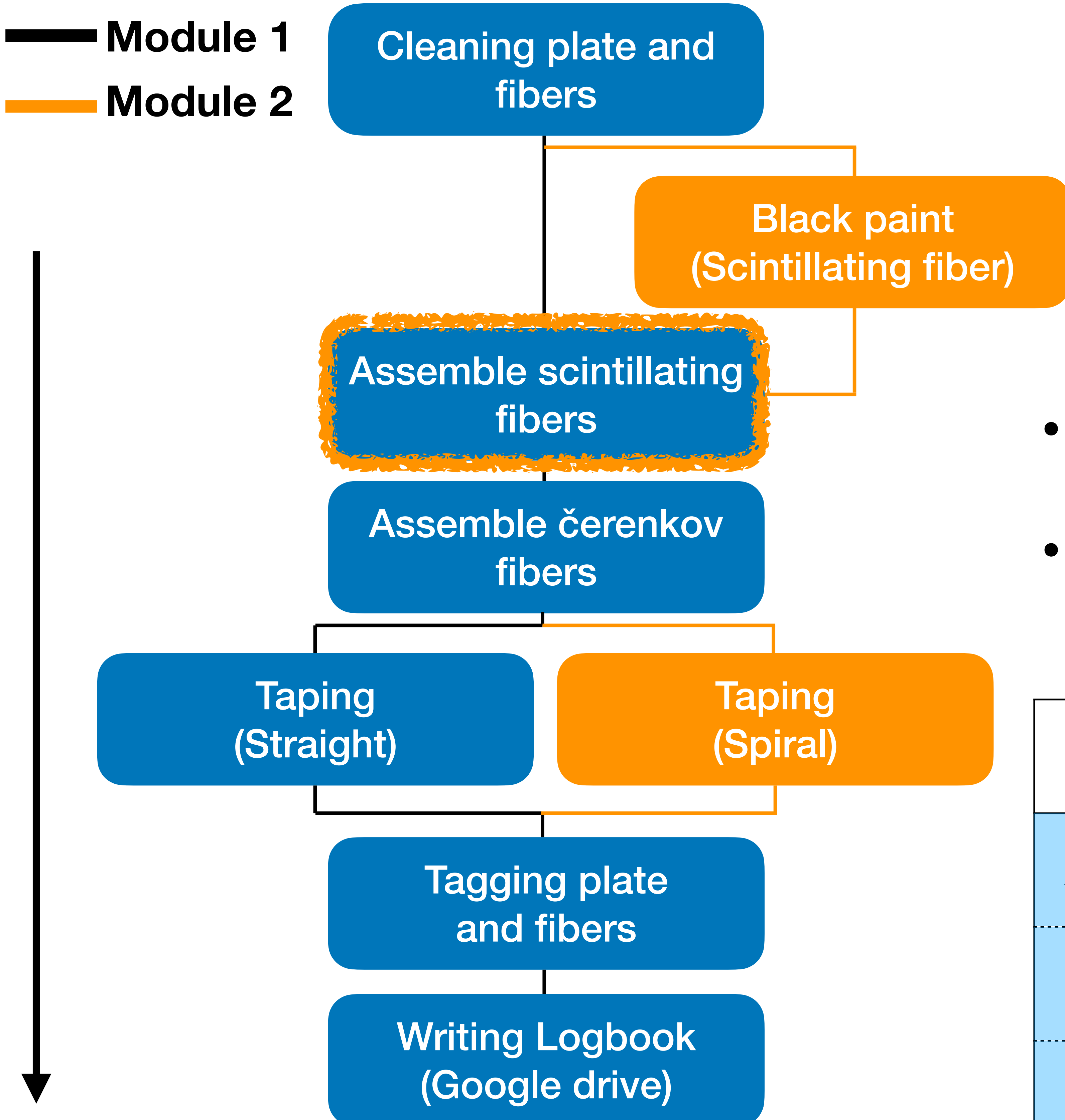
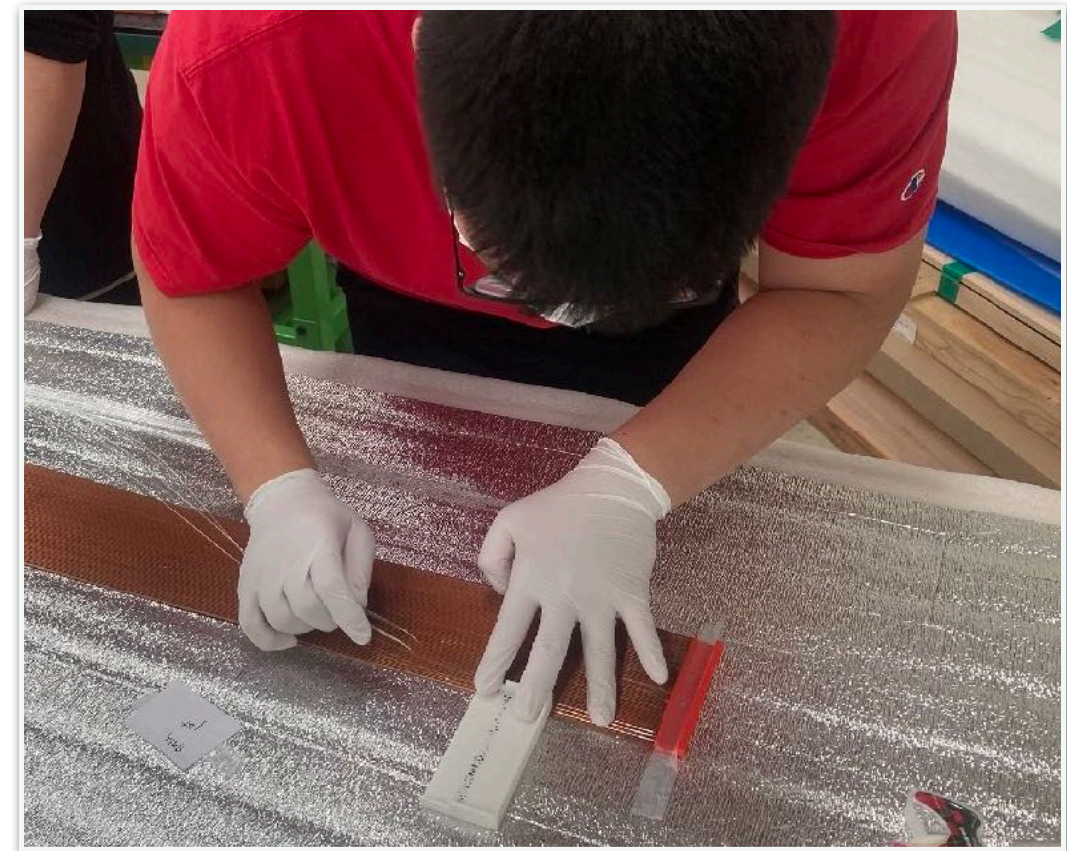
3-2. Assembly





alignment, **taping**, and **painting scintillating fibers**

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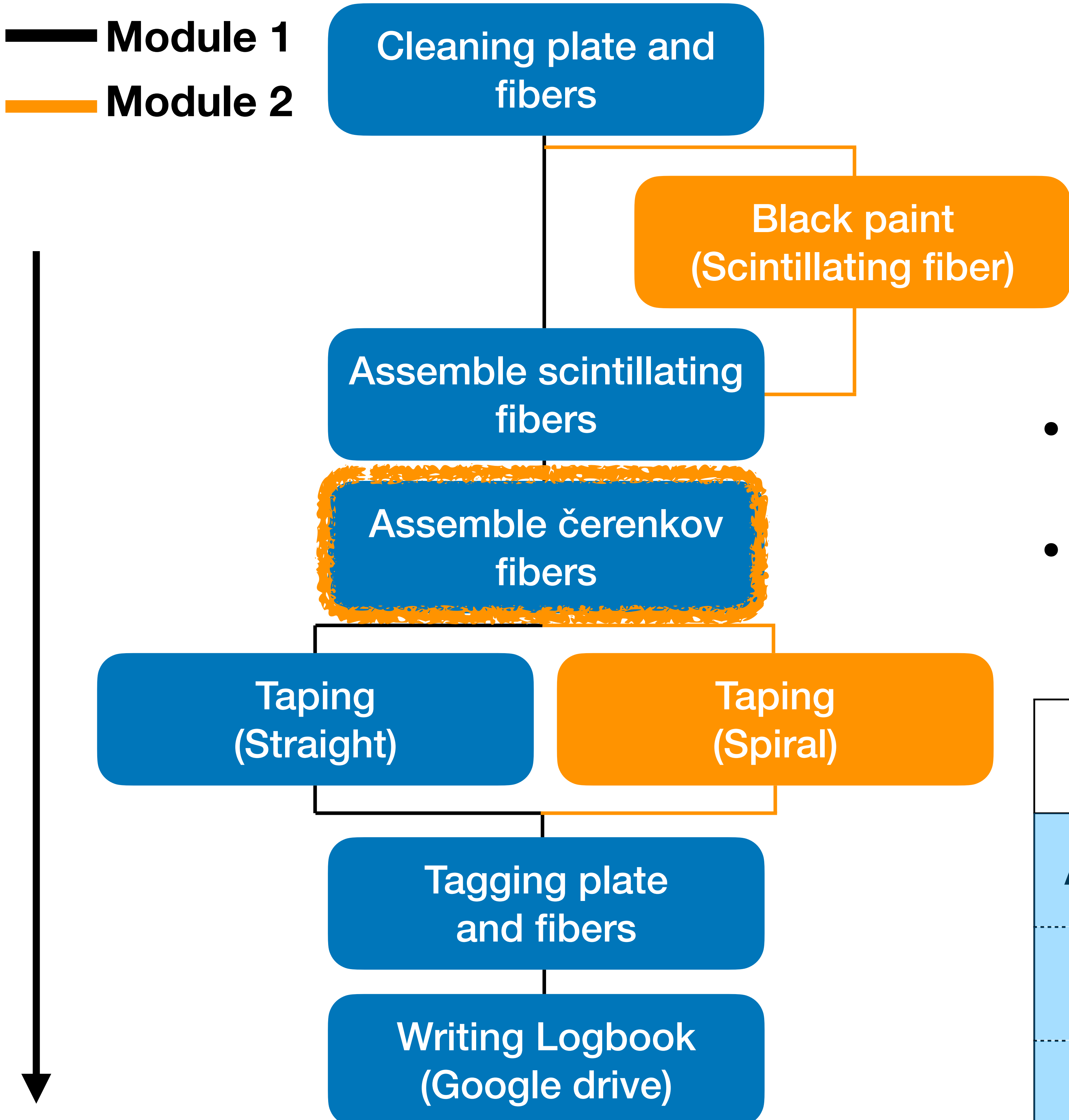
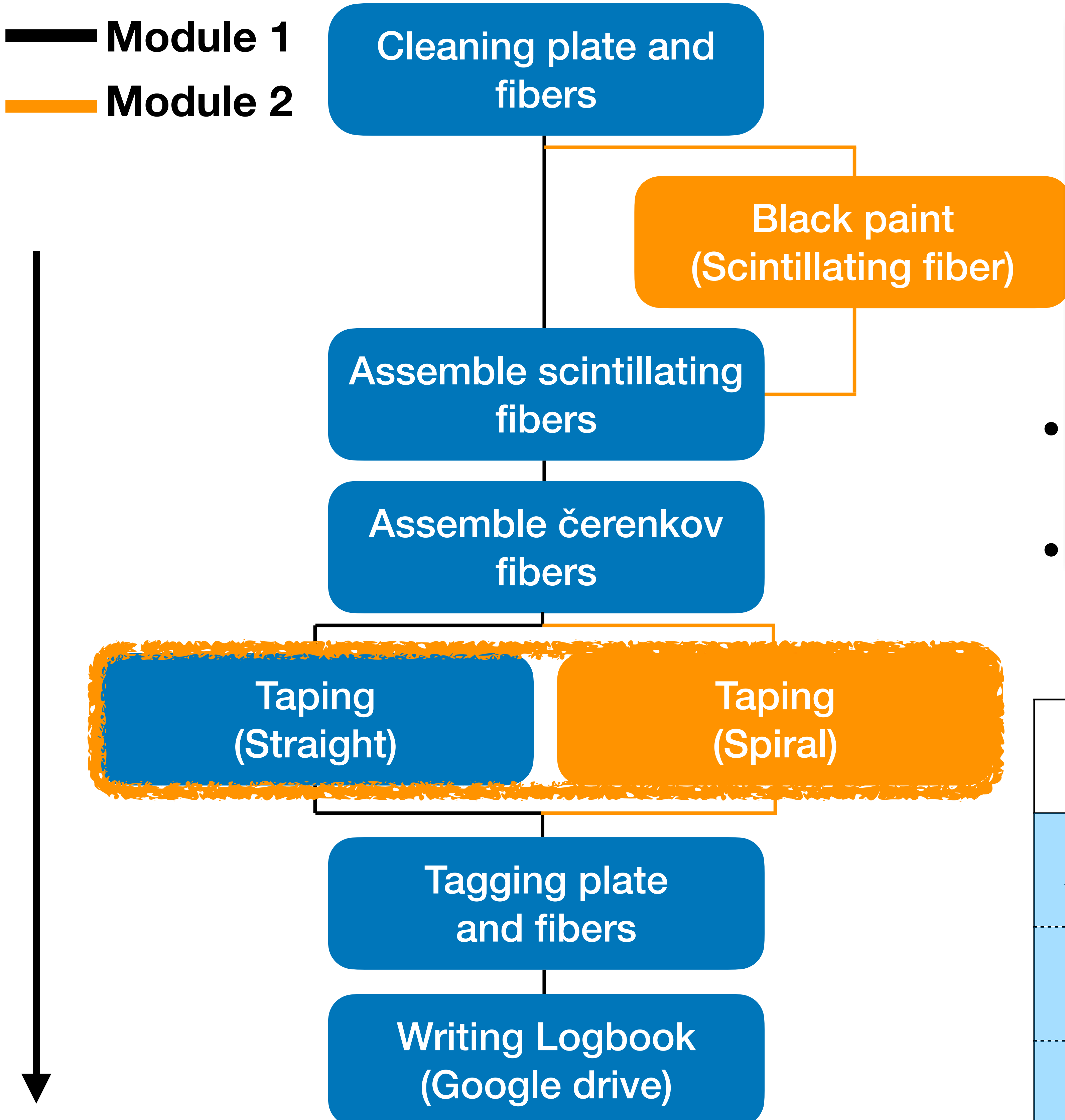
3-2. Assembly



alignment, taping, and painting scintillating fibers

	Module 1	Module 2
Alignment	C: 30mm S: 2mm	C: **2mm** S: **0mm**
Taping	Straight	**Spiral**
painting	After inserting fibers	Before inserting fibers



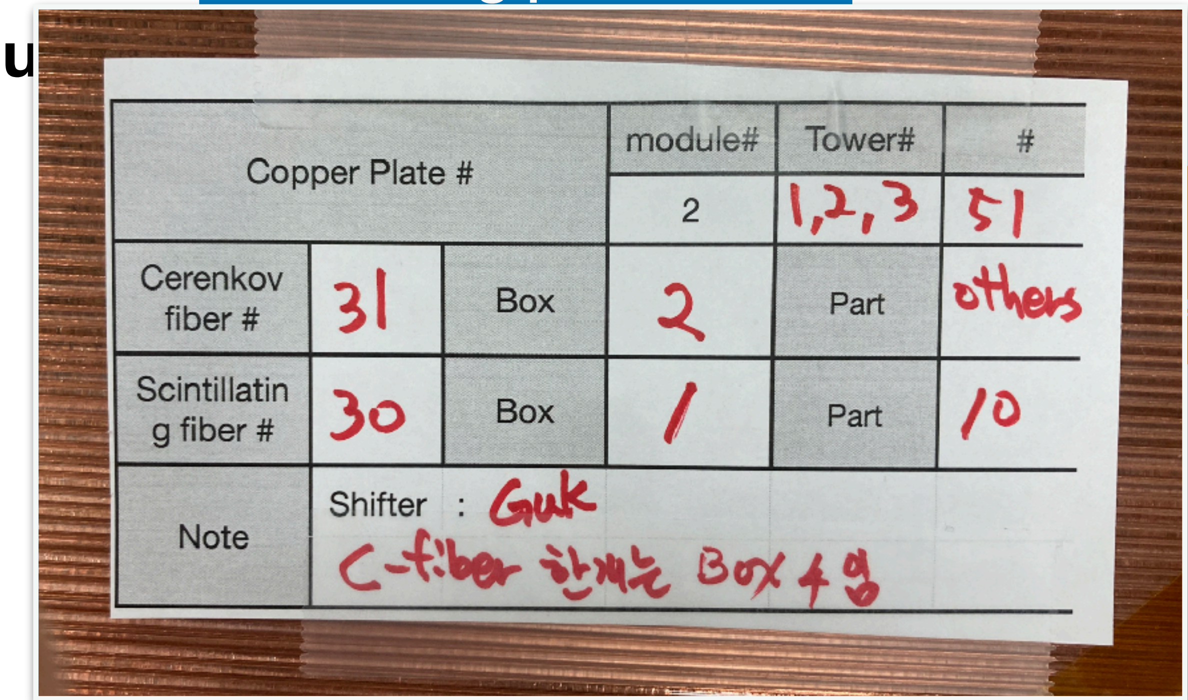
-
- **alignment**, **taping**, and **painting scintillating fibers**

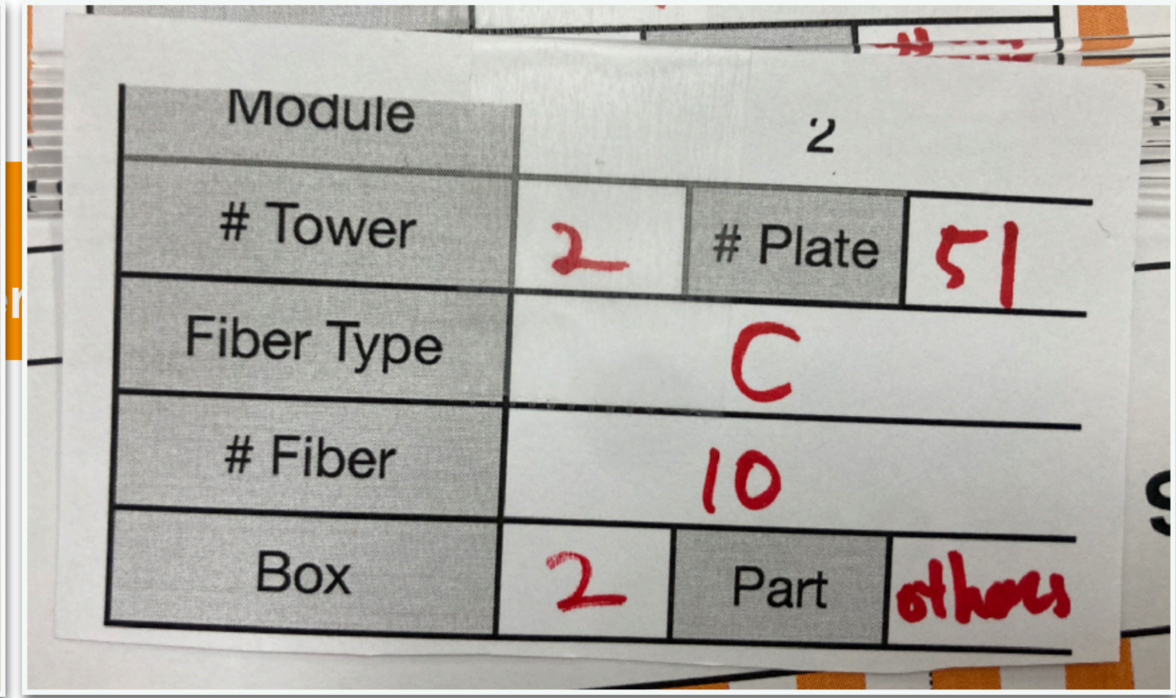
	Module 1	Module 2
Alignment	C: 30mm S: 2mm	C: **2mm** S: **0mm**
Taping	Straight	**Spiral**
painting	After inserting fibers	Before inserting fibers

3-2. Assembly

Module 1
Modu

Cleaning plate and





fibers

Taping (Straight)

Taping (Spiral)

Tagging plate and fibers

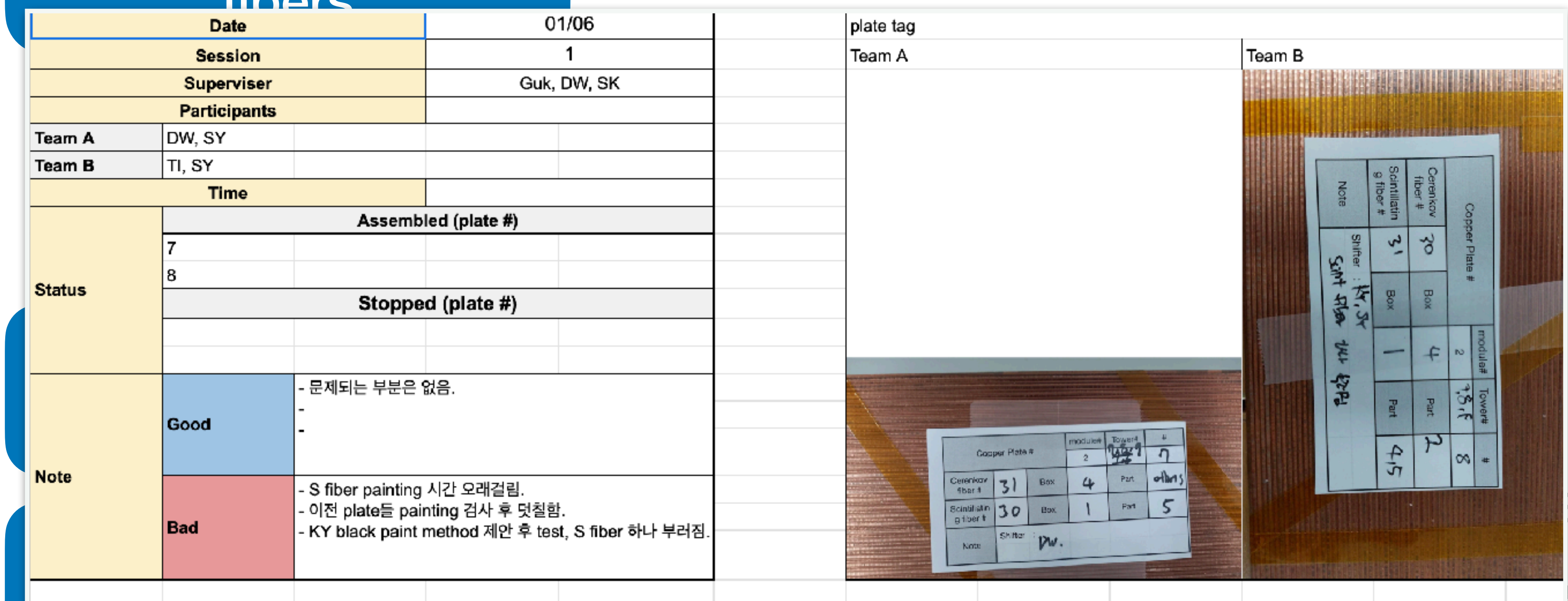
Writing Logbook (Google drive)

- However, there are differences in **alignment**, **taping**, and **painting scintillating fibers**

	Module 1	Module 2
Alignment	C: 30mm S: 2mm	C: **2mm** S: **0mm**
Taping	Straight	**Spiral**
painting	After inserting fibers	Before inserting fibers

Module 1 (black)
Module 2 (orange)

Cleaning plate and fibers



Date	01/06
Session	1
Superviser	Guk, DW, SK
Participants	
Team A	DW, SY
Team B	TI, SY
Time	
Status — Assembled (plate #)	7 8
Status — Stopped (plate #)	
Note — Good	- 문제되는 부분은 없음. - -
Note — Bad	- S fiber painting 시간 오래걸림. - 이전 plate들 painting 검사 후 덧칠함. - KY black paint method 제안 후 test, S fiber 하나 부러짐.

fibers

Taping (Straight) | Taping (Spiral)

Tagging plate and fibers

Writing Logbook (Google drive)

...ly for
...e
...rences in **alignment**, **taping**, and **painting scintillating fibers**

	Module 1	Module 2
Alignment	C: 30mm S: 2mm	C: **2mm** S: **0mm**
Taping	Straight	**Spiral**
painting	After inserting fibers	Before inserting fibers

1) Reflectors

- The characteristics of lights

Light	Scintillating light	Čerenkov light
Quantity	Bright	Not bright
Speed	Slow (~2 ns)	Fast (~0 ns)
Attenuation lengths	Small (~3m)	Long (6~10m)

At the front side of copper plate,

- Scintillating fiber: **block** the light
- Čerenkov fiber: **reflect** the light which gives **the depth of light** in the module

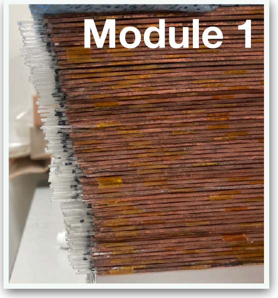
- The 1st trial
  - We tried to attach **an aluminum mirror**, which is adhered to 3D-printed holder
  - Reflectors impact on the height of module 1

- The 2nd trial
  - We changed the material as a reflector from the aluminum mirror to an **aluminum foil**

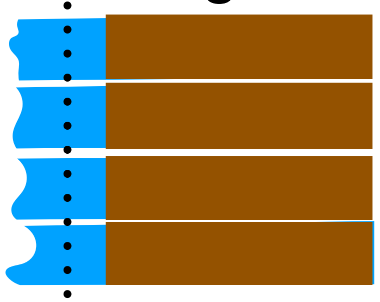
- Method

1) Remove cerenkov holders for module 1

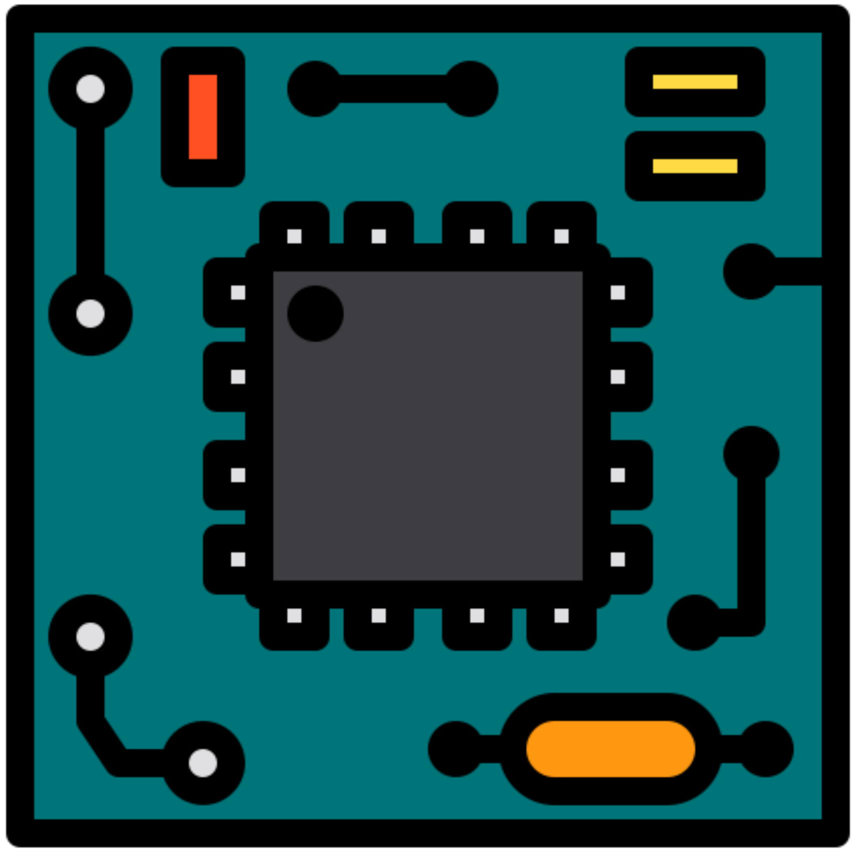
Removed čerenkov holders



2) cutting fibers



3) Polishing fibers
   - Sandpaper: 400 grit -> 1000 grit -> 2000 grit ->
   - polishing film: 9um -> 3um -> 1um



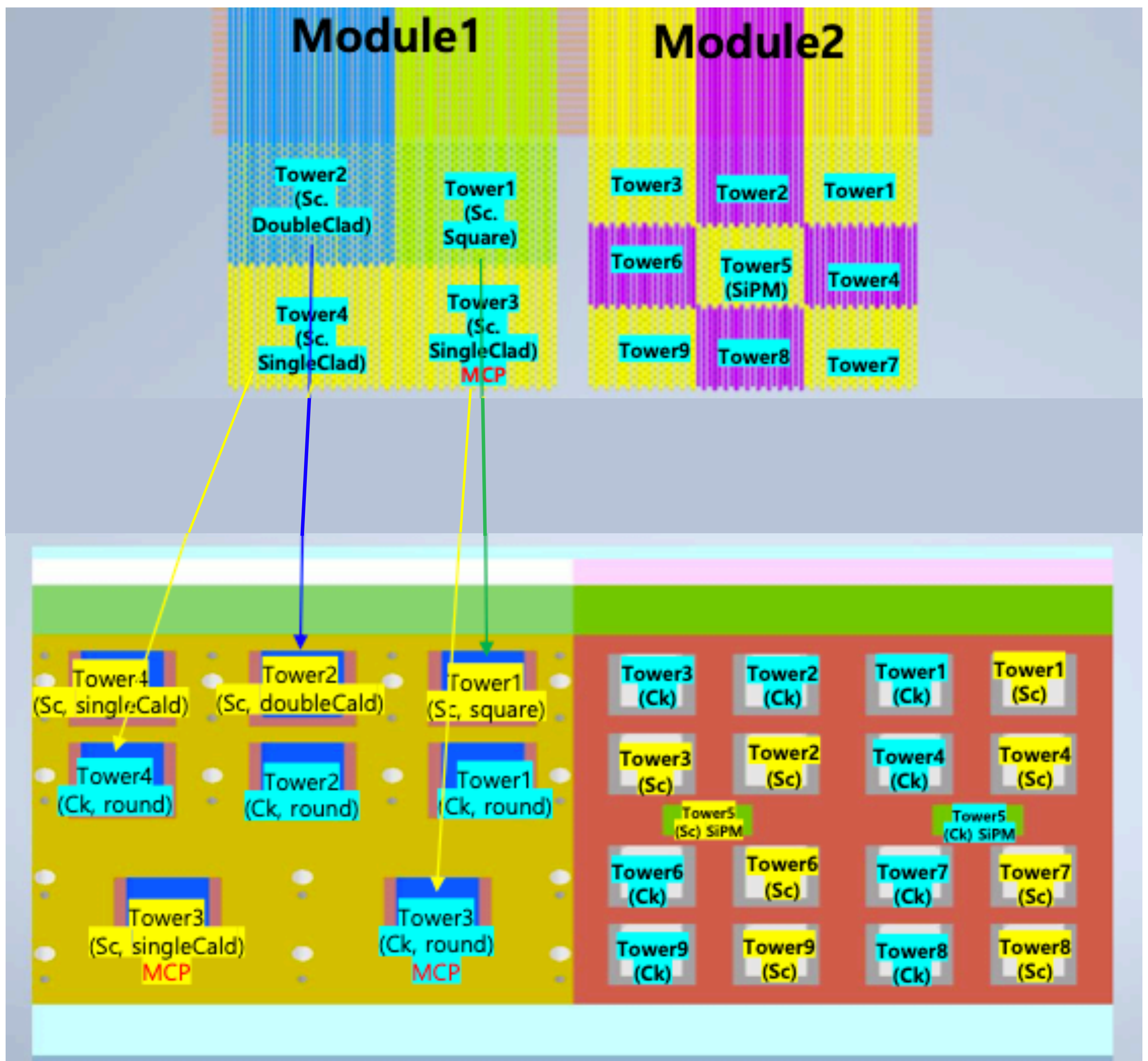
4. Readout System

4-1. Configuration
4-2. PMT

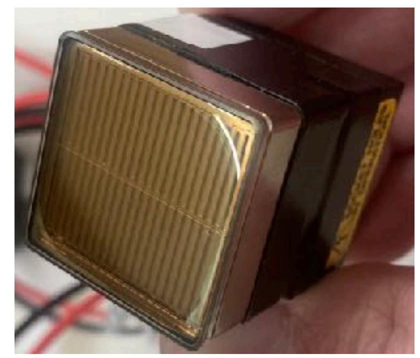
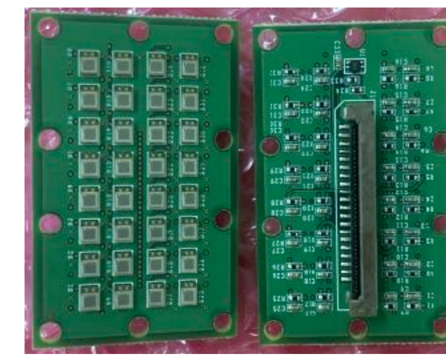
4-1. Configuration

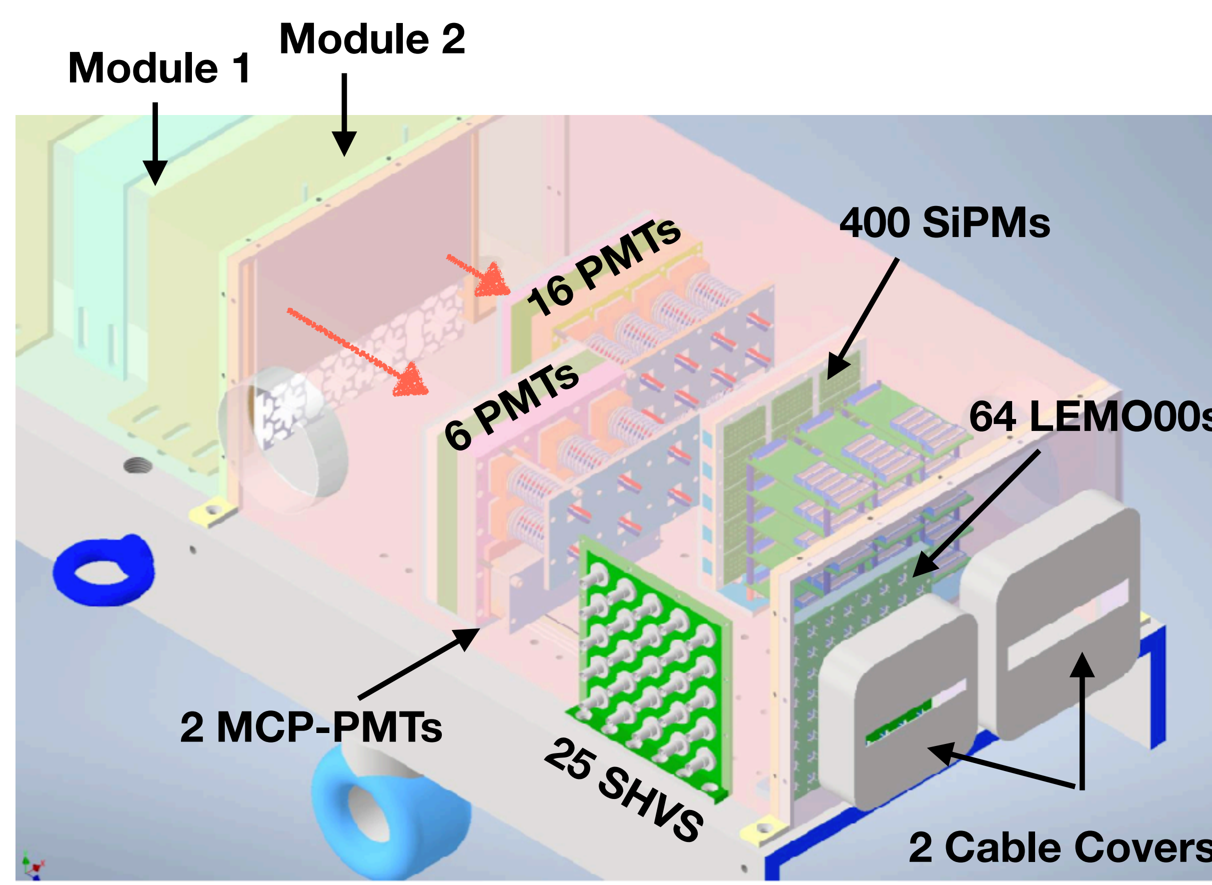
- All the towers for modules 1 & 2 will be attached to PMTs except for tower 3 of module 1 & tower 5 of module 2

- **Tower 3** of module 1: **MCP-PMT**
- **Tower 5** of module 2: **SiPM**



Readout Detector

PMT	MCP-PMT	SiPM
		



4-2. PMT

- **Procedure**

1) bundle case & epoxy

↓

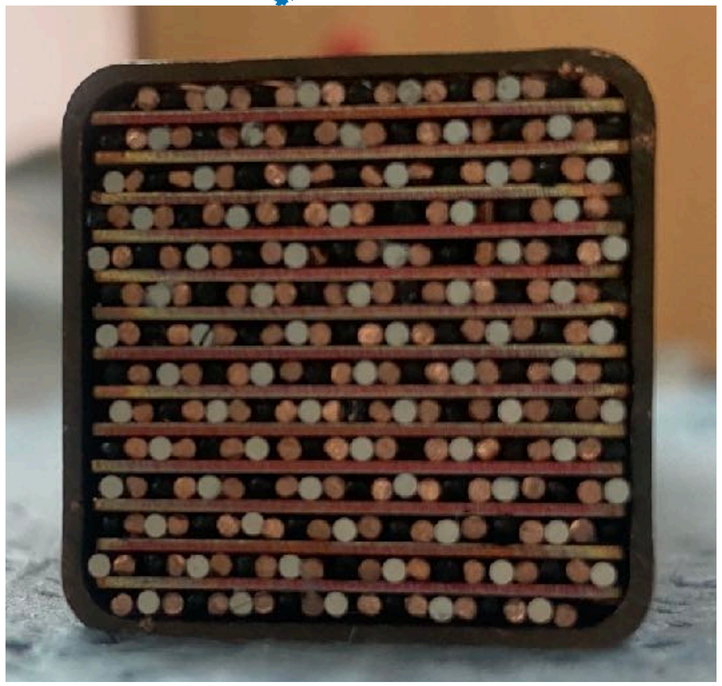
2) cutting bundles

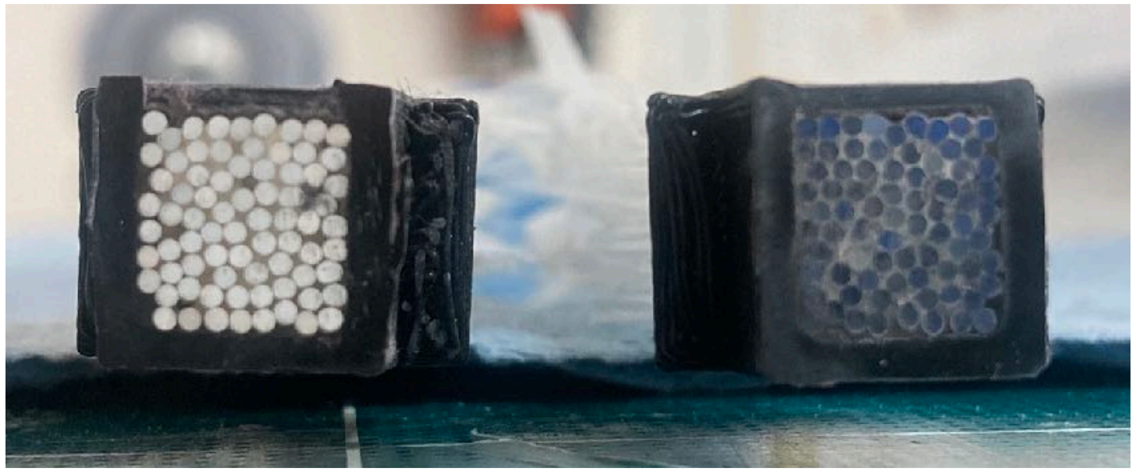
↓

3) polishing bundles

↓

4) attaching PMT





4-2. PMT

- **Procedure**

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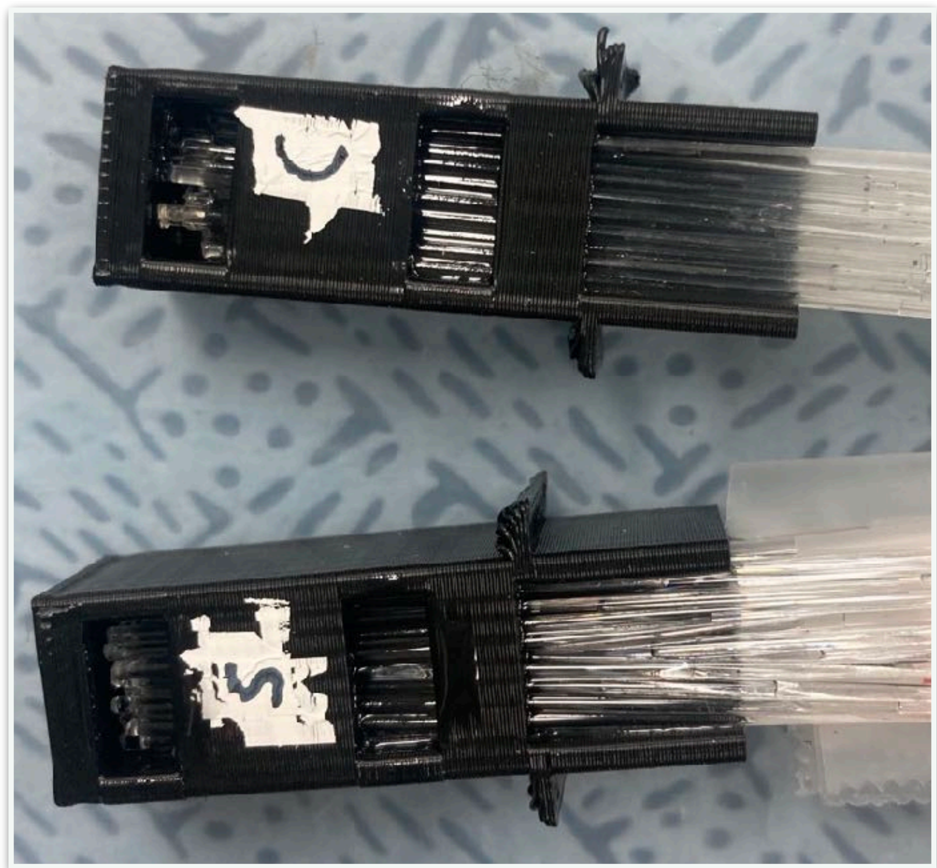


Hardener 1g : Resin 4g

- **Procedure**

1) bundle case & epoxy

↓

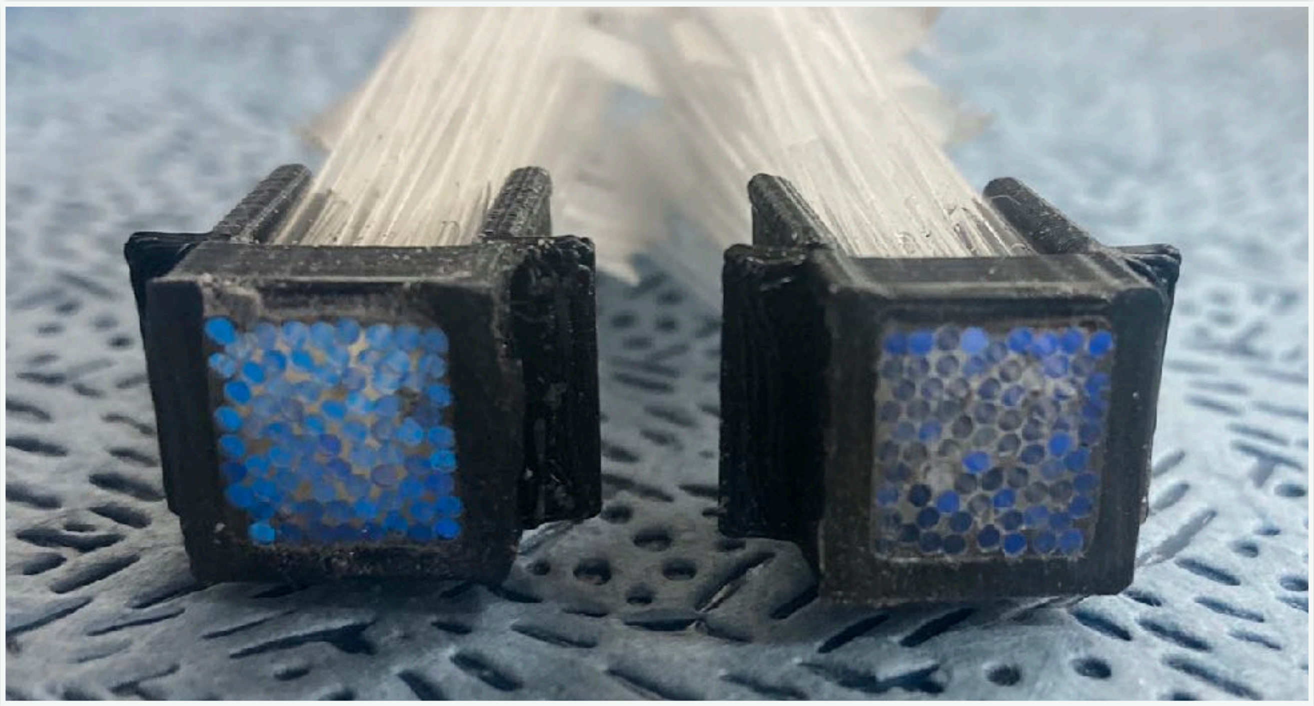
2) cutting bundles

↓

3) polishing bundles

↓

4) attaching PMT



4-2. PMT

- **Procedure**

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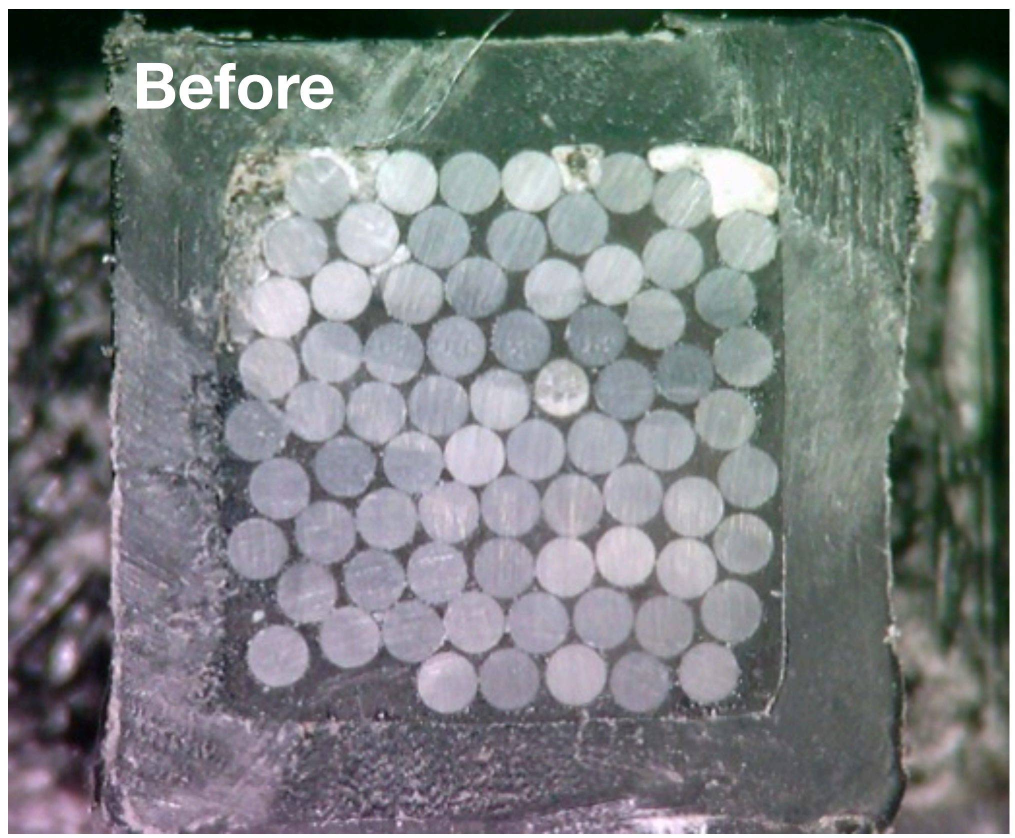
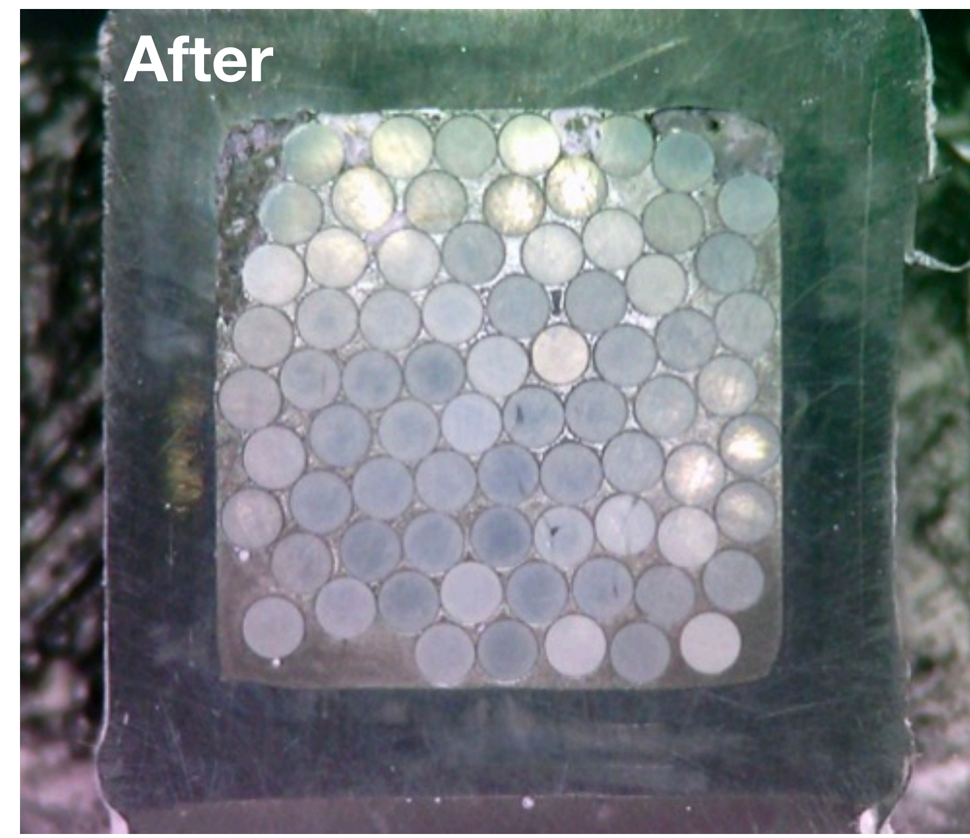




4-2. PMT

- **Procedure**

1) bundle case & epoxy

↓

2) cutting bundles

↓

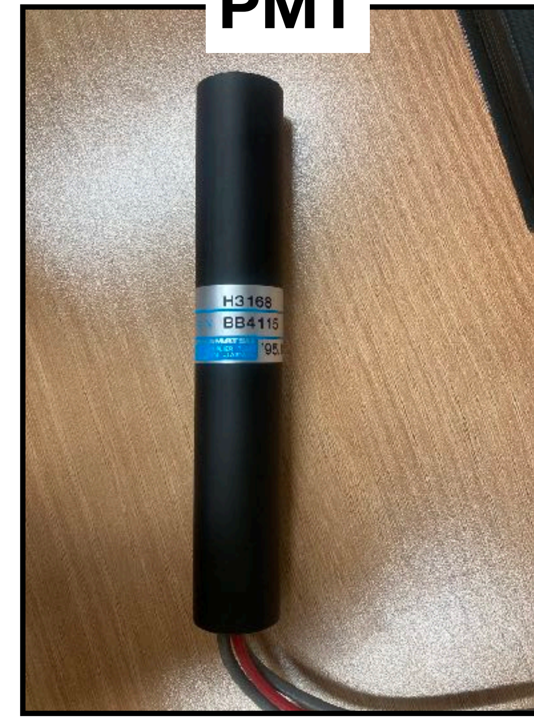
3) polishing bundles

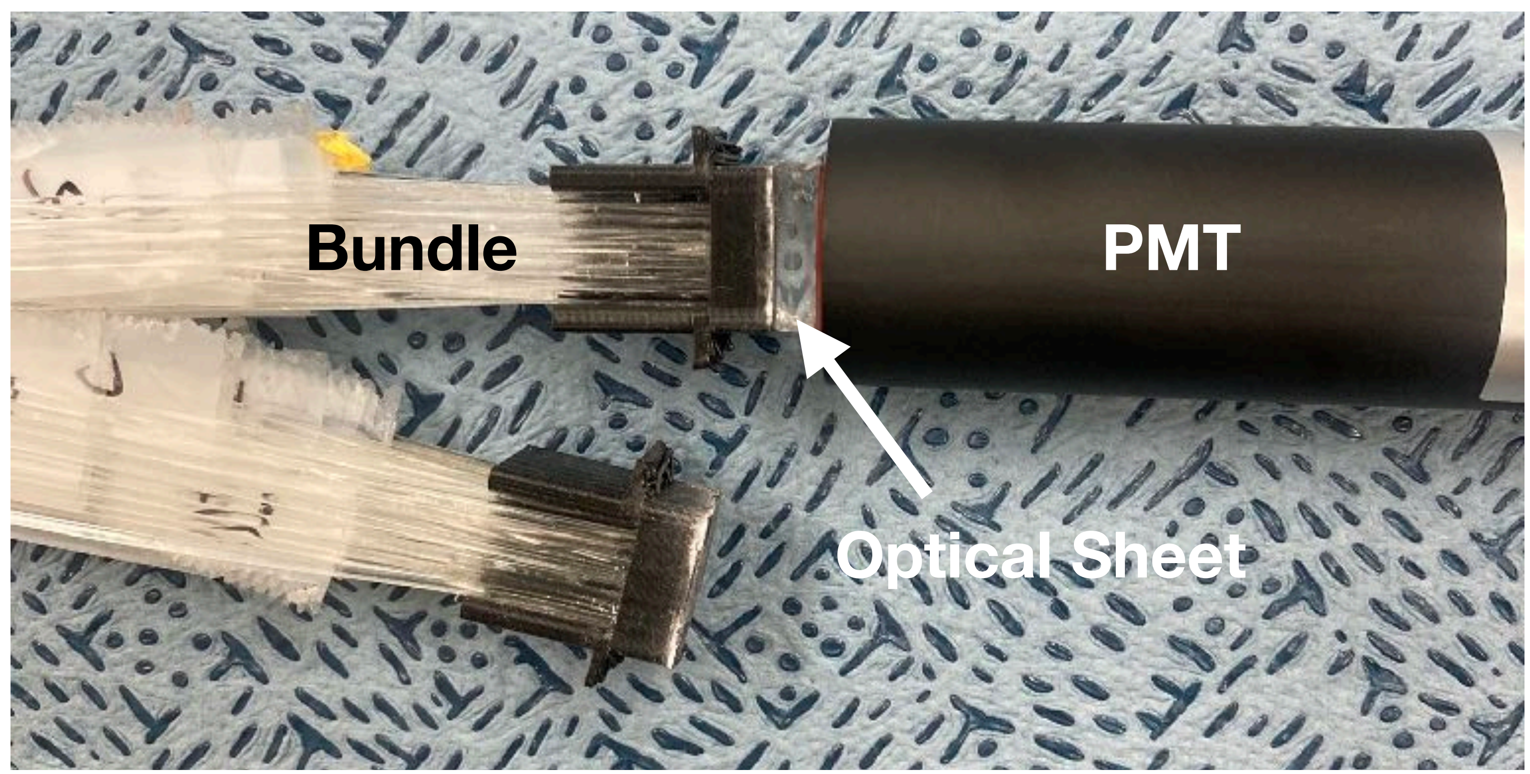
↓

4) attaching PMT

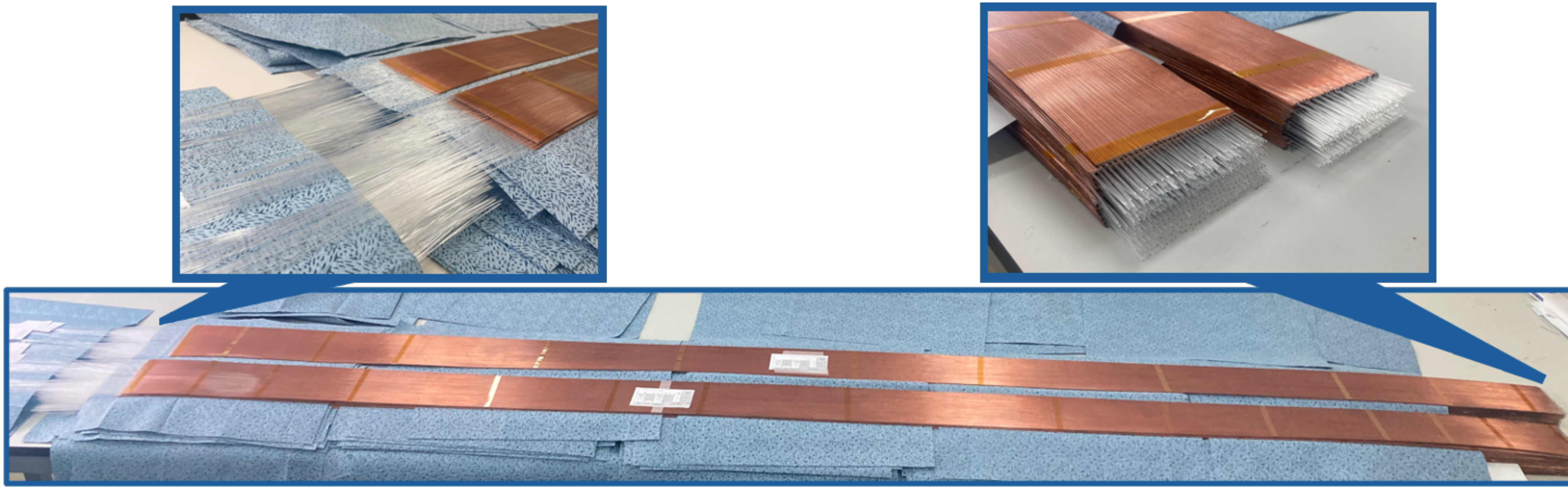
Optical Sheet

PMT





5. Summary



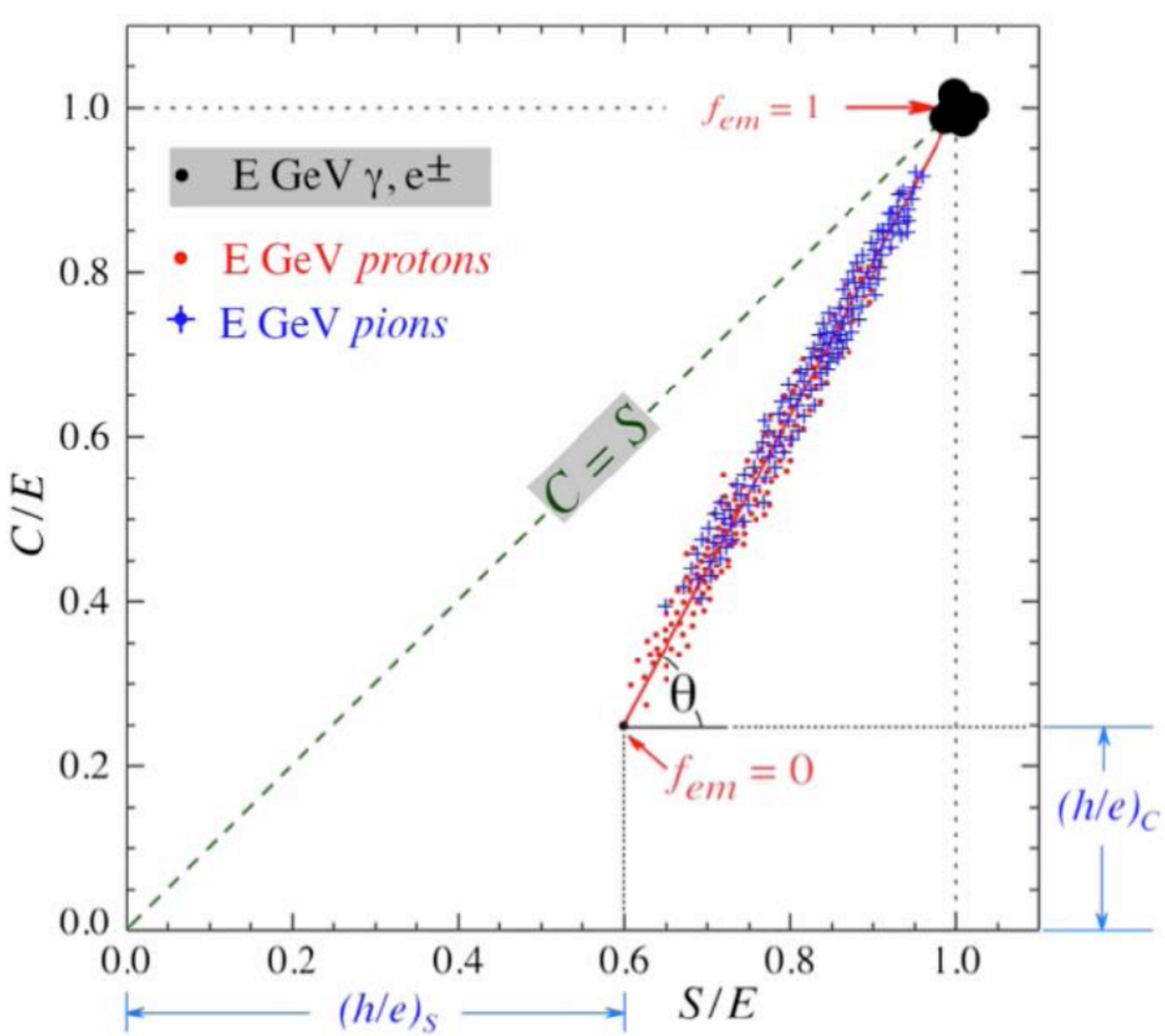
- We are building 2 modules and planning to test at CERN
- The first important is **the alignment of fibers** during building modules
- The second is that inserted fibers on the copper plate is not escaped
  - We introduced **the spiral taping method** to prevent bulging fibers
- Now, the assembly is finished, polishing and reflector steps are on going

Back up

Dual-Readout Calorimeter

KyuyeongHwang's slide, 2021.01.22, Saga-Yonsei workshop

- Čerenkov and scintillating fibers which are implemented on copper plate can measure EM particles and hadronic particles at the same time
- f_{EM} can be measured by implemented two different type of fibers with different h/e responses in a calorimeter



1. $C = E\left[f_{EM} + \frac{1}{(e/h)_C}(1 - f_{EM})\right]$

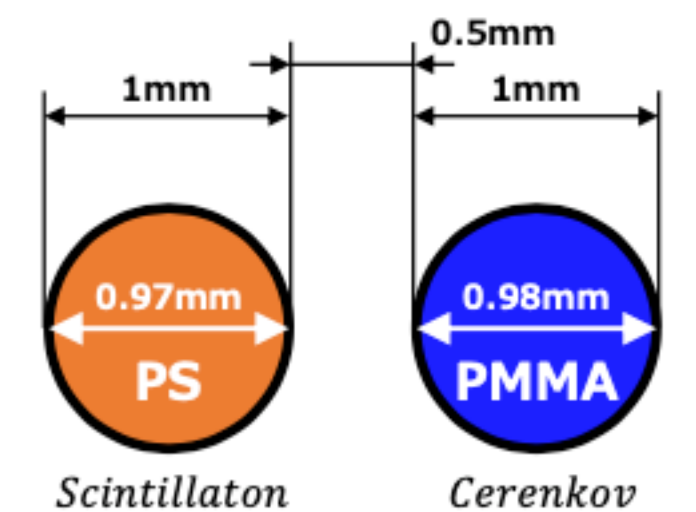
2. $S = E\left[f_{EM} + \frac{1}{(e/h)_S}(1 - f_{EM})\right]$

3. $f_{EM} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1-(h/e)_S] - [1-(h/e)_C]}$

4. $\chi \equiv \cot\theta = \frac{1-(h/e)_S}{1-(h/e)_C}$

5. $E = \frac{S - \chi C}{1 - \chi}$

Implemented Optical Fibers



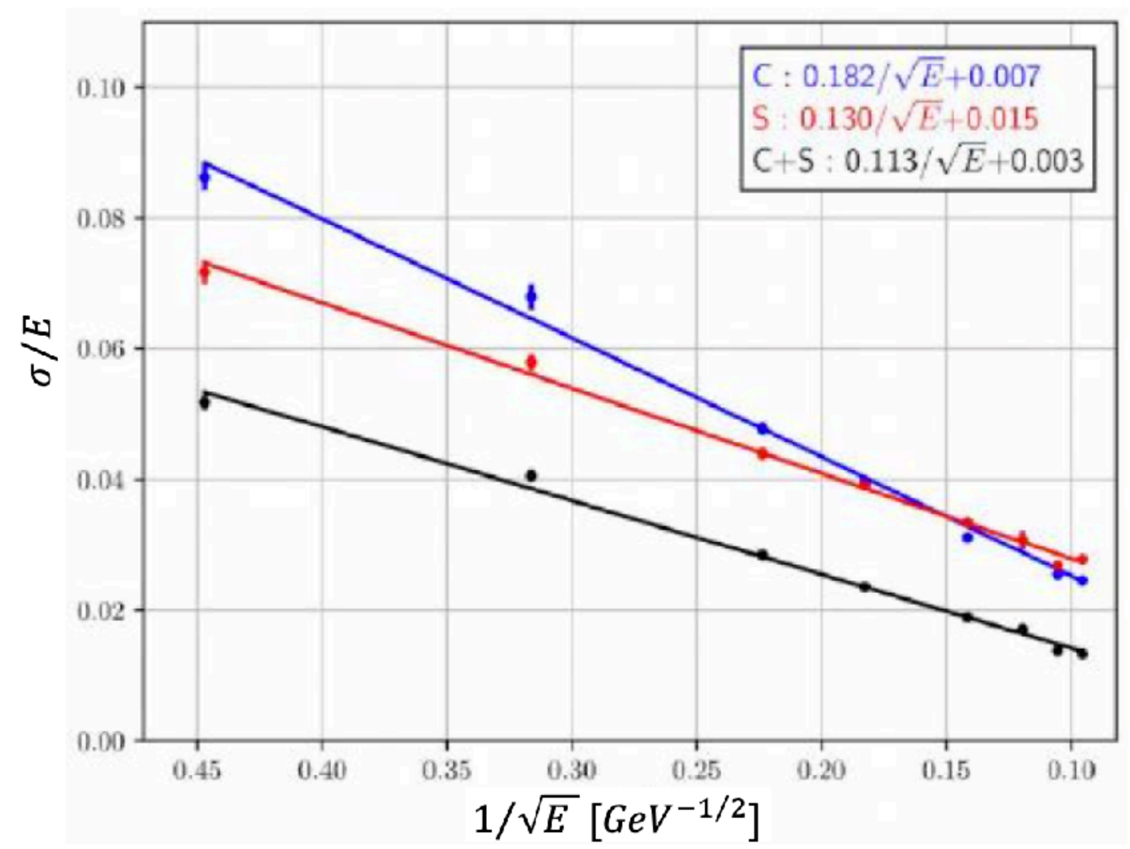
Energy Resolution

KyuyeongHwang's slide, 2021.01.22, Saga-Yonsei workshop

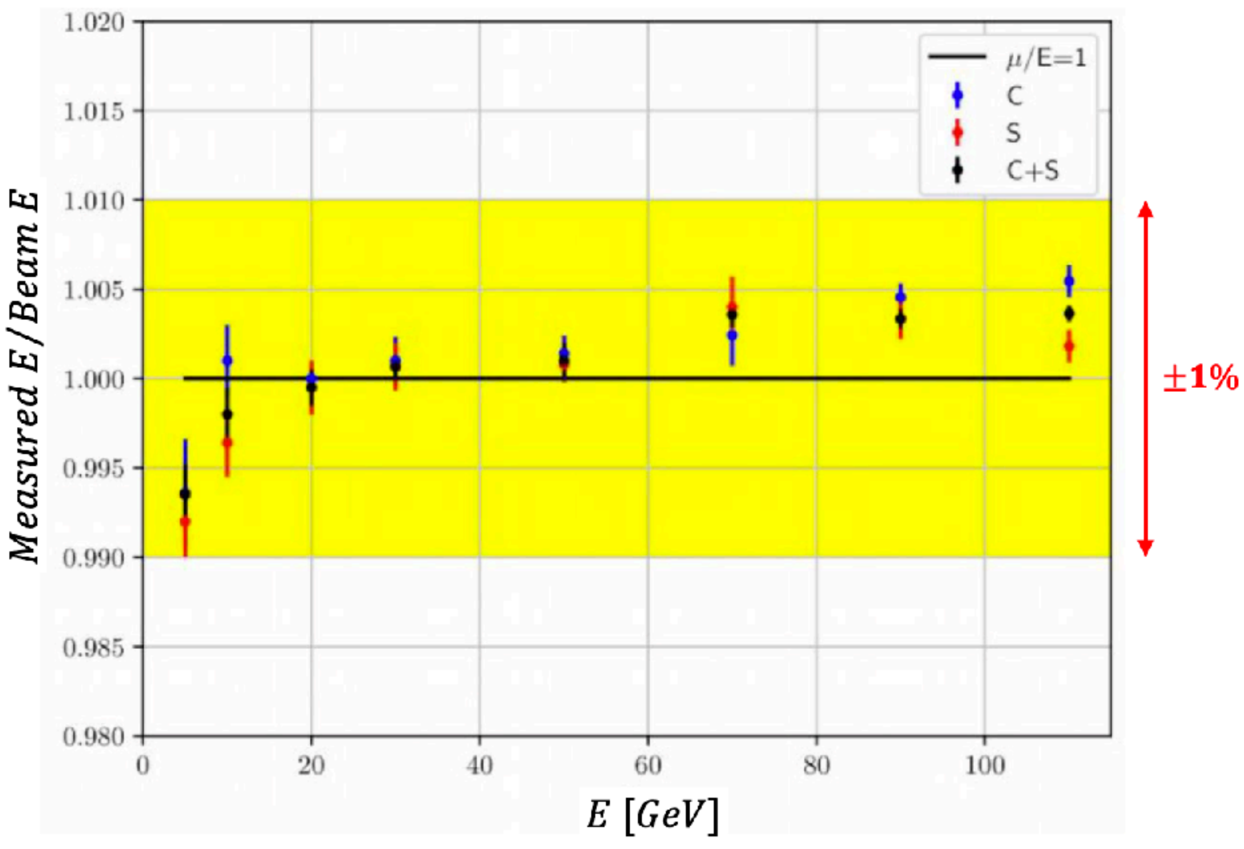
EM Energy Resolution

- EM energy resolution is measured with different 8 energy points electron and scaled with $1/\sqrt{E}$.
- Stochastic & constant term of energy resolution can be obtained by linear fitting.

EM Energy Resolution



EM Energy Linearity



- Stochastic term for EM energy resolution is ~11%.
- Measured EM energy satisfies linearity within 1% level at both scintillation and Cerenkov channels.

Energy Resolution

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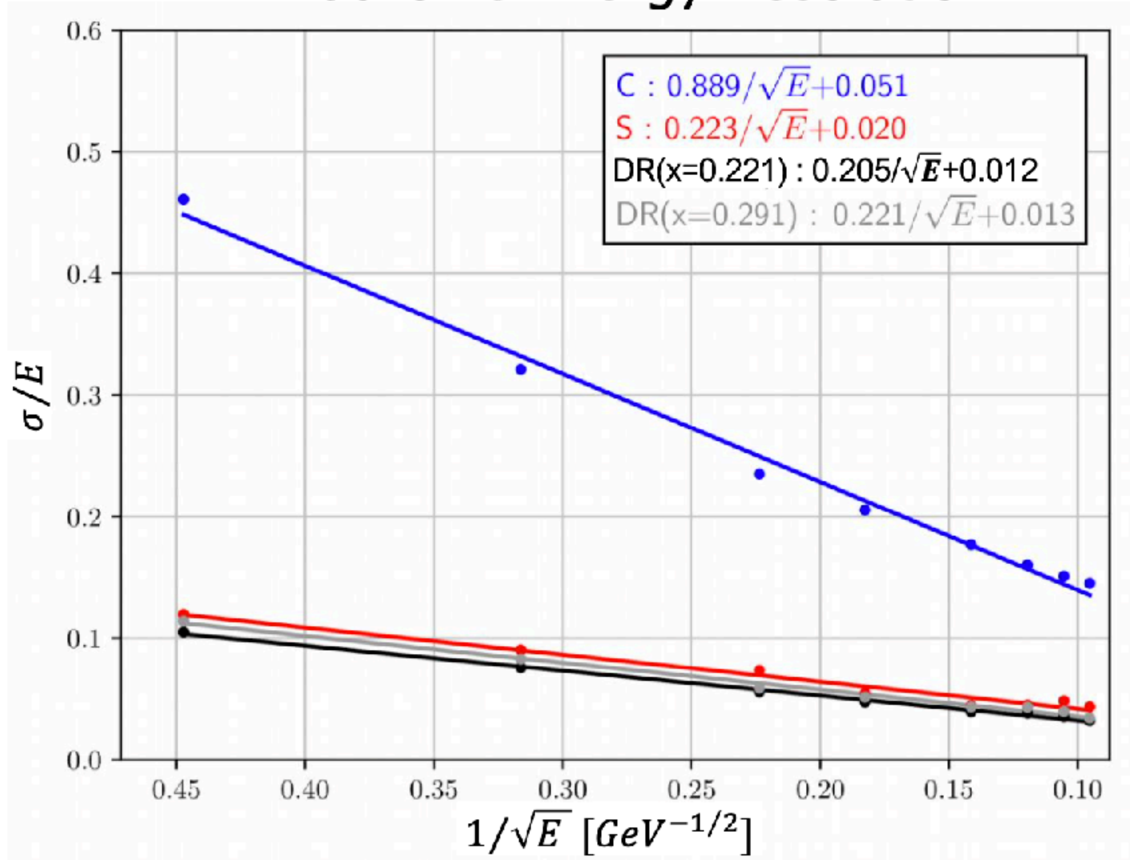
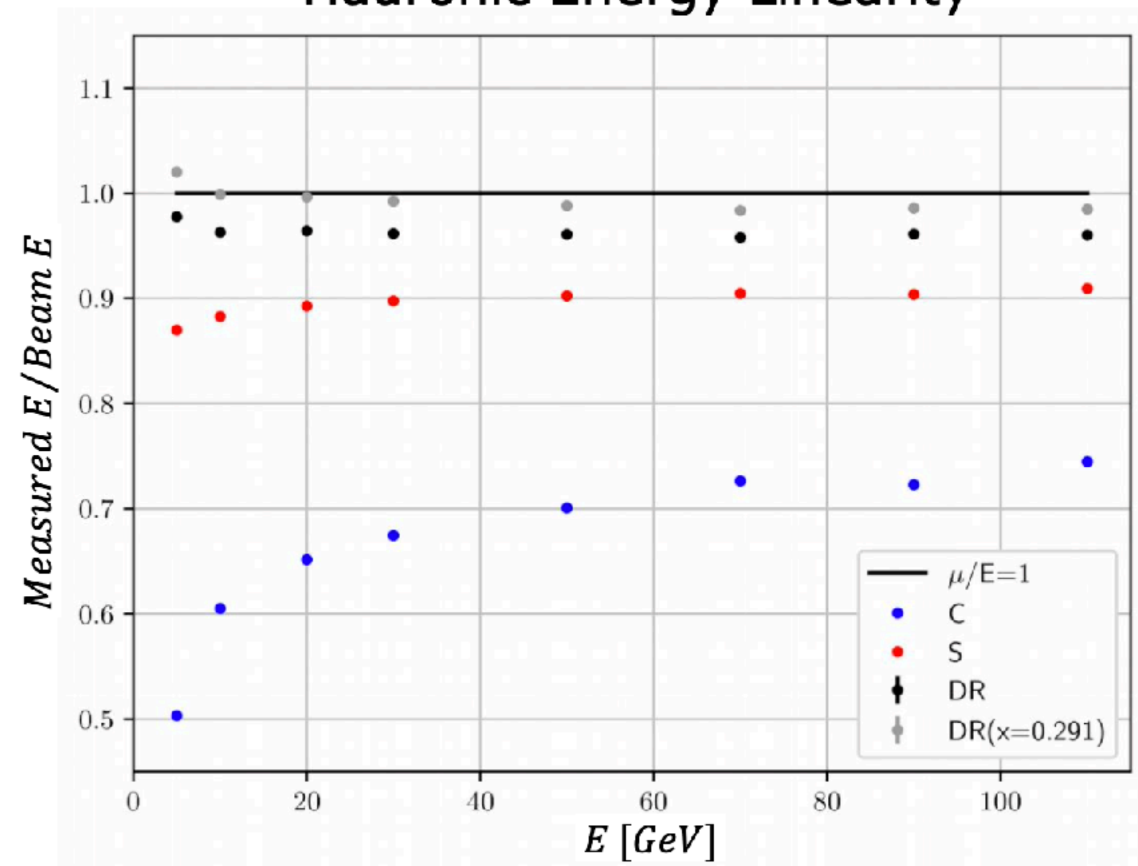
Hadronic Energy Resolution

- Hadronic energy resolution is measured with 8 different energy single pion beams.
- Two chi values(0.221 and 0.291) are used for DR correction.

Hadronic Energy Resolution



Hadronic Energy Linearity



- Stochastic term for hadronic energy resolution is ~21%.
- Energy resolution differs with chi values.

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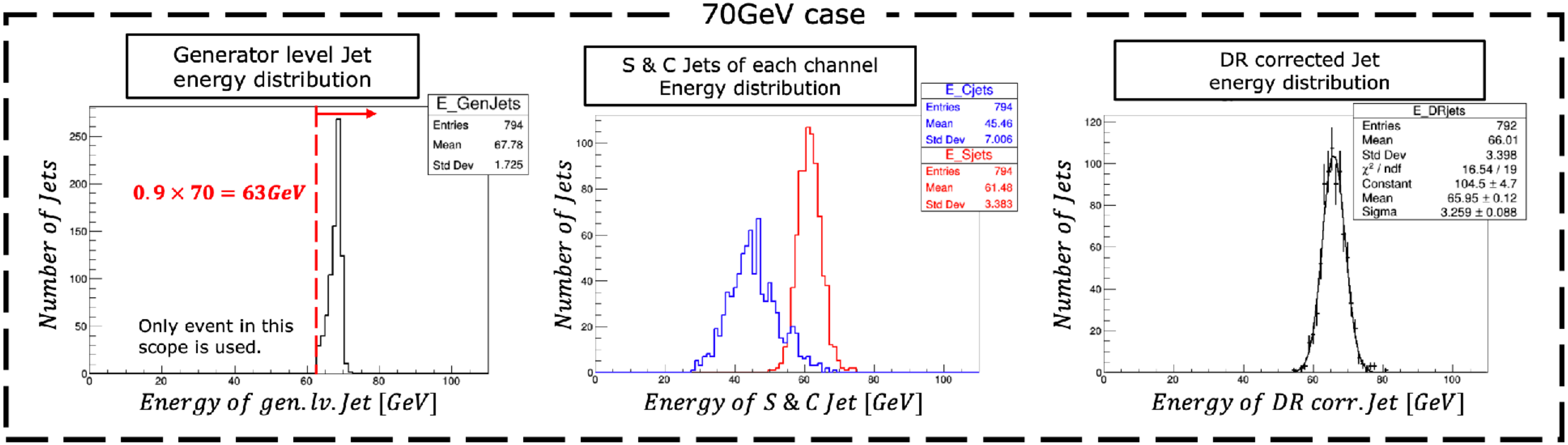
Jet Energy Resolution

- Jet energy resolution is measured with 4 different energy u quar. (50, 70, 90, 110 GeV)
- Jet is reconstructed with anti-kt algorithm(R=0.8) and chi value for DR correction is 0.221.

70GeV case



- Missing energy from neutrino and neutron during simulatation makes resolution worse.
- Only events are used for jet energy resolution measurement whose Gen. lv. Jet has an energy over 90% of generated jet.

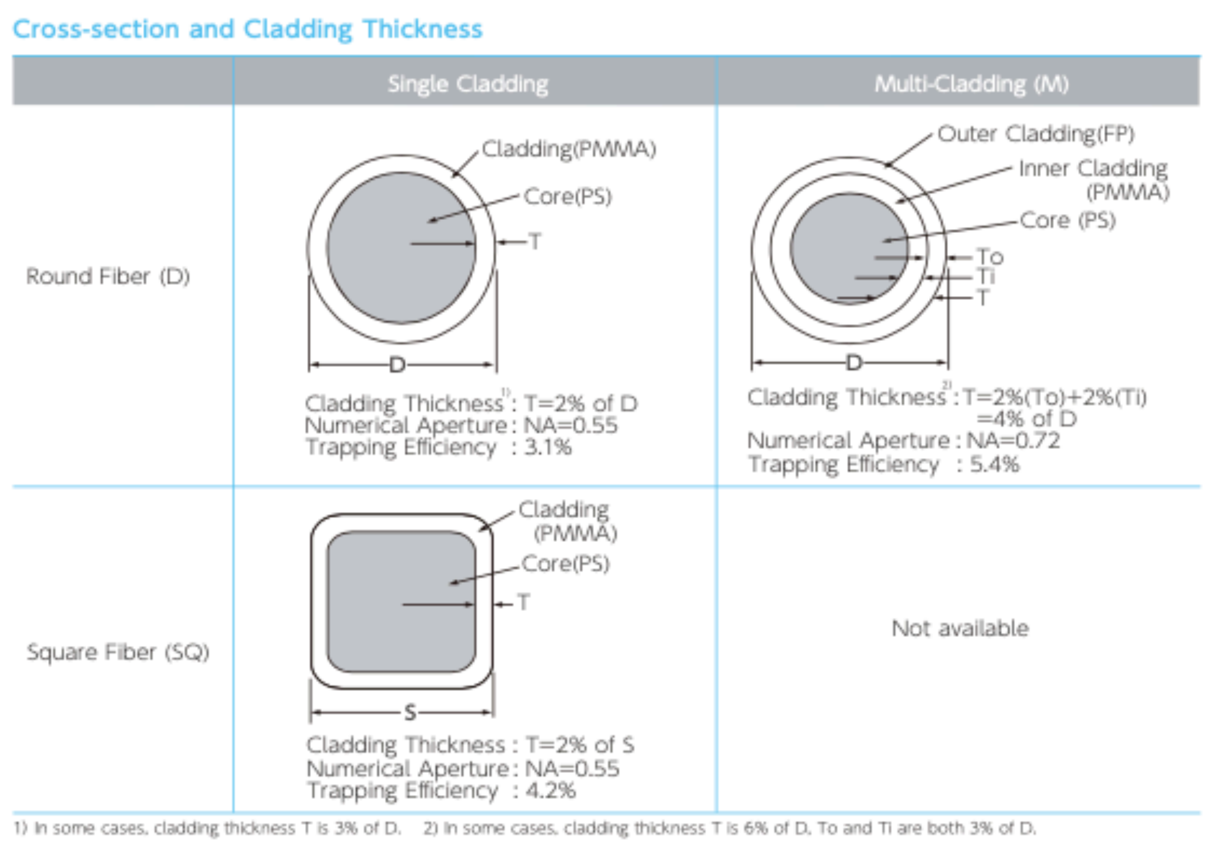
Fiber Specification

- **Čerenkov fiber**

Table 1

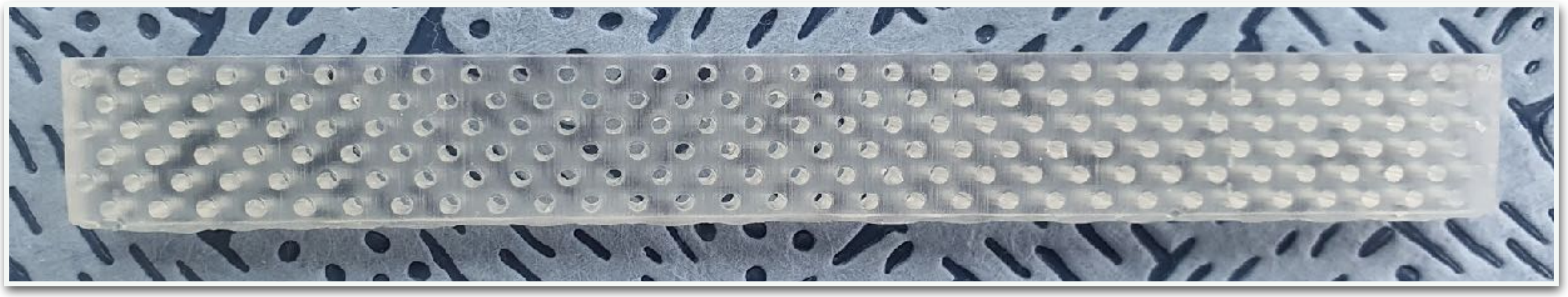
Item		SK-40			
		Specification			
		Unit	Min.	Typ.	Max.
Optical Fiber	Core Material	–	Polymethyl-Methacrylate Resin		
	Cladding Material	–	Fluorinated Polymer		
	Core Refractive Index	–	1.49		
	Refractive Index Profile	–	Step Index		
	Numerical Aperture	–	0.5		
	Core Diameter	μm	920	980	1,040
	Cladding Diameter	μm	940	1,000	1,060
Approximate Weight		g/m	1		

- **Scintillating fiber**



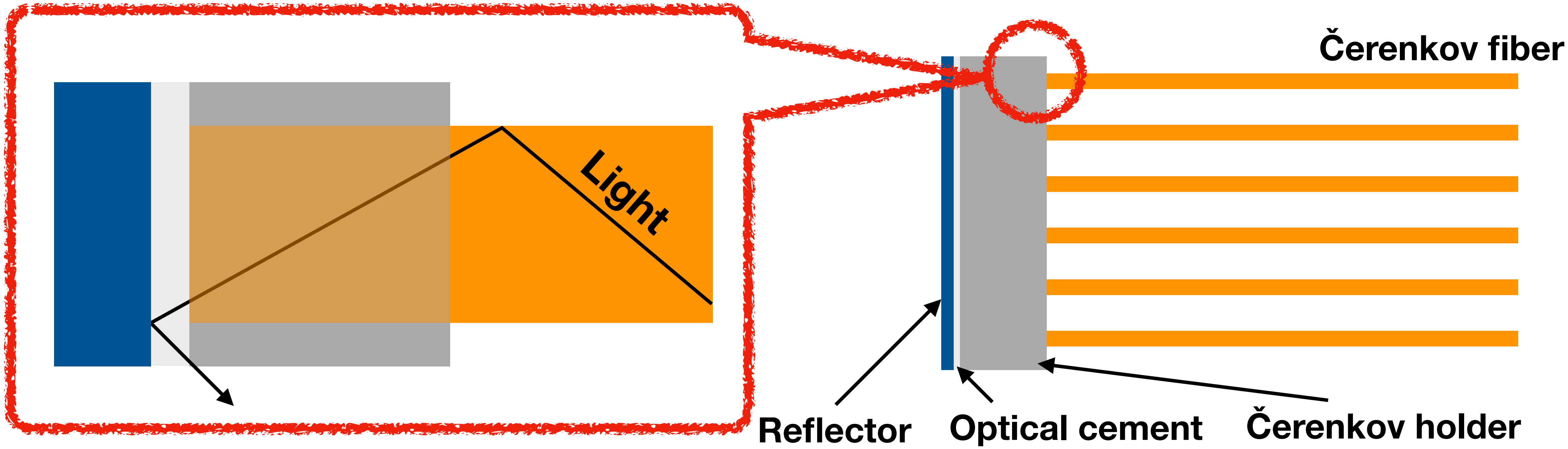
Reflector: Čerenkov holder

- We choose 3D-printed holder as a reflector
- And, tried to attach holders to čerenkov fibers
- But **FAIL**



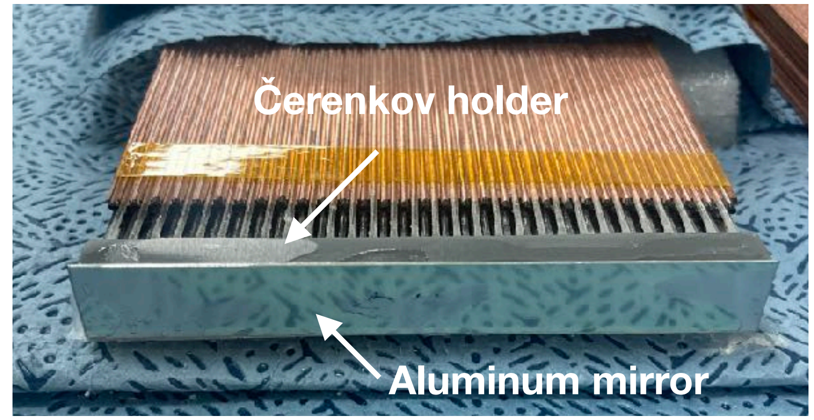
Čerenkov holder

- At this method using čerenkov holders, we also worry about that there may be **having a gap between holder and reflector**

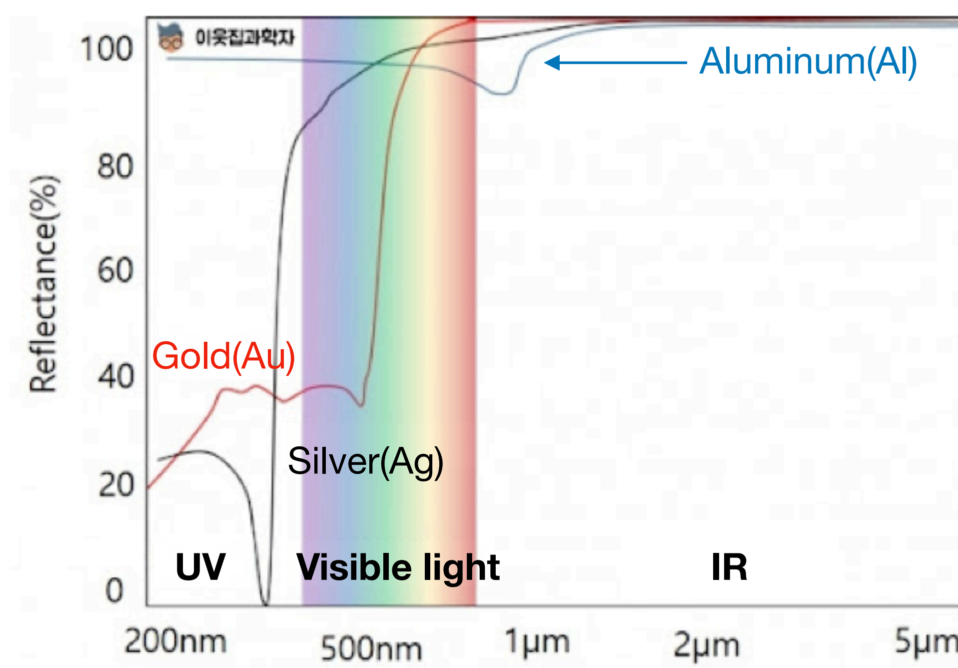


Reflector: Aluminum Foil

- The material as a reflector is changed from aluminum mirror to aluminum foil



- **Aluminum Foil**
  - We choose aluminum foil as a reflector
  - Aluminum foil has advantages
    1) high reflectance: over **~90%**
    2) availability: easy to get
    3) low cost

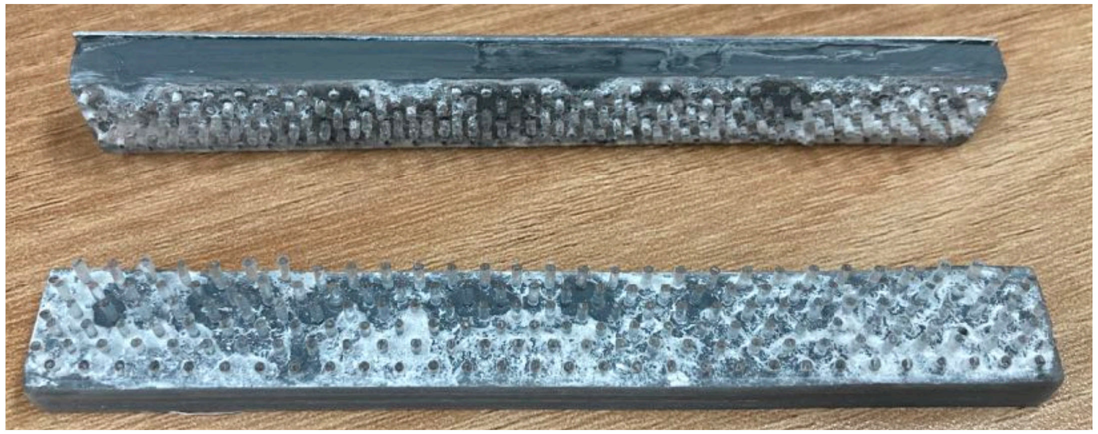


- Method and key point
  - The key point is **how well it adheres to the fiber**
  - Procedure (plan)
    - Cutting fibers at the front side using a grinder
    - Polishing fibers by hand
    - Attaching aluminum foil

EXAMPLE

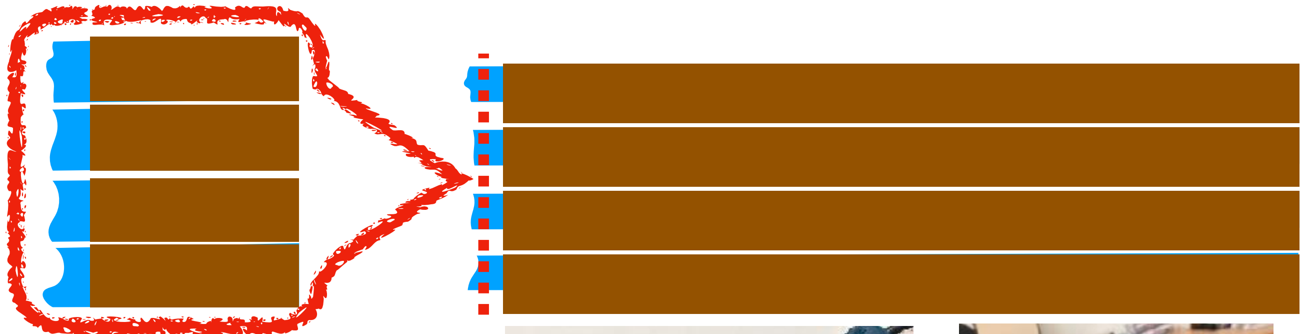
Reflector: Procedure

1) **Procedure for čerenkov fibers of module 1**
   1) Remove cerenkov holders

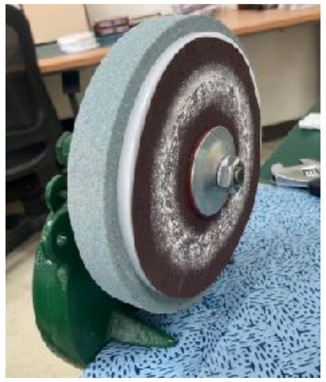


Removed čerenkov holders

   2) cutting fibers to flat the edge



Auto-grinder



Manual grinder

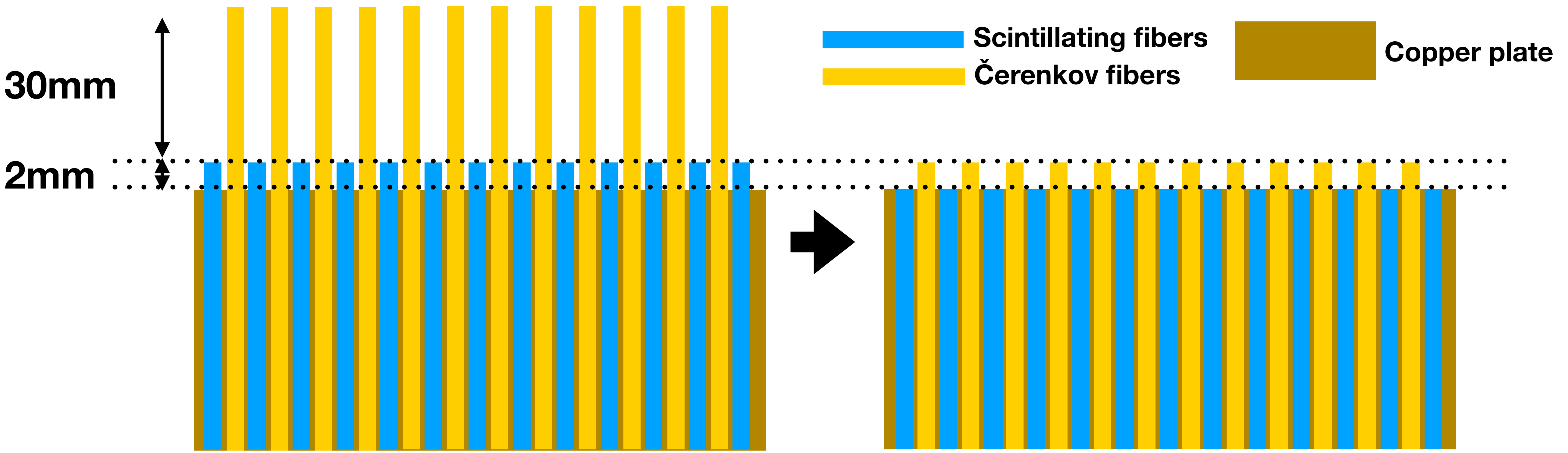
   3) Polishing fibers
      - Sandpaper: 400 grit -> 1000 grit -> 2000 grit ->
      - polishing film: 9um -> 3um -> 1um

Sandpaper

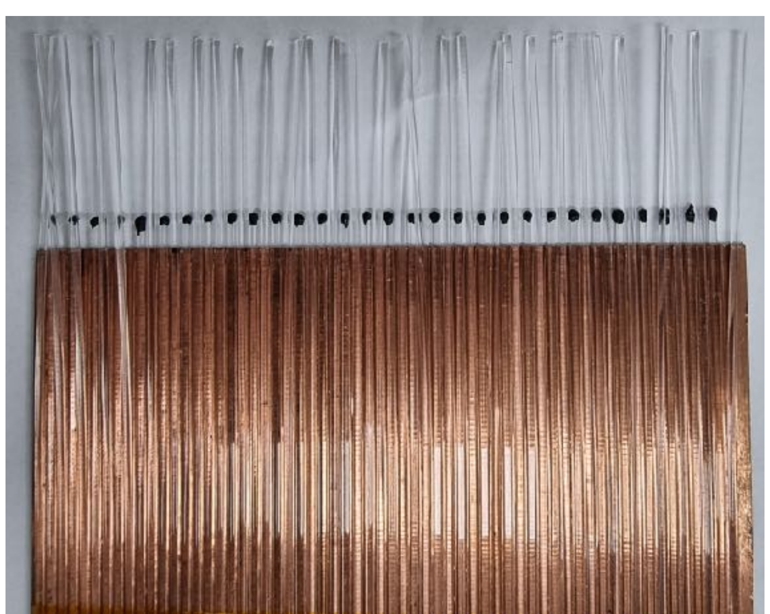
Polishing film

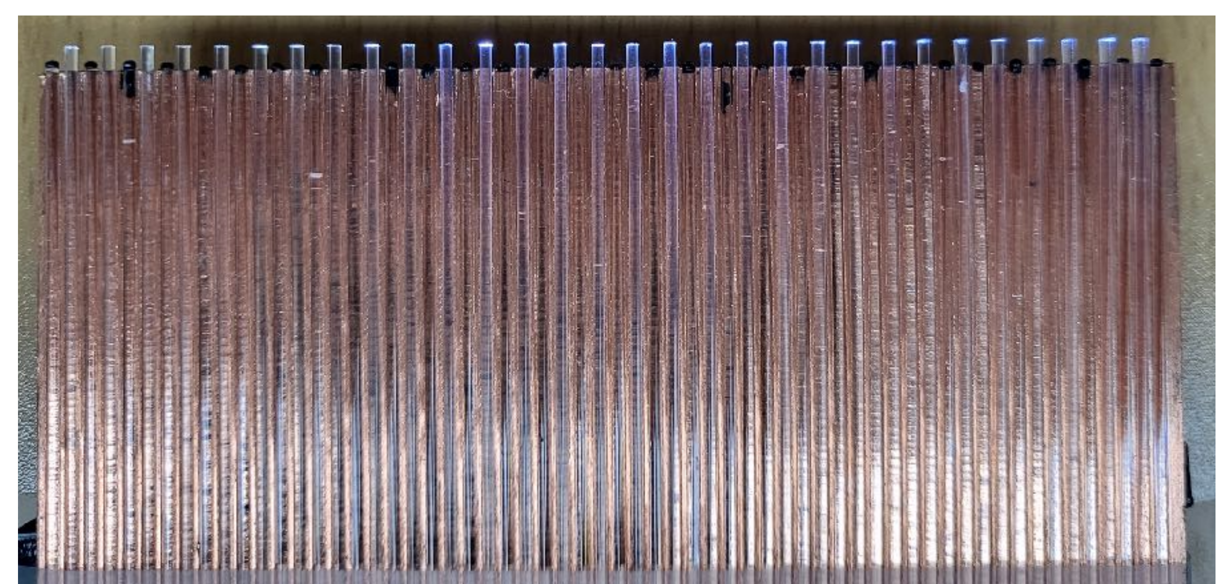
The alignment of Fibers

- **Differences between module 1 and 2**
  1) **The alignment of fibers**



Module 1 **Module 2**



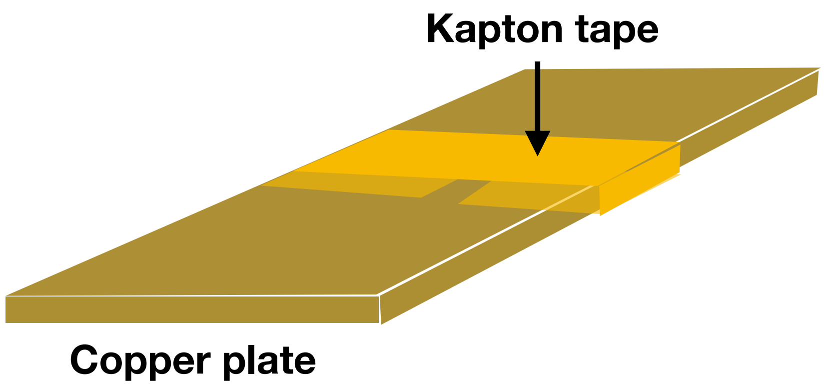


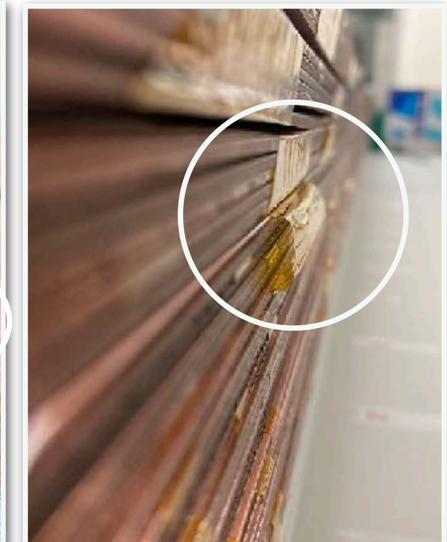
Taping Methods

- **Differences between module 1 and 2**

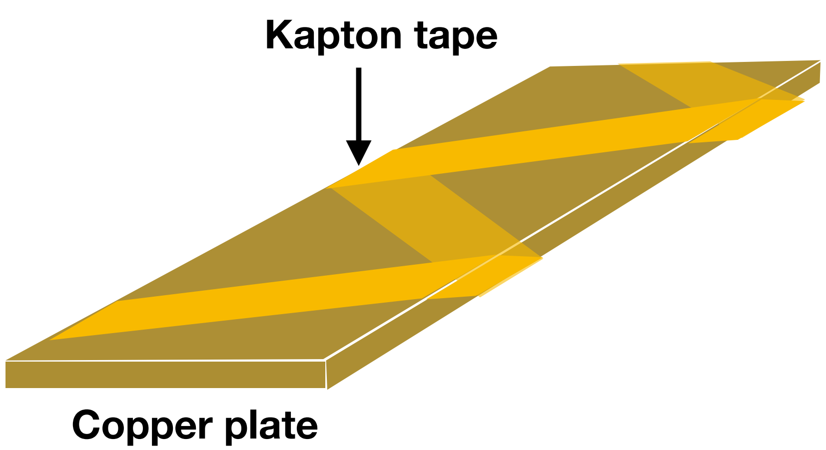
  2) Taping

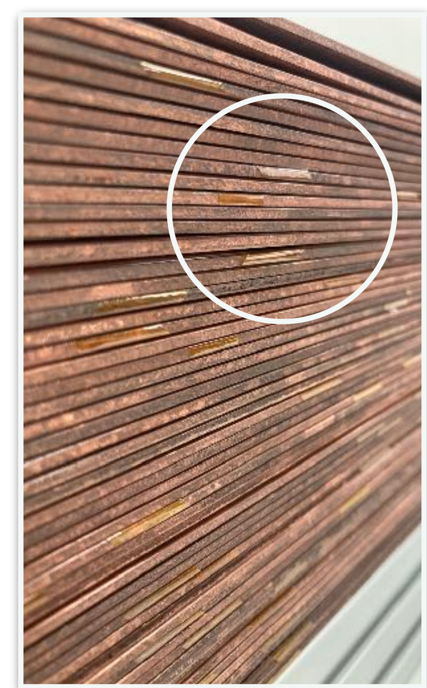
Module 1

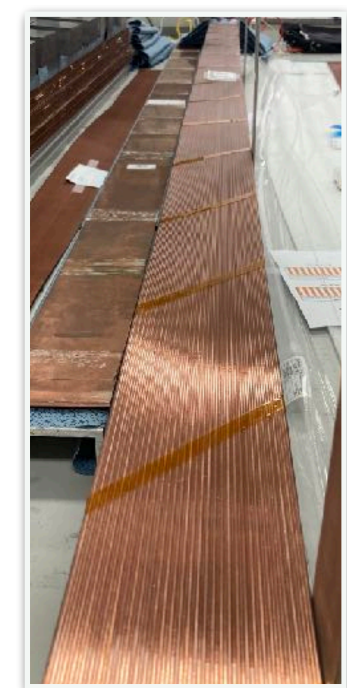




Module 2







Module Frame