Advanced R&D of the Dual-Readout Calorimeter

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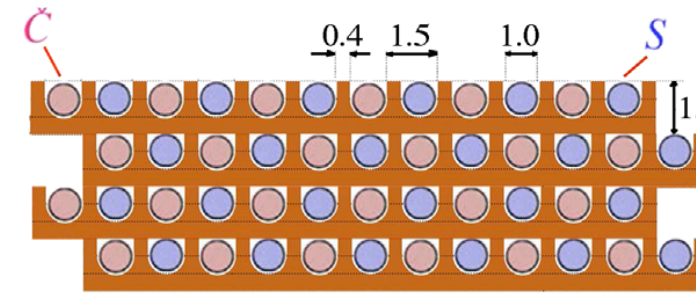
On behalf of
the Dual-Readout Calorimeter Collaboration

CPAD workshop, Mar. 19, 2021

Supported by KiSTi www.kisti.re.kr

Dual-Readout Calorimeter (DRC)

- DRC offers high-quality energy measurement for both EM particles and hadrons
  - DRC consists of two different optical fibers (S, C) in a single component
  - The main culprit of poor hadronic energy resolution is fluctuations of the EM shower components of hadron showers (f_{em})
  - f_{em} can be determined using the measured values of scintillation and Cerenkov signals
- Excellent hadron energy resolution can be achieved by correcting the energy of hadron event-by event



Fiber pattern RD52

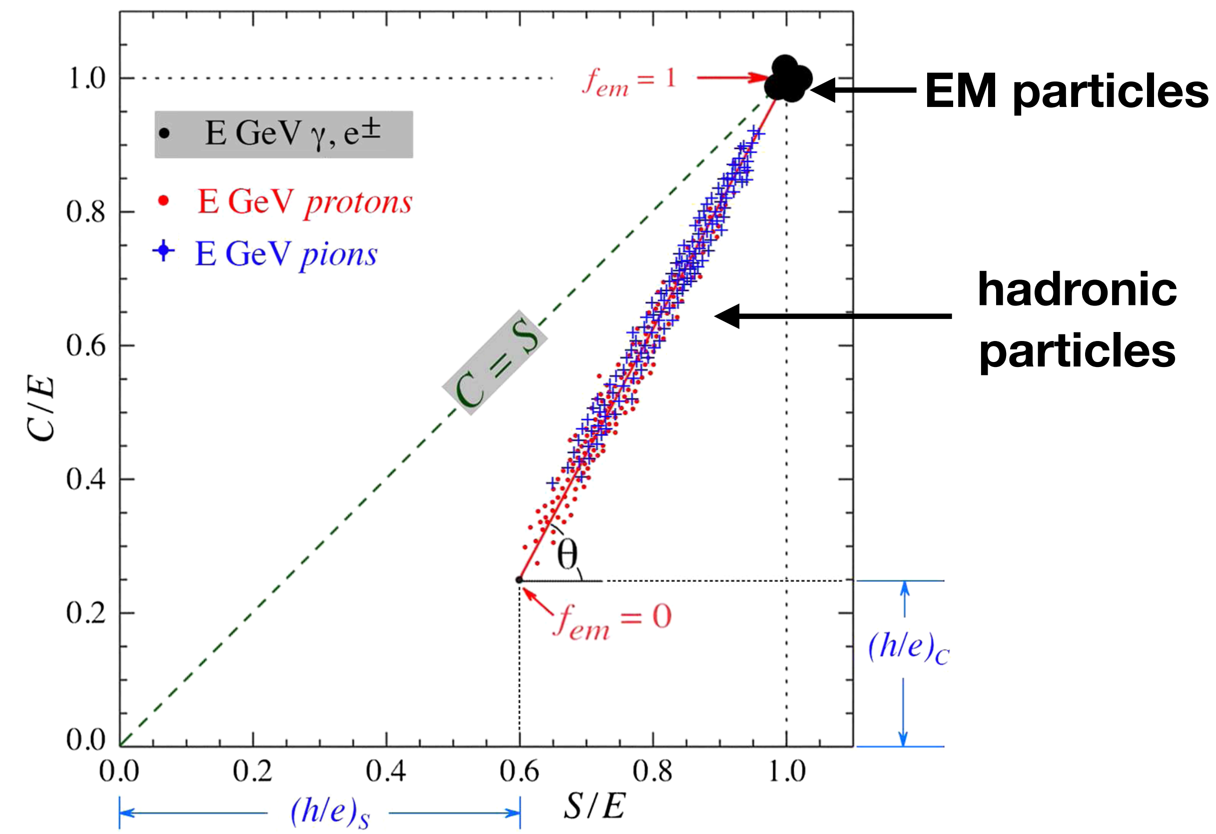
$$S = E\left[f_{\rm em} + \frac{1}{(e/h)_S}(1 - f_{\rm em})\right],$$

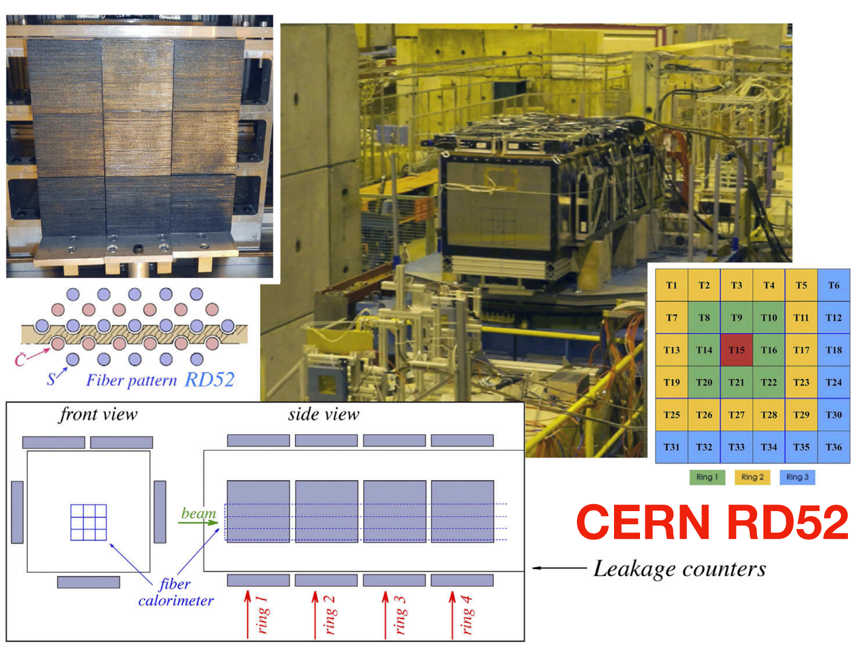
$$C = E\left[f_{\rm em} + \frac{1}{(e/h)_C}(1 - f_{\rm em})\right],$$

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

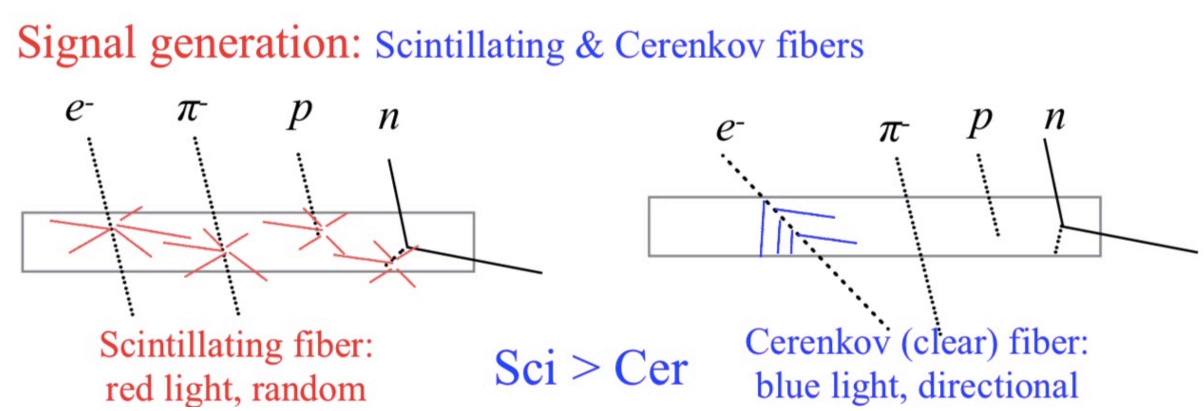
$$E = \frac{S - \chi C}{1 - \chi}.$$

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



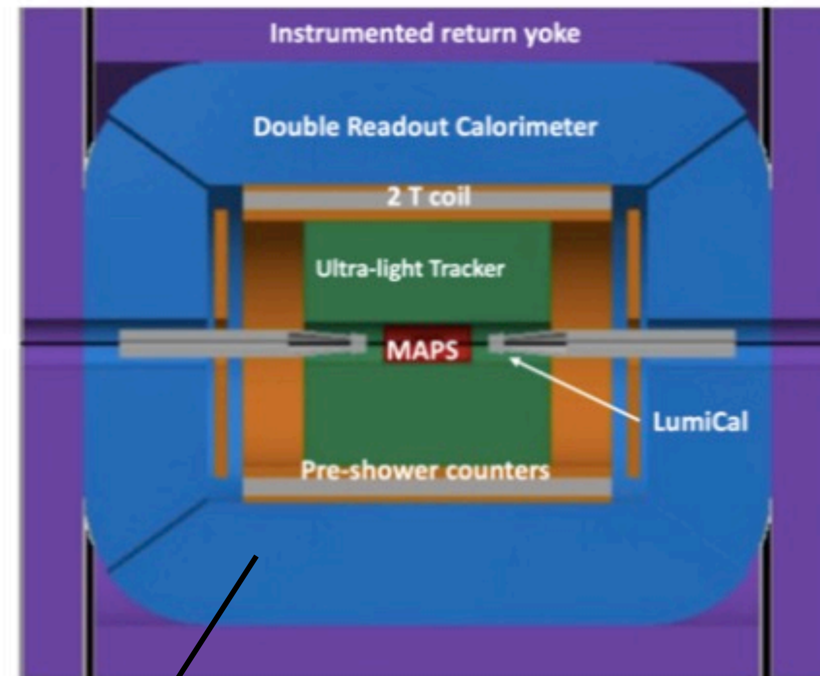


CERN RD52 experiment

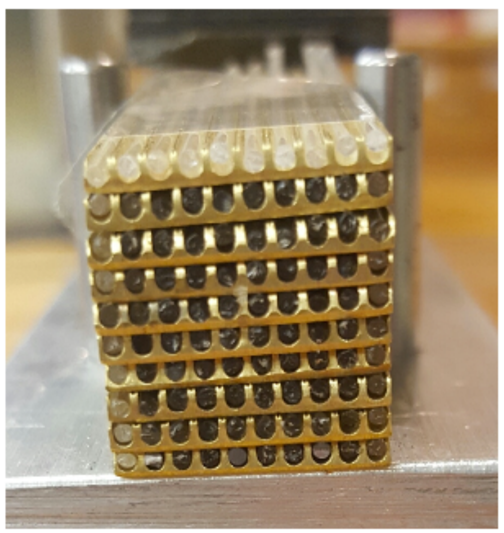


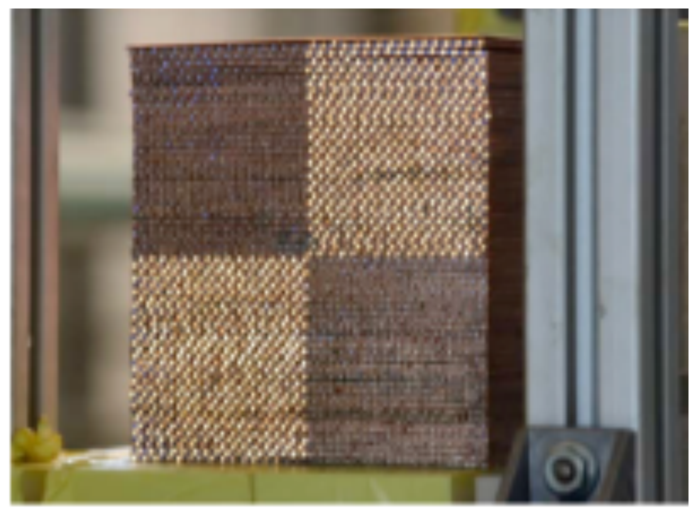
DRC Geometry and Module

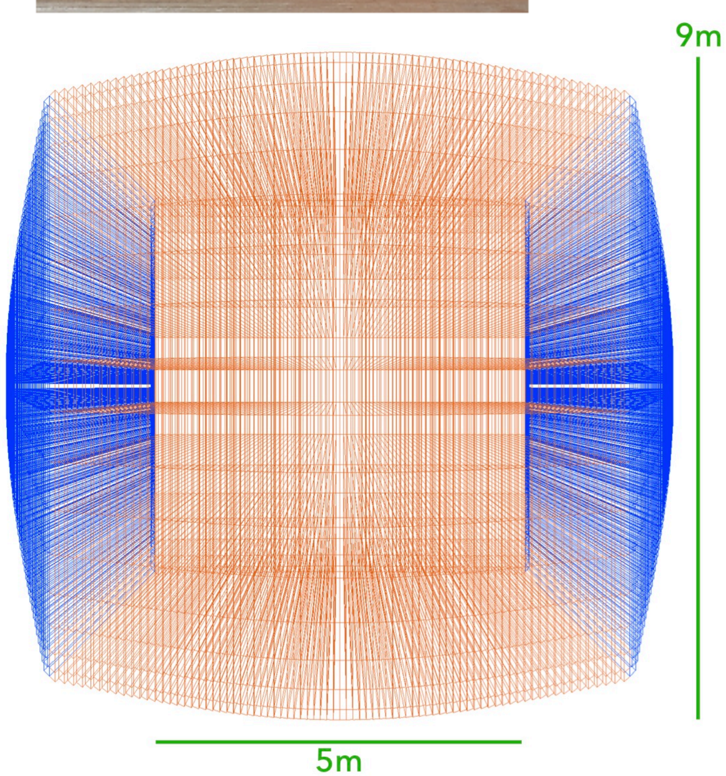
- Korean team led the design of the Dual-Readout Calorimeter (DRC) for IDEA detector
  - Included in the CDRs of both FCC-ee and CEPC, published at the end of 2018
- **Calorimeter design for EIC project** with Korea HI community is also on-going

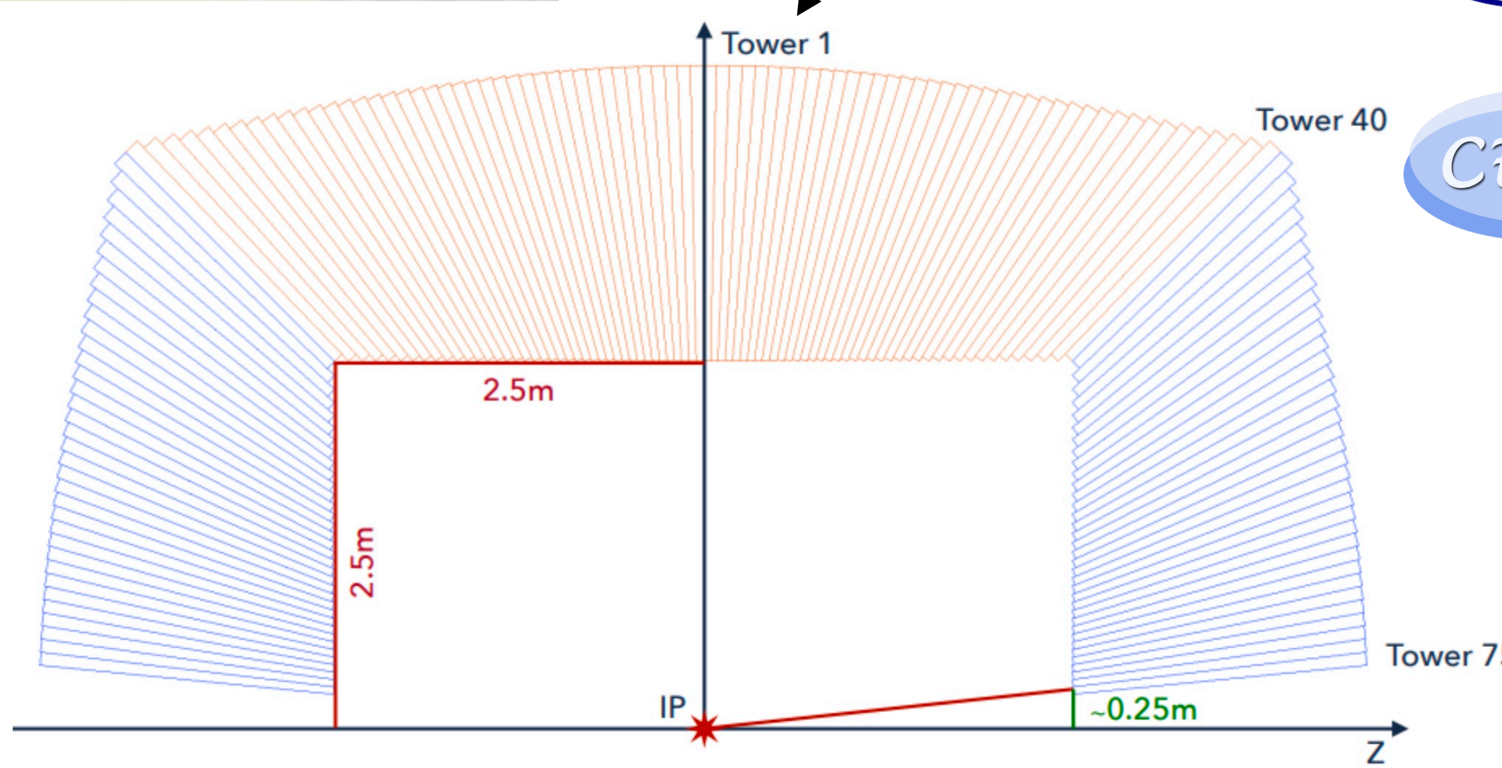


IDEA





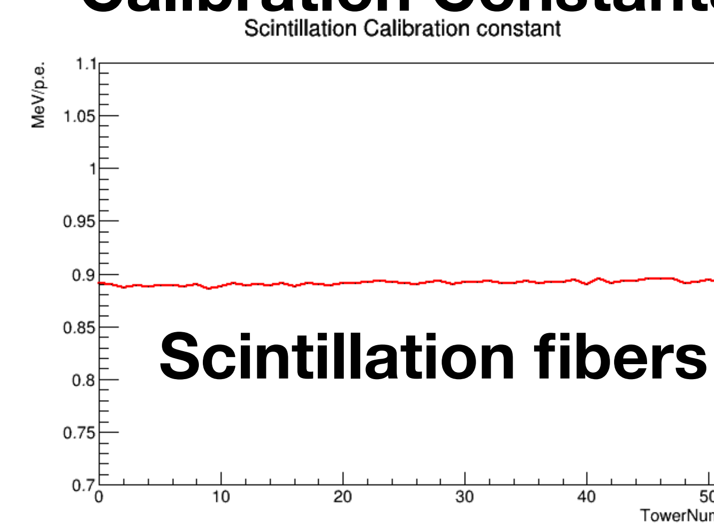


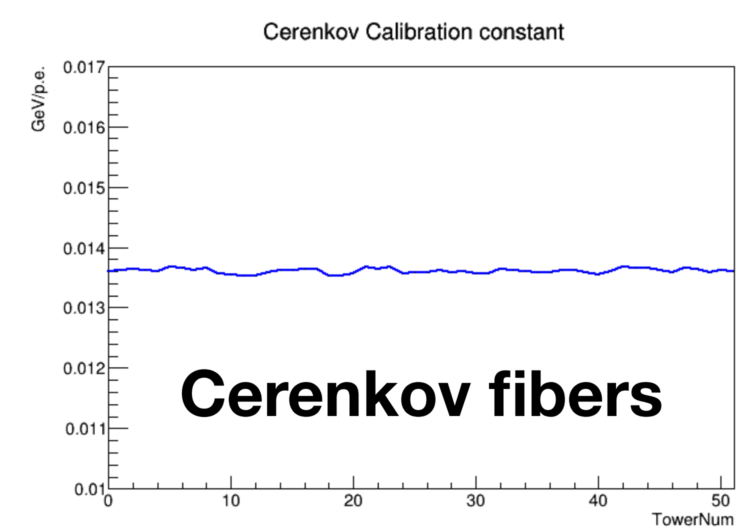


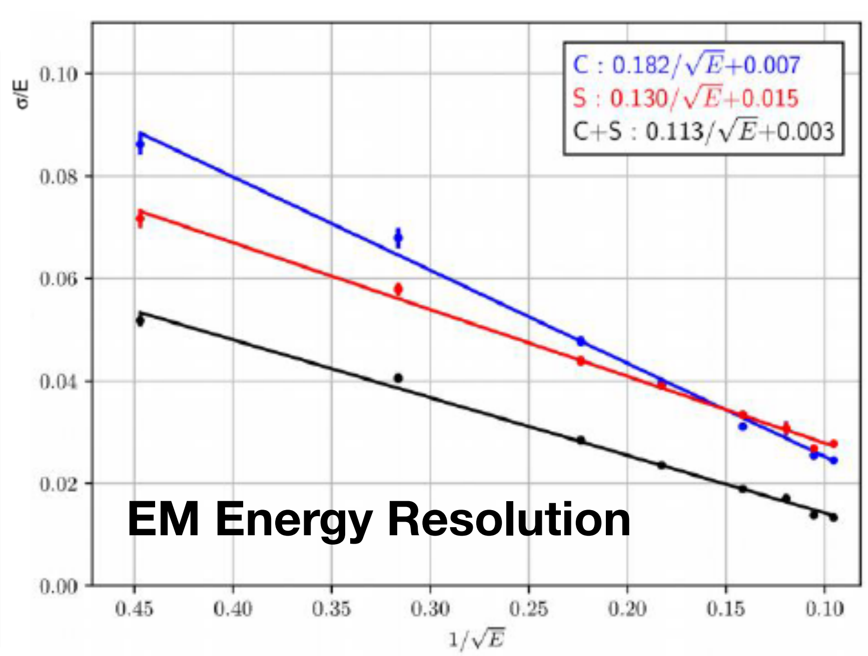
Energy Resolution

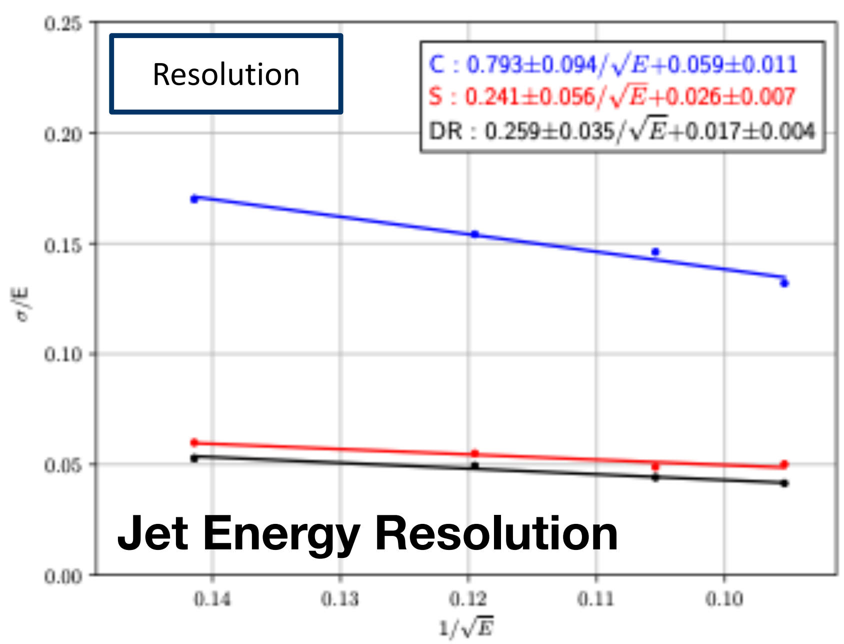
- Production of calibration constant with full GEANT4 simulation is on-going
  - Both barrel and endcap have been done
- Excellent EM and hadronic energy resolutions obtained by GEANT4 simulation
  - EM energy resolution: ~$11\,\%/\sqrt{E}$
  - Jet energy resolution: ~ $26\,\%/\sqrt{E}$
- Many other simulation studies for performance and ML applications on-going

Calibration Constants









Tower #

International Collaboration

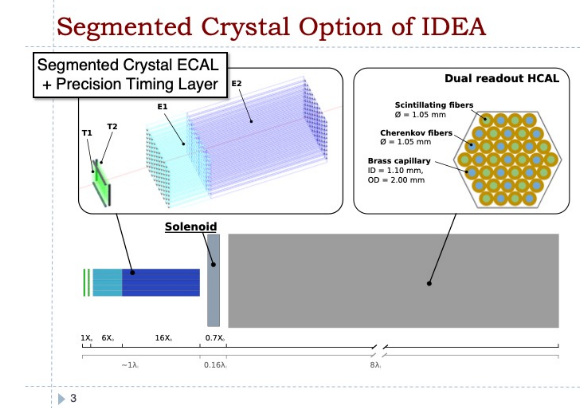
Prof. Hyonsuk Jo (KNU)
Prof. Yongsun Kim (Sejong U.)
Prof. Jason Lee (UoS)
Prof. Sehwook Lee (KNU)
Prof. Hwidong Yoo (YU)

Prof. Rong-Shyang Lu

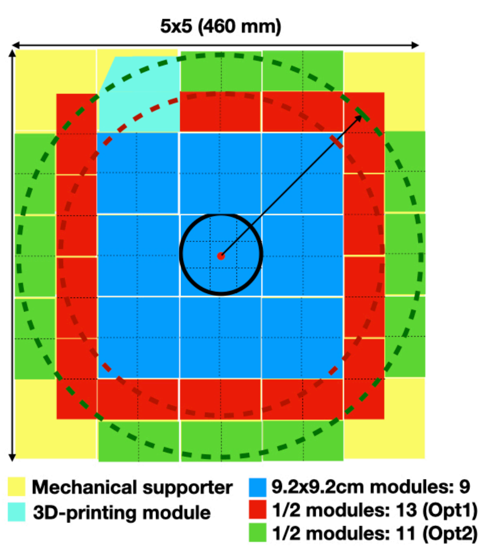
Prof. Chia Ming Kuo

Taiwan

DRC with crystal



Full-size prototype detector



Korea

Japan

Prof. Yuji Enari
(Active from 2021)

DREAM FOR FUTURE

USA

Prof. Sarah Eno

Prof. Chris Tully

Prof. Richard Wigmans

Prof. John Hauptman

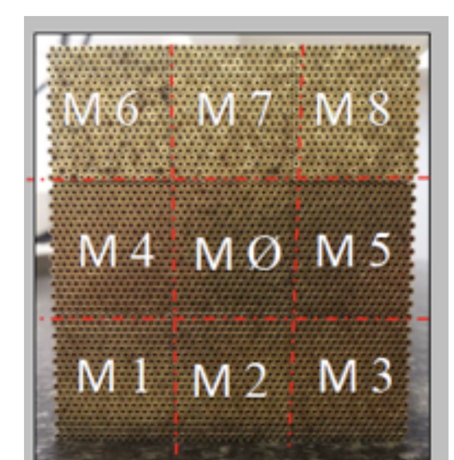
Europe

Prof. Paolo Giacomelli (Bologna)
Prof. Romualdo Santoro (Insubria)
Prof. Roberto Ferrari (Pavia)
Prof. Franco Bedeschi (Pisa)

Prof. Iacopo Vivarelli

Prof. Valery Chmill

Bucatini prototype

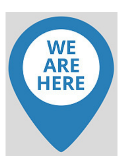


International collaboration forms

- Regular meeting
- Compensated R&D options
- Combine efforts

Korea Prototype Detector

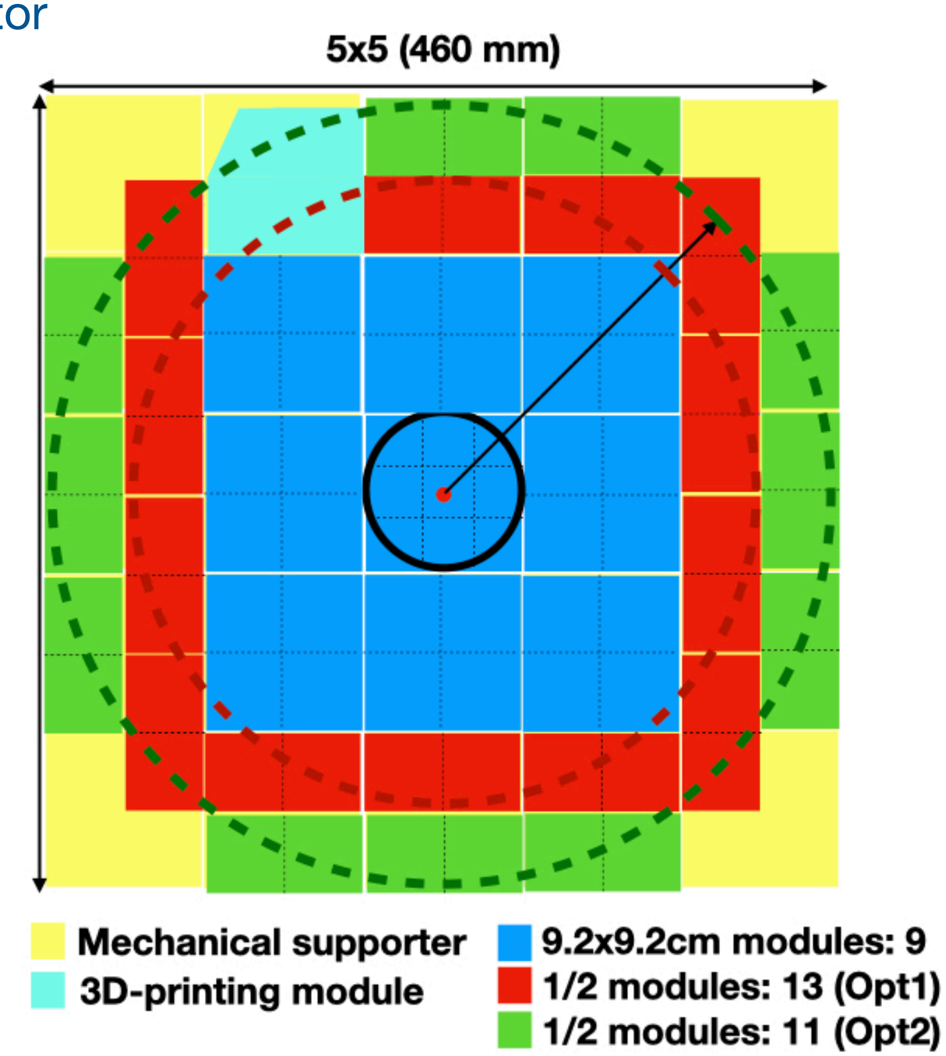
- Primary goal: build a prototype detector for the detector design of CEPC experiment
  - **5 year (2020.Mar. - 2025.Feb.) R&D funding** supported by Korea NRF ($~0.4M/year, total **$~2M** for 5 years)
  - Contain almost (97.5%) full hadronic shower energy
  - Demonstrate engineering aspects for full geometry detector
- Secondary goal: train next generations as experts of the (DRC) detector



2017-9	2020-1	2022-5	TBD
Design	R&D	Prototype	Production

Stage	Topic
Design	Propose a design of Dual-Readout Calorimeter to IDEA detector concept
R&D	Perform R&D (including engineering aspects) based on HW & SW
Prototype	Build 4x4 detector and perform test beams
Production	TBD

Prototype Detector (2025)



Test-beam at 2021

Goal	Details
Physics	Measurement of nuclear interaction length using proton beam
	Measurement of energy and position resolution using electron beam
R&D	Readout test (MCP vs. SiPM)
	Time resolution (< 50 ps)
	Optical fibers (various types)
Training	Next generation experts for DRC HW

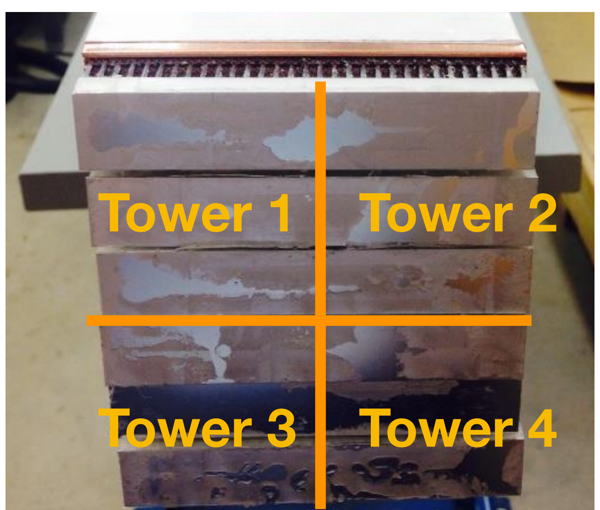
Signal starting time difference: 2 ns/m

Time resolution: 10 ps —> 5 mm precision

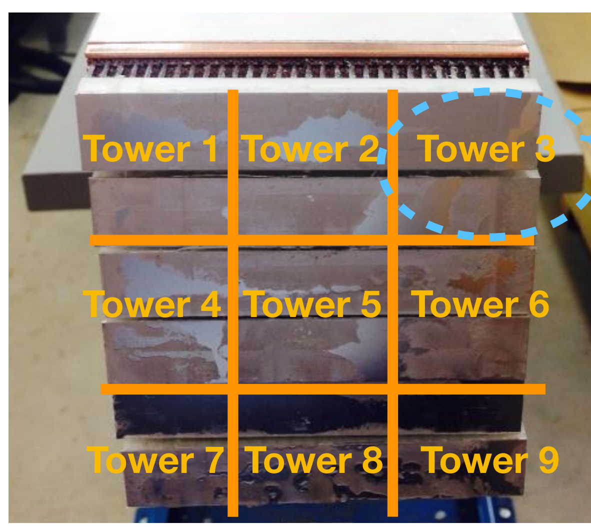
Time resolution: 50 ps —> 25 mm precision

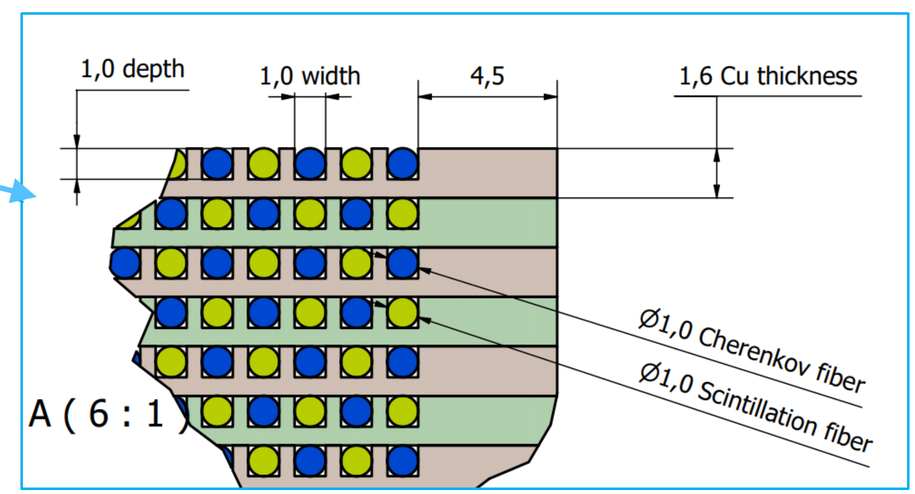
Time resolution: 100 ps —> 50 mm precision

Module #1 (2x2)

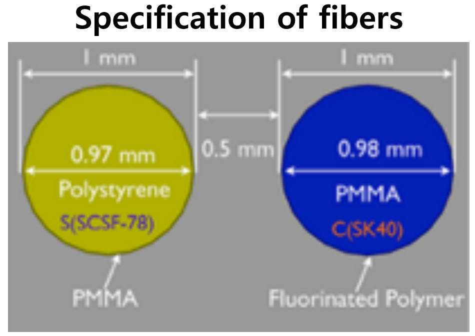


Module #2 (3x3)

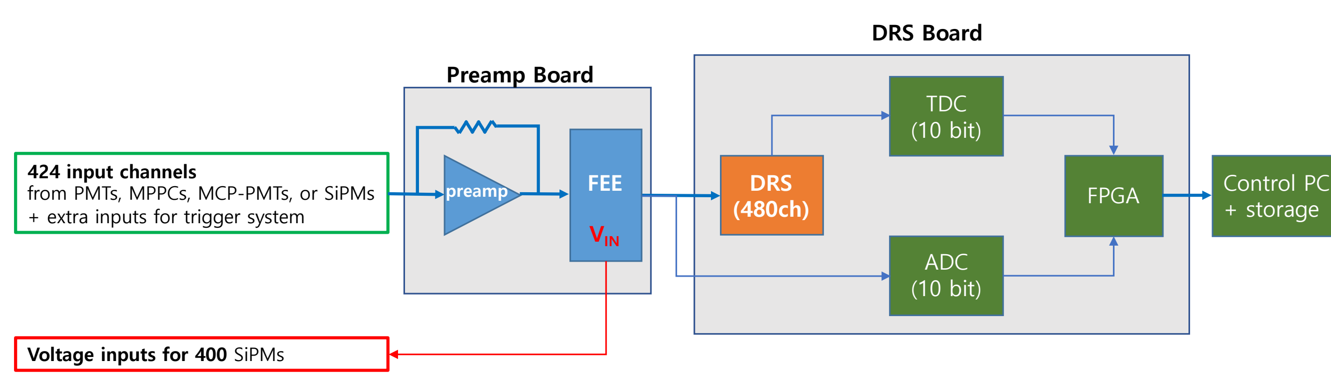




Specification of fibers

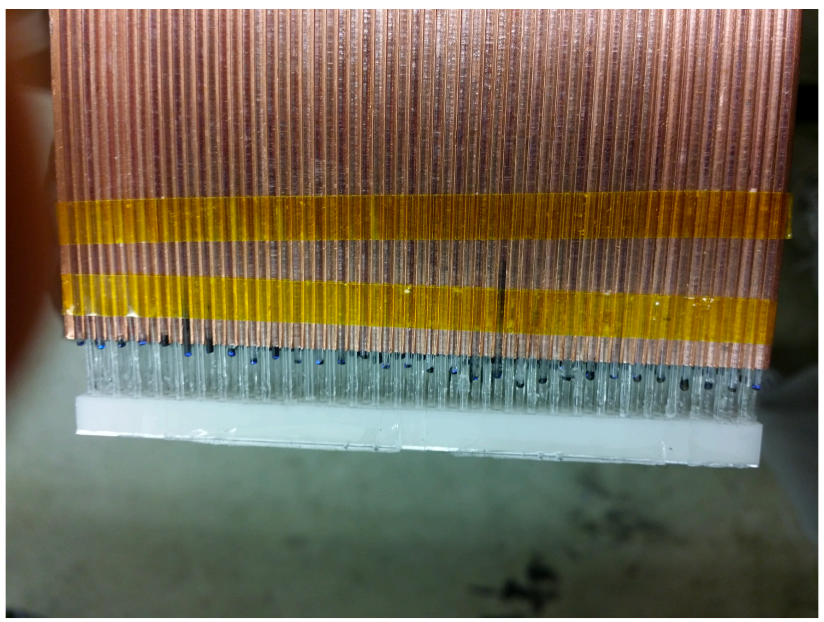


NIM A 762 (2014) 100, N. Akchurin et al.



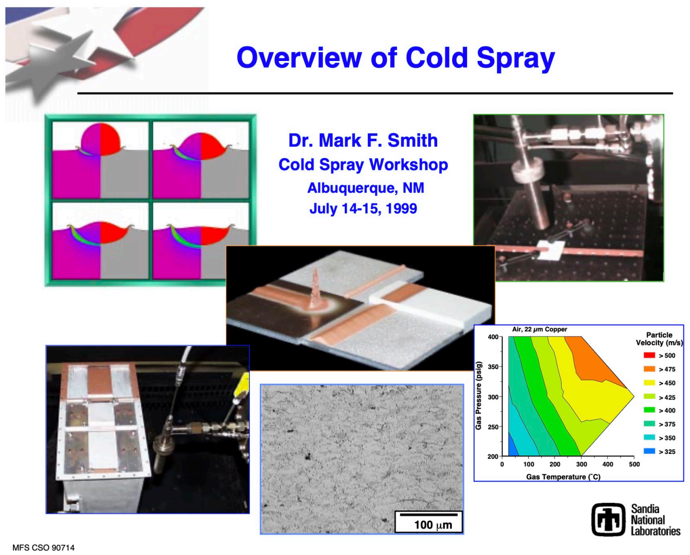
Module Building in 2016

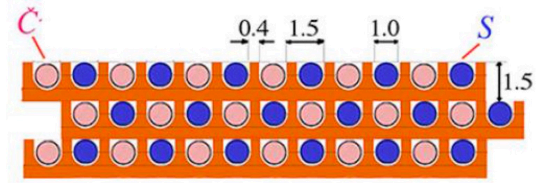
- For 2016 test beam, two Cu modules were produced by cutting
- This technical approach has already been proved well by previous module building
- Testing innovative 3D printing for alternative possibility at 2020




Previous Copper Forming R&D

- We tried many options (by John Hauptman et al in CERN RD52)





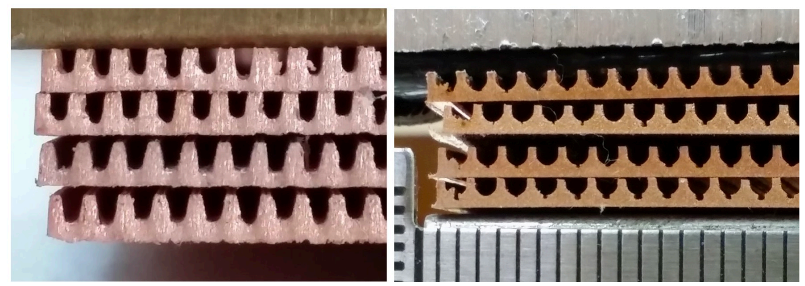
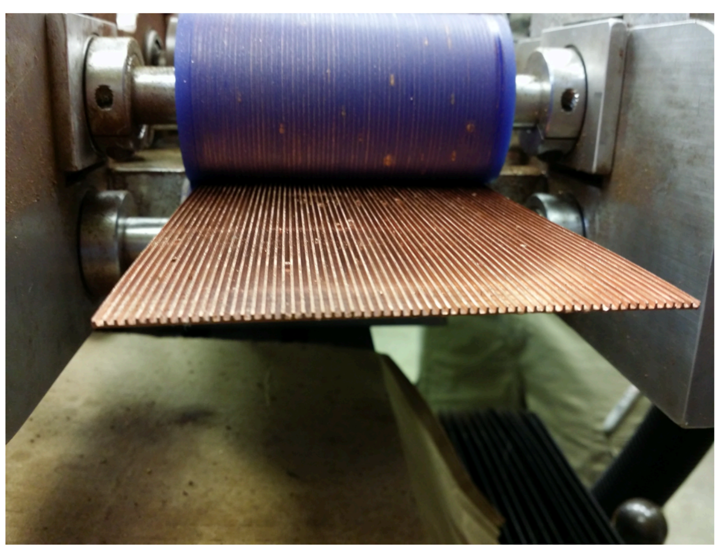
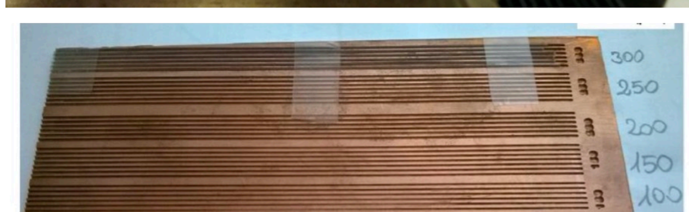
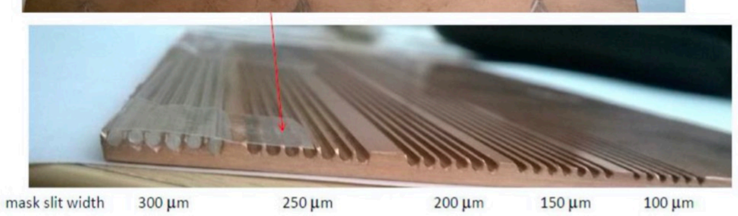
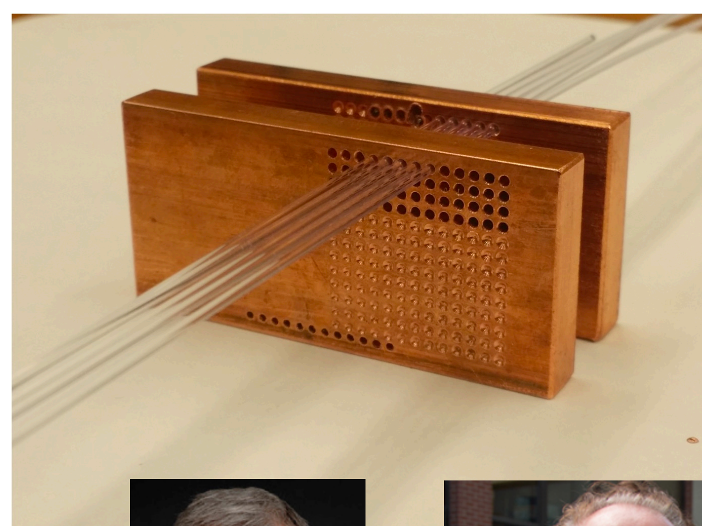


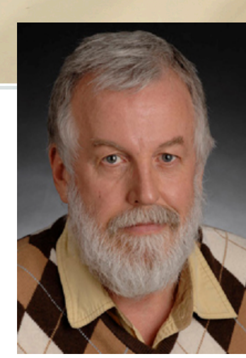
Figure 25: Water-jet grooved plates on the left (2.5 meters long) and the precision rolled corresponding grooves on the right.











R. Wigmans

J. Hauptman

RD52 Copper Forming (draft)

distribution

John Hauptman, Sehwook Lee, Fabrizio Scuri, Silvia Franchino, Bobae Kim, Ryonghae Ye, Hyunsuk Jo, Richard Wigmans

15 March 2018

Contents

Is It Possible with 3D Metal Printing?

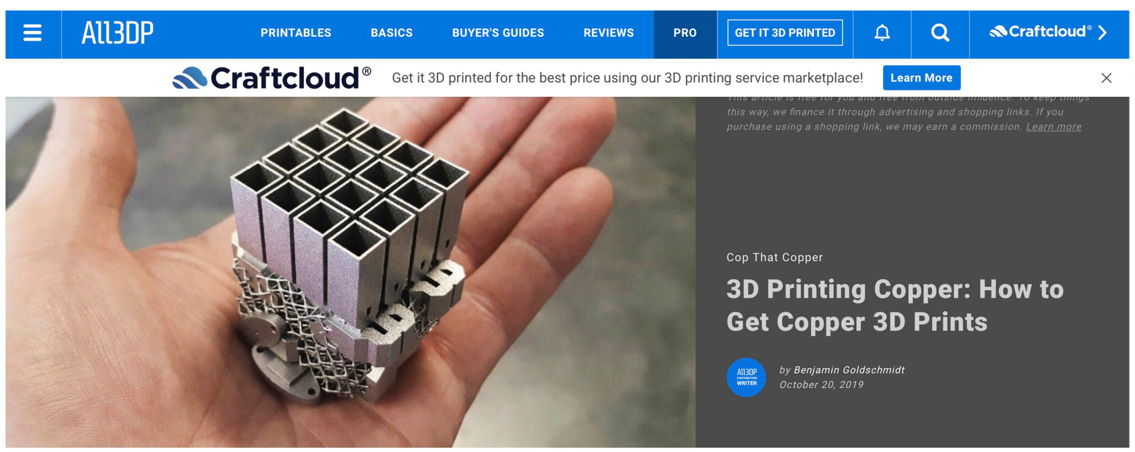
- Ok, German company …, let's check it out

4.3 3D Printing

A German company advertises a 3-D printer for tungsten, and it seems copper cannot be more difficult. I have not looked into this, but the largest 3d printer I have seen is less than a square meter, but it should not be a problem to extend one dimension to 3 meters.

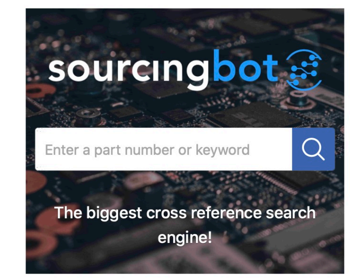
3D Copper Printing Technology

- Copper is not easy to be used for 3D metal printing
  - But technology is being developed very fast …

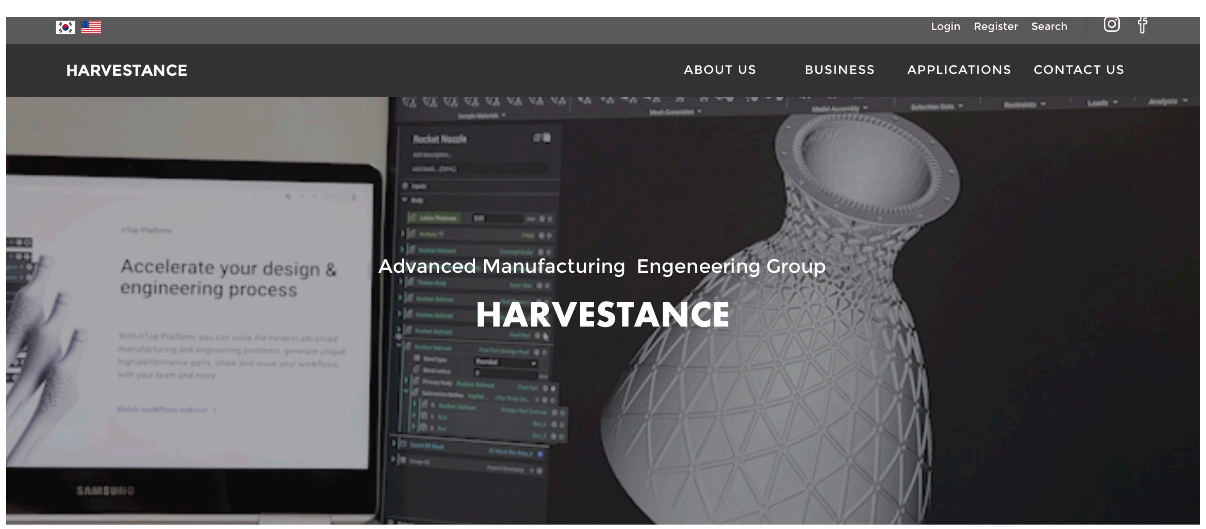


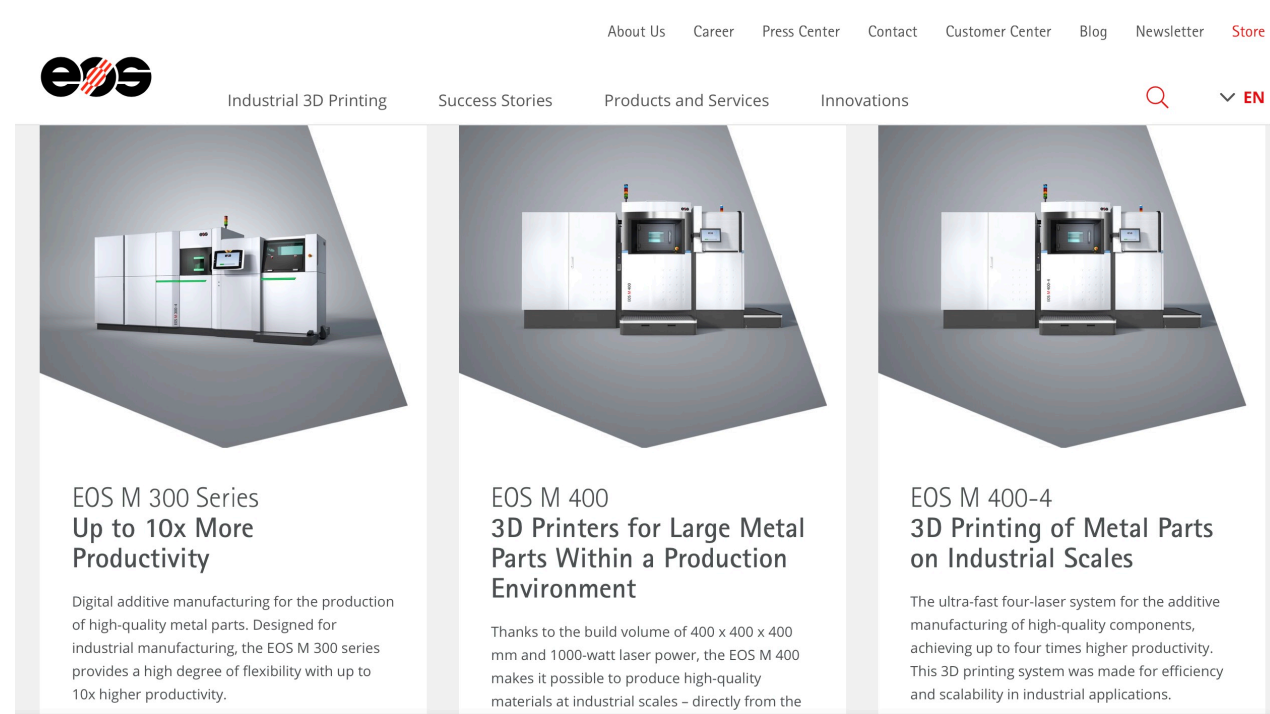
CERN exploring GH Induction's copper 3D printing

30.7.2019 Reading Time: 4min read



- We contact a local 3D consultant company



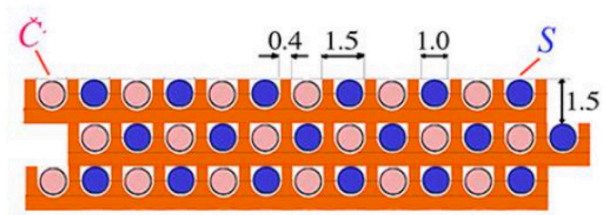


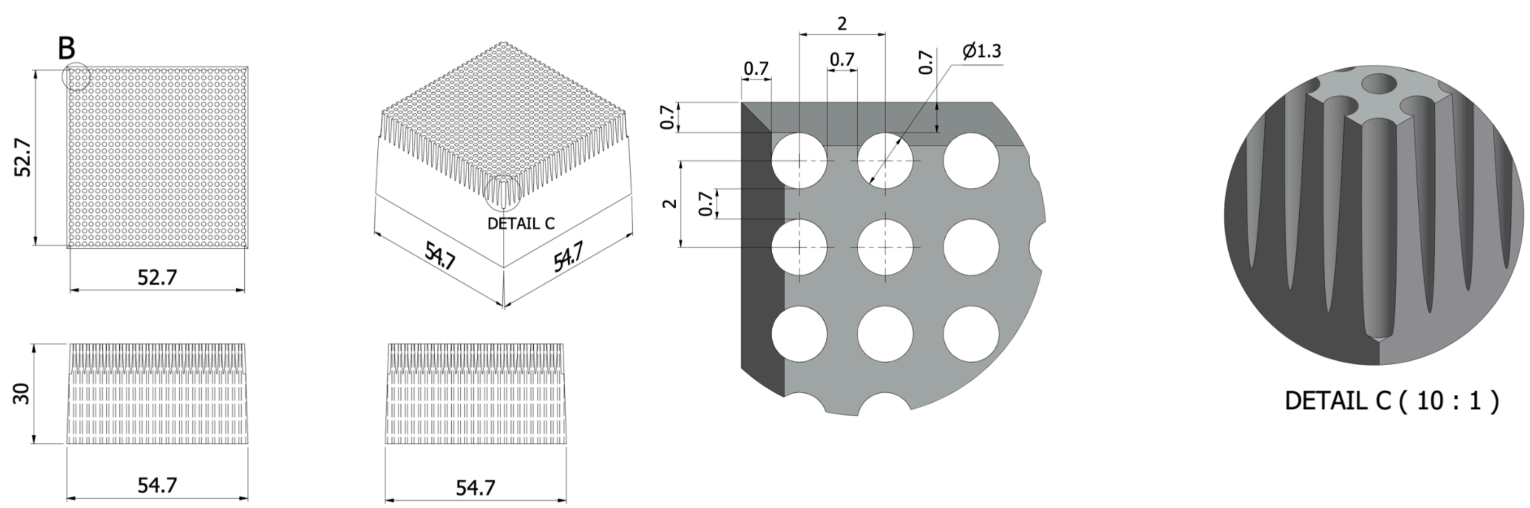
3D Printing Module R&D

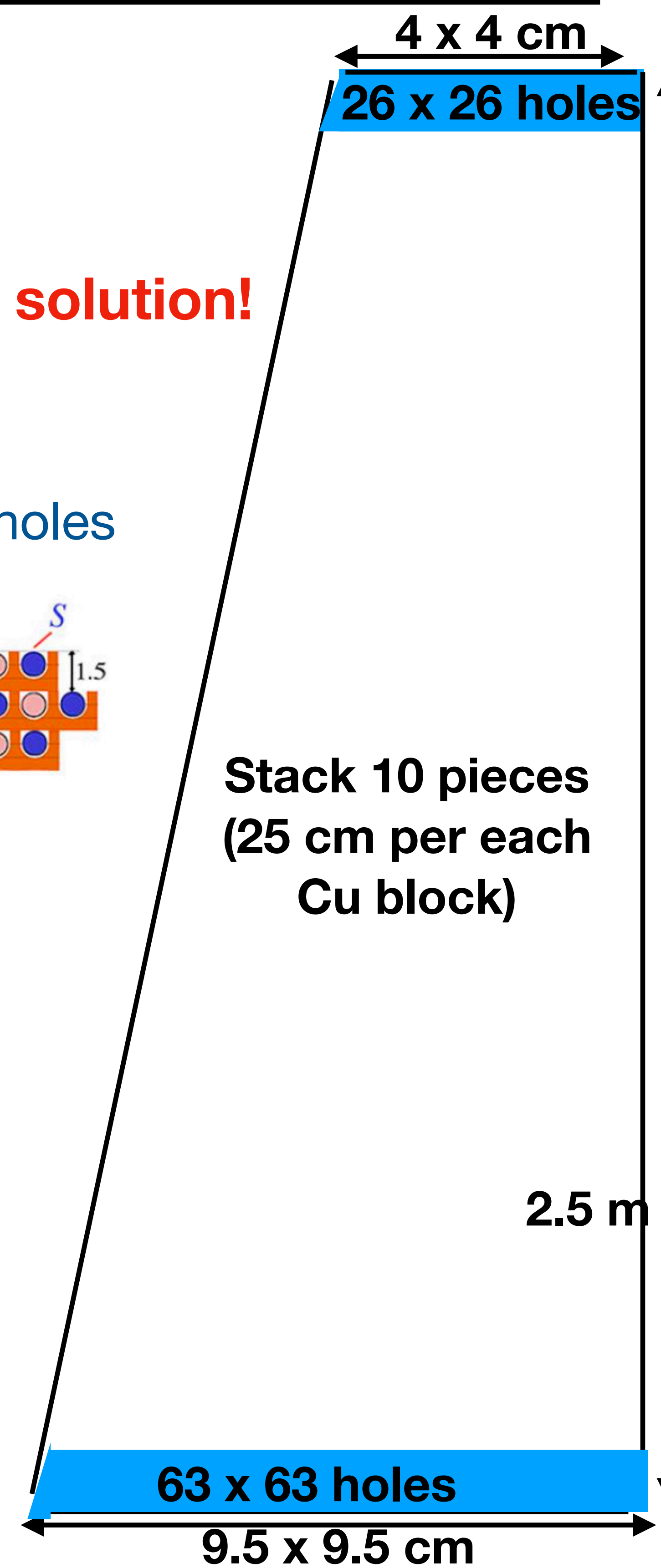
- Two major questions on the DRC for engineering aspects
  - Complex design
  - Projective shape

→ **3D printing can be a solution!**

- Use 3D metal printer to produce Cu blocks with fine structure holes
  - ~1 mm diameter for a hole
  - ~0.5 mm wall thickness between holes



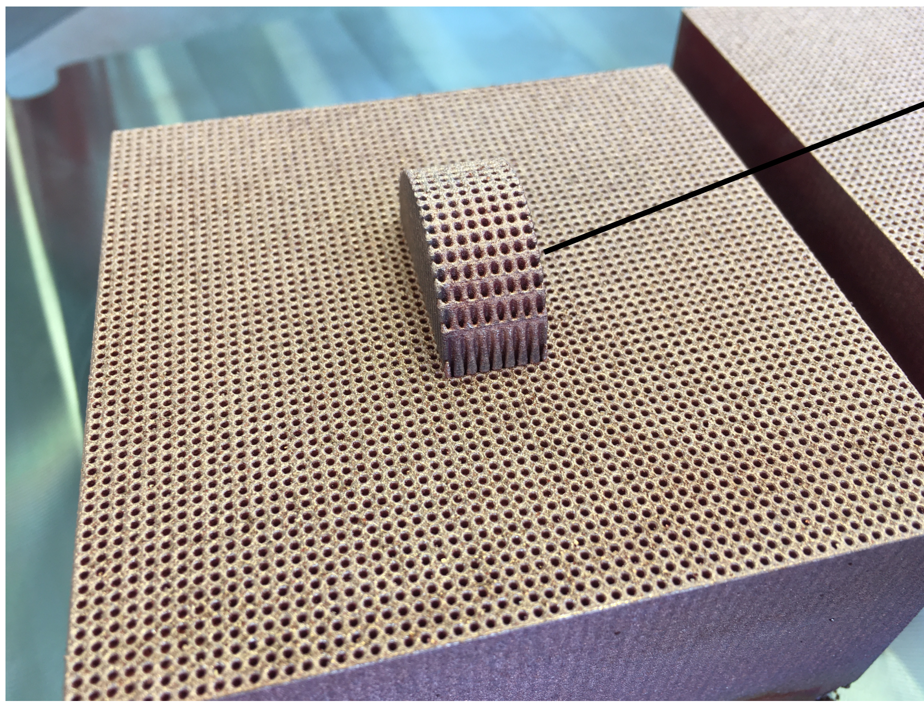




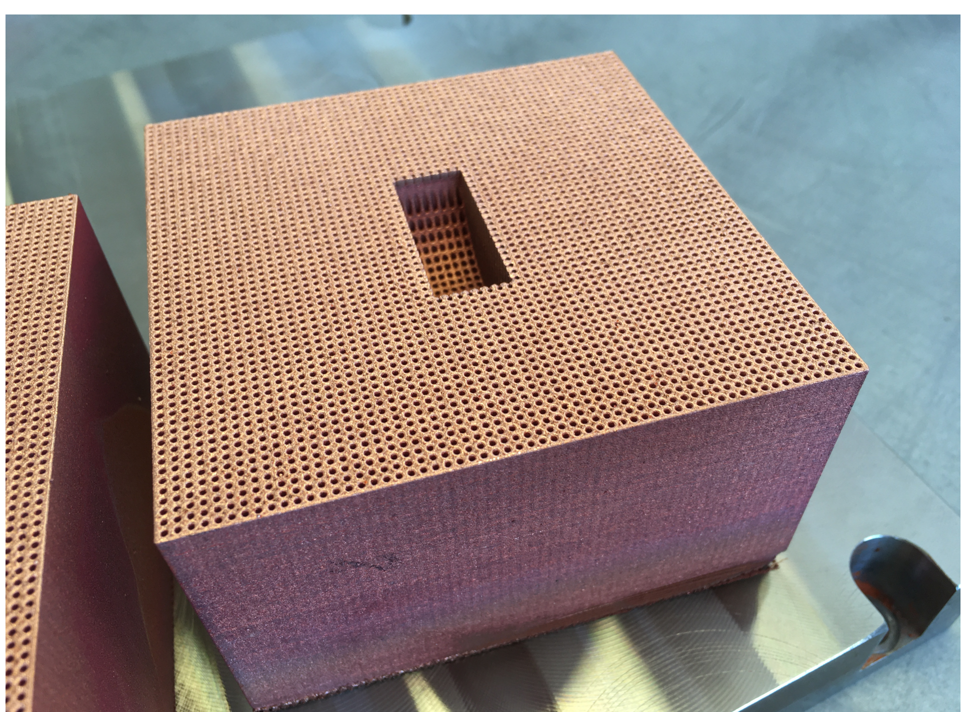
With 3D printing consultant company in Korea
- have world-wide expert networking

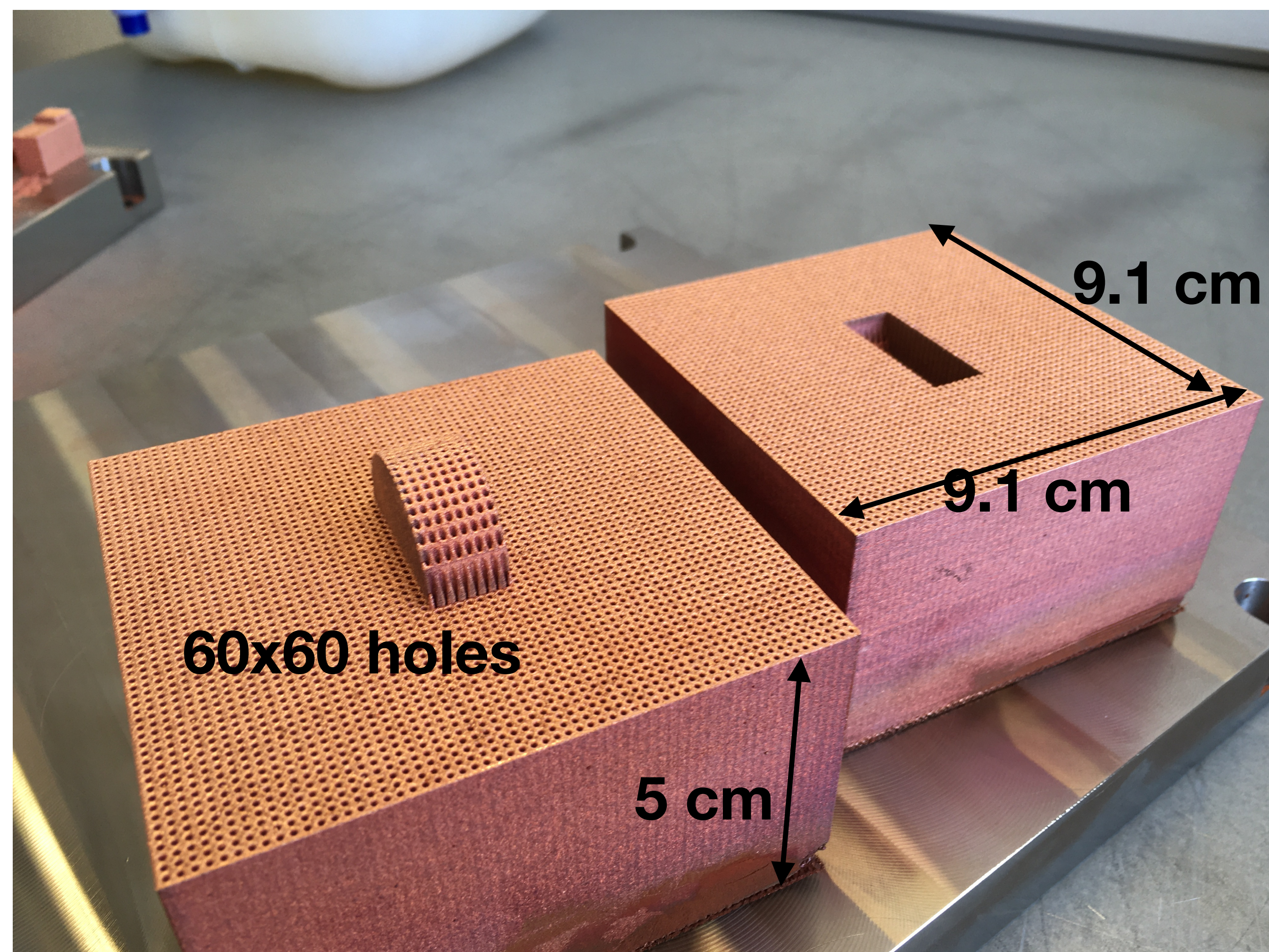
1st Trial: Finland Company

- The 1st trial is not hopeless, but the hole size is < 0.7 mm, therefore can not assemble the optical fibers

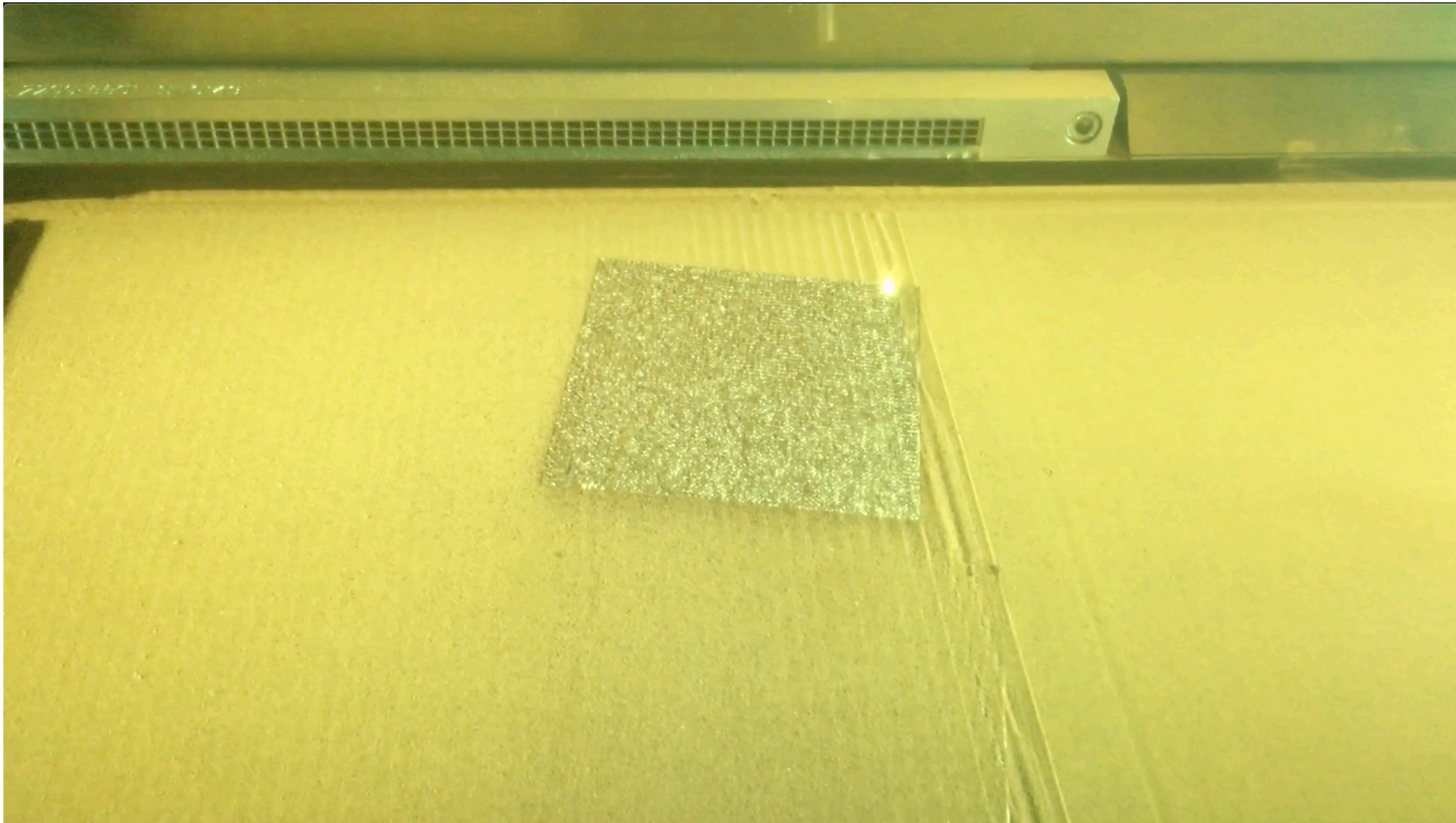


Nose (not sufficient quality)





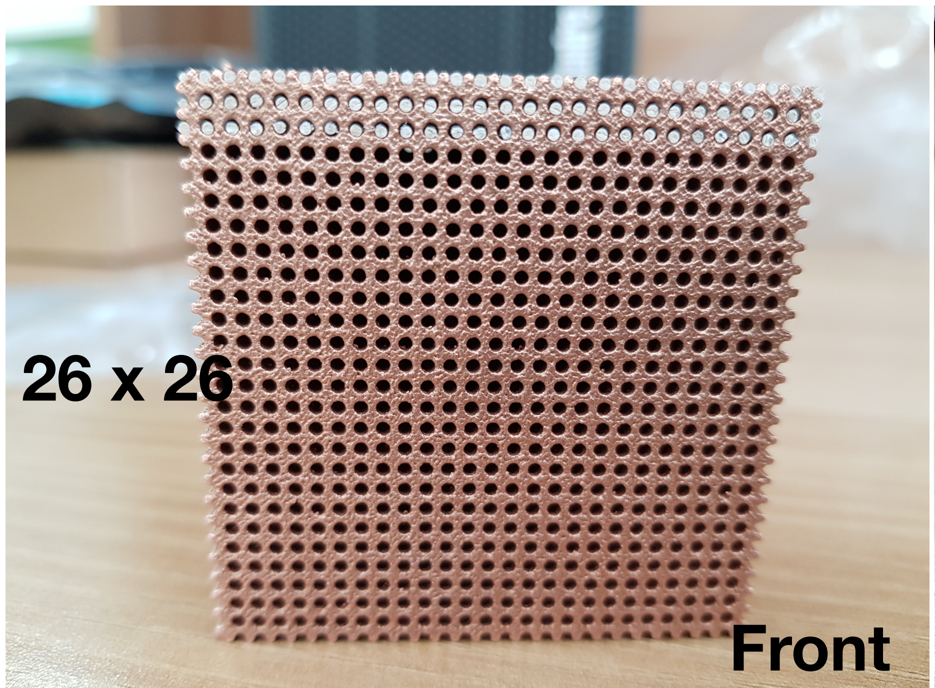
How to Do Additive Manufacturing

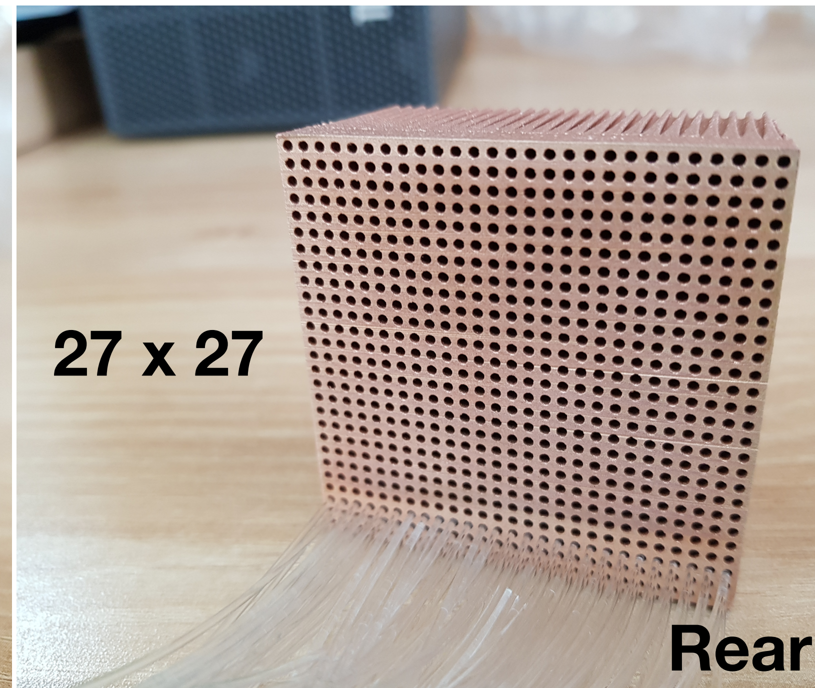


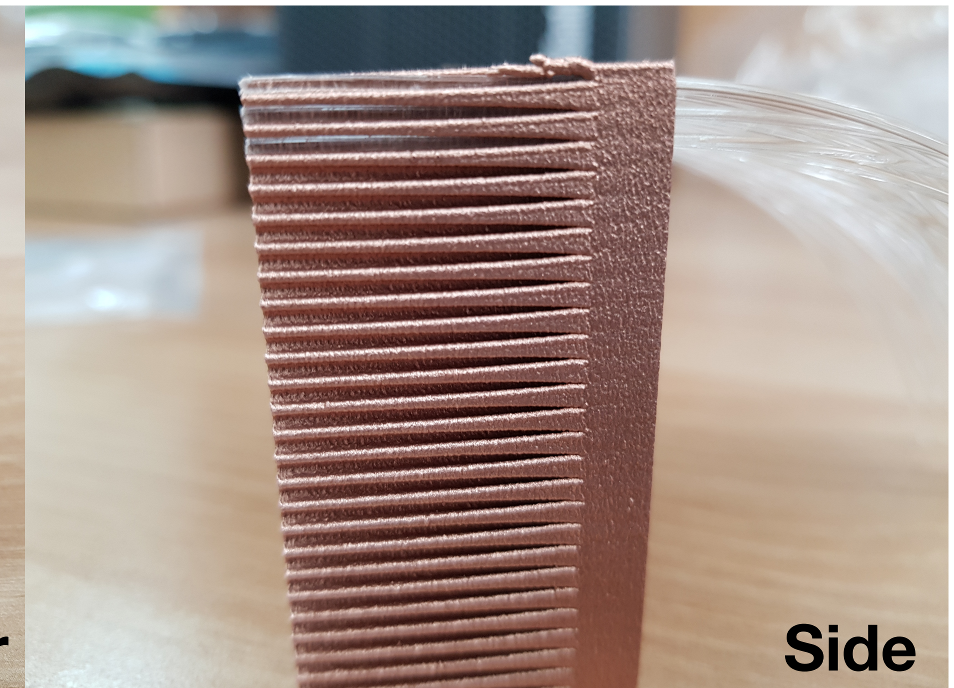
Movie link (click)

2nd Trial: Finland Company

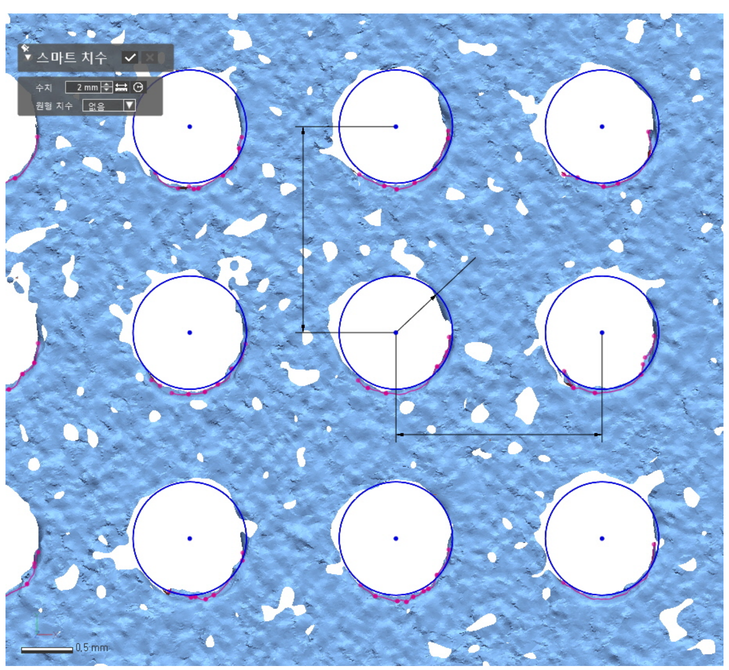
- Very successful projective shape and ~1.1mm diameter of the hole, but failed for < 0.5 mm wall thickness

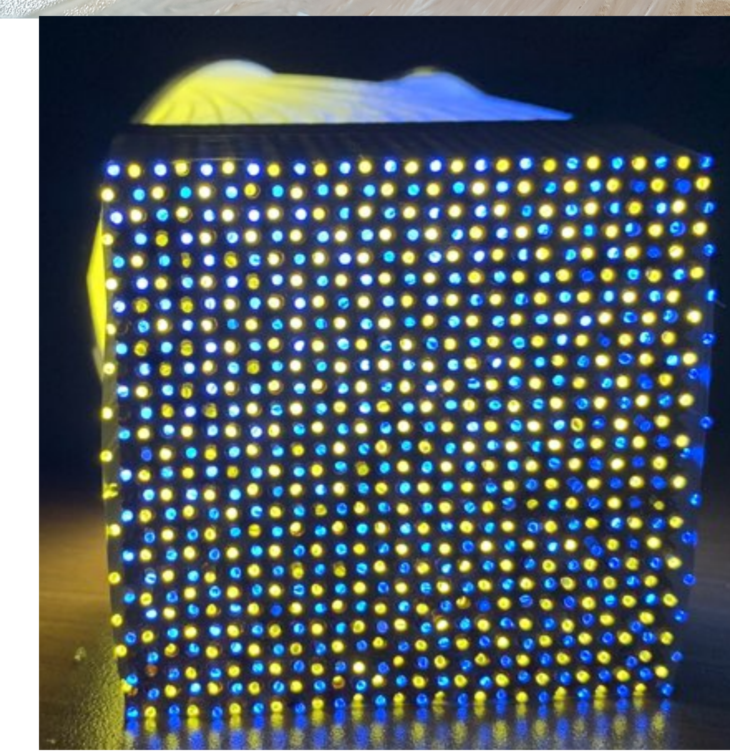


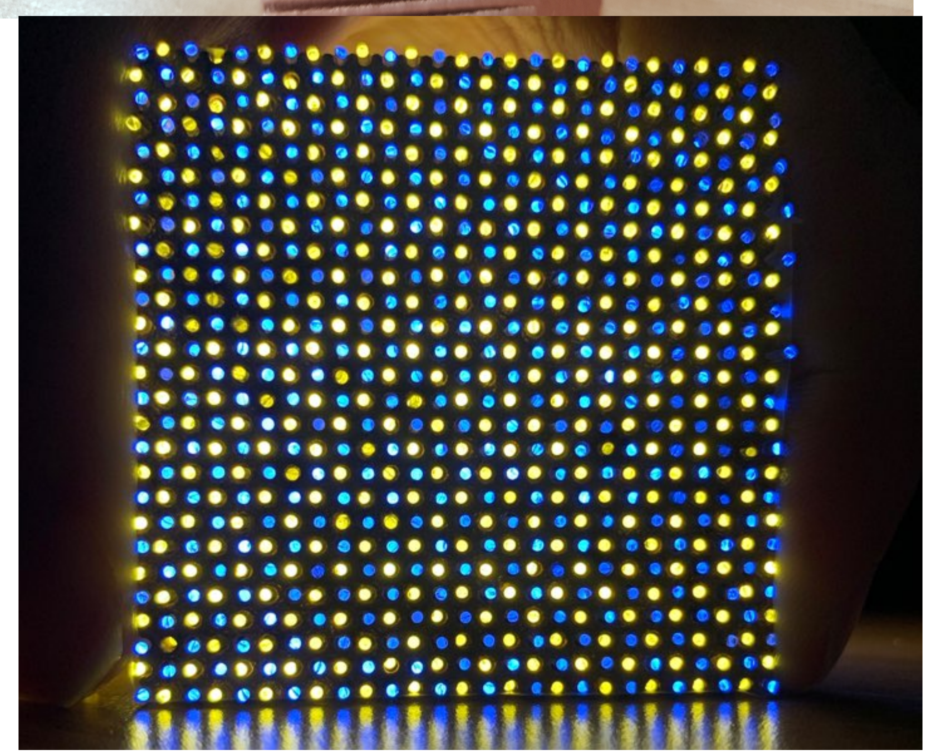




3D Scan of the hole structure



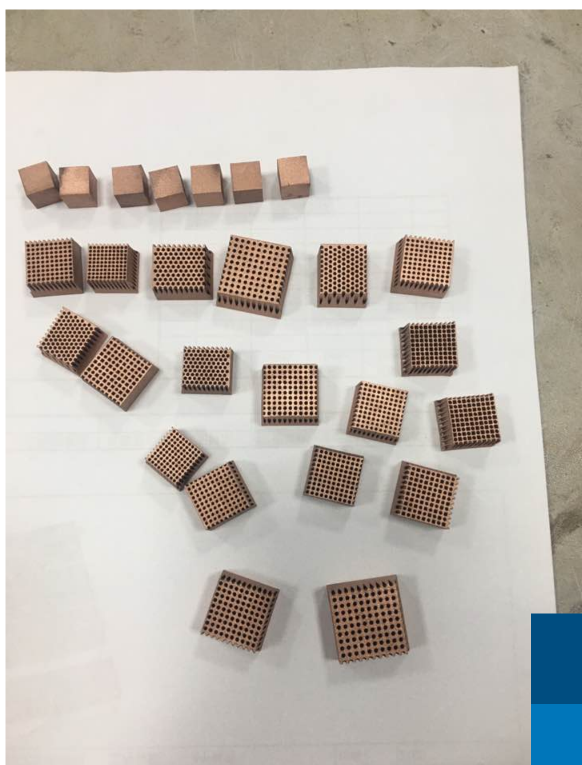


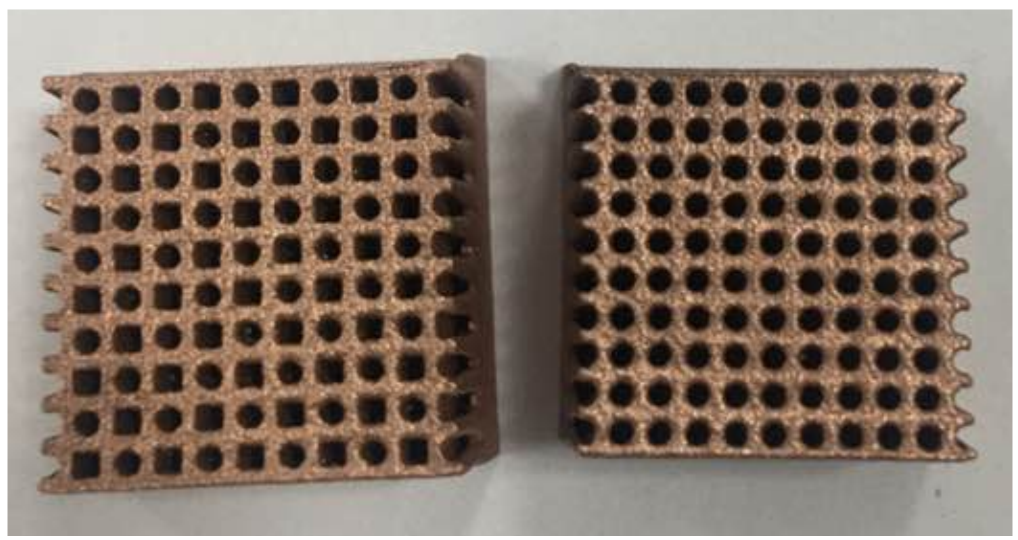


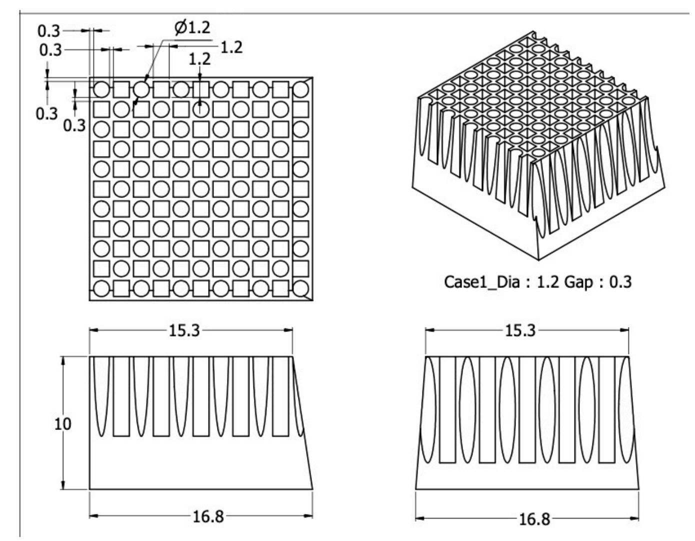
3rd Trial: China Company

- Scan various values and designs for the diameter and wall thickness
- Achieve < 0.5 mm wall thickness with ~1.0mm diameter of the hole!!

Farsoon



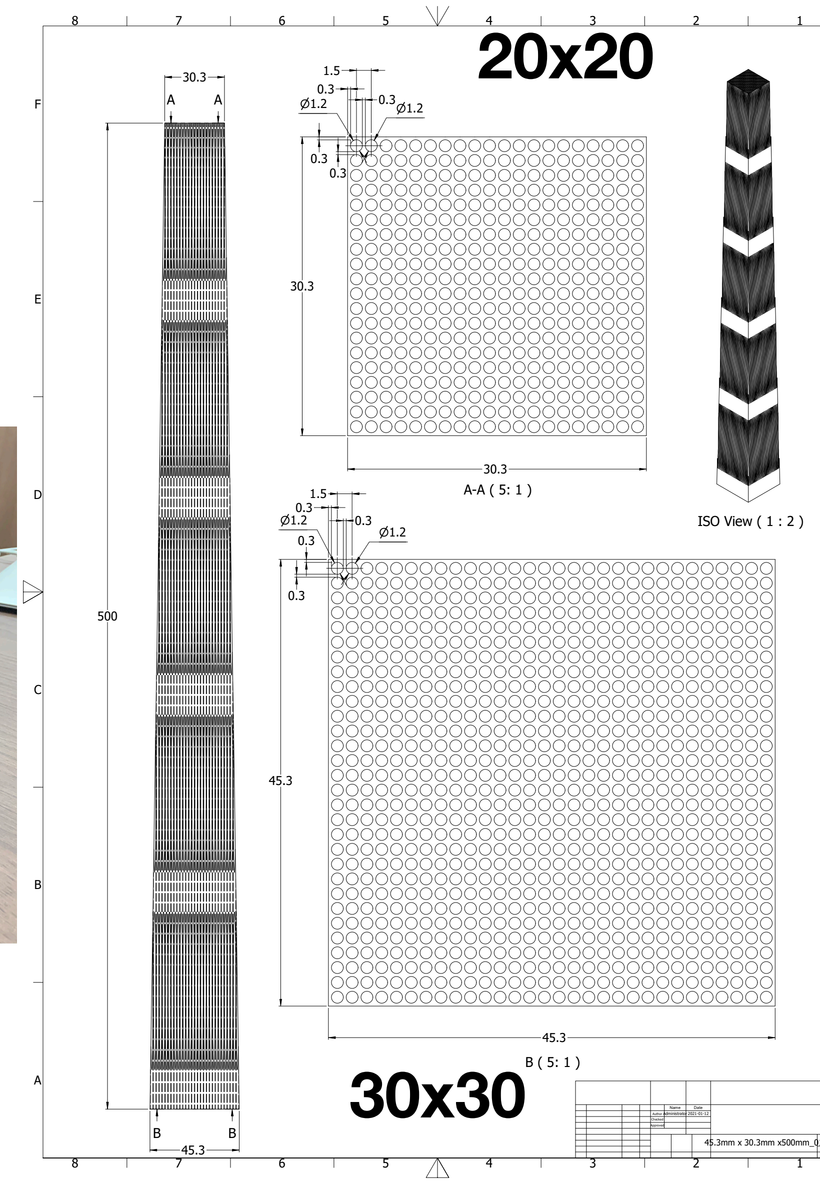


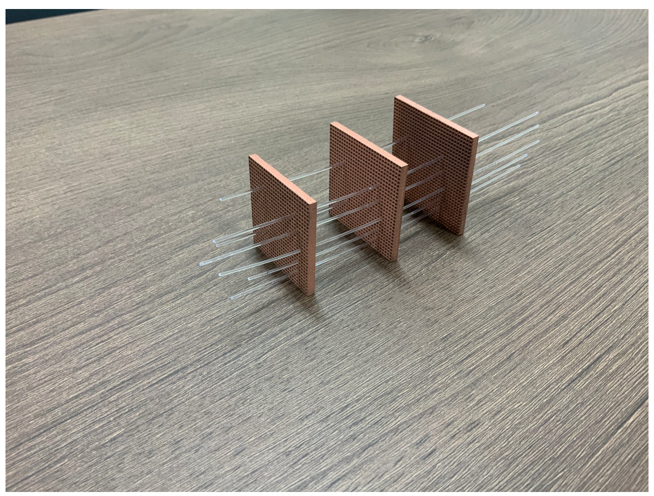


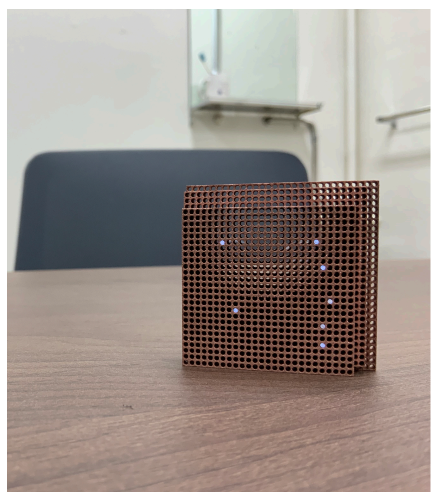
	Samples	1	2	3	4	5	6	7	8	9	10
Hall diameter (mm)	Designed	1.0	1.1	1.2	1.1	1.0	1.3	1.1	1.2	1.2	1.1
	Outcome	0.9-0.95	0.9-0.95	1.0-1.05	0.8-0.85	0.8-0.85	1.1-1.15	0.9-0.95	1.0-1.05	1.0-1.05	0.9-0.95
Wall thickness (mm)	Designed	0.5	0.5	0.5	0.4	0.3	0.7	0.5	0.3	0.5	0.4
	Outcome	0.52	0.6	0.62	0.5	0.45	0.81	0.6	0.4	0.65	0.52

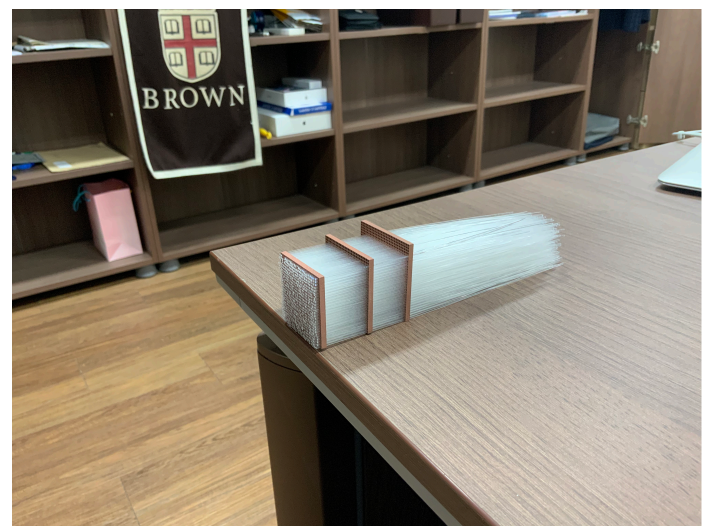
Toward Prototype 3D Module

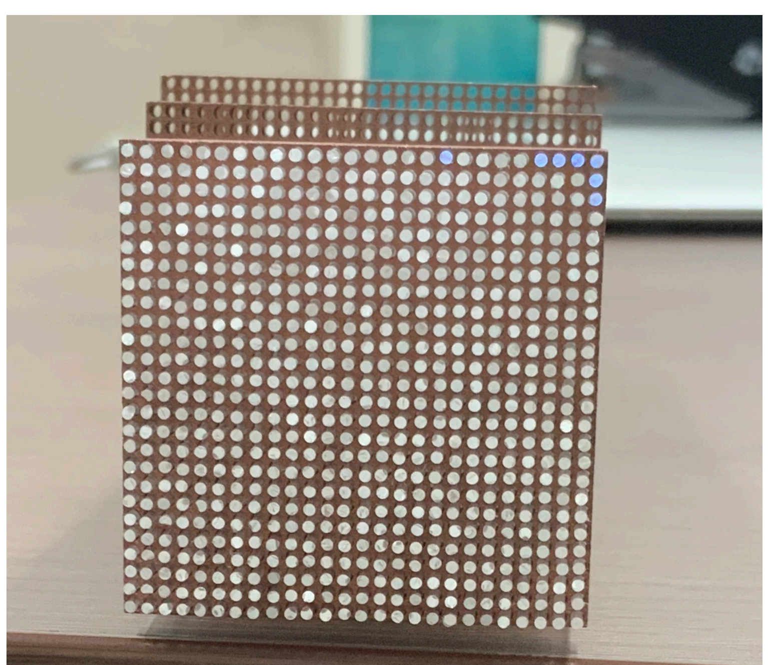
- Under test and design: check alignment of holes and very successful!
- Ordered five 3D-printed copper blocks (10 cm length each) for the prototype module

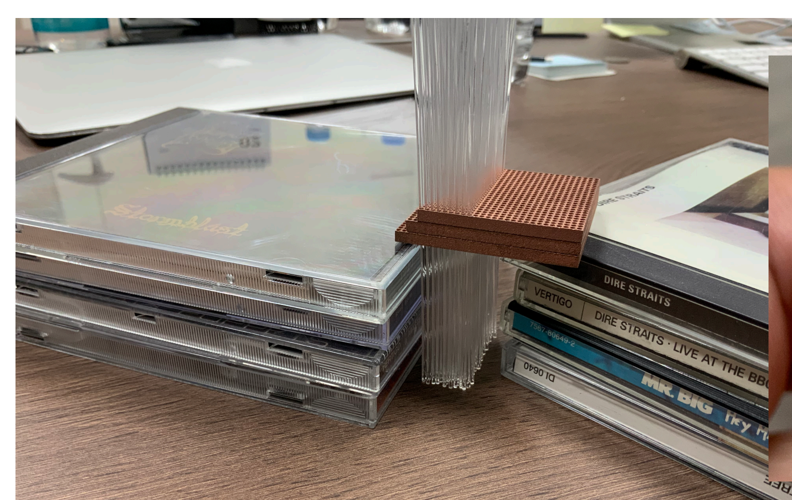






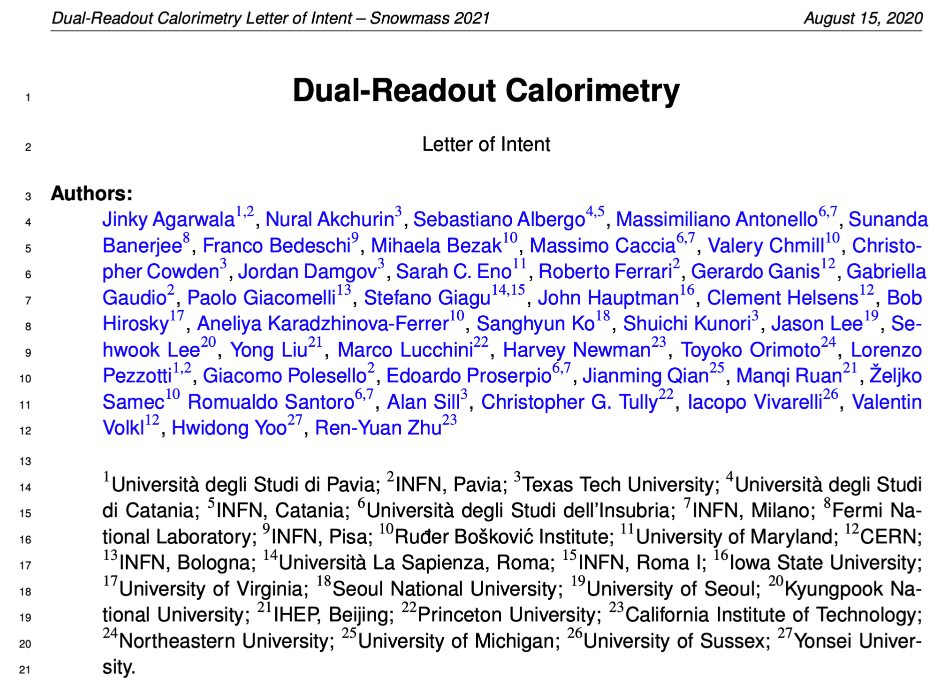






Snowmass21 (SM2021)

- Excellent opportunity to
  - Integrate US and world-wide research campai
  - Increase visibility our local activity to internatic colleagues
- International dual-readout team prepared a single interest (LoI): overview of dual-readout activities
  - https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF6-008.pdf
- Additional 7 LoIs related to the dual-readout calorimeter R&D project have been submitted too!
- Various MC production such as multi-jets, Higgs and tau events are underway with GEANT4 + DD4hep infrastructure


Dual-Readout Calorimetry Letter of Intent – Snowmass 2021 *August 15, 2020*

Dual-Readout Calorimetry

Letter of Intent

Authors:

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SM2021 with DRC in Korea

- Topic 1: Feasibility study of combining a MIP Timing Detector with the Dual-readout Calorimeter at future e+e- colliders (link)
  - Collaborators: D. Stuart (UCSB), C.S. Moon (KNU), J.H. Yoo (Korea Univ.)
- Topic 2: Heavy flavor tagging using machine learning technique with silicon vertex detector and Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: J. Huang (BNL), Q. Hu (LLNL), S.H. Lim (PNU)
- Topic 3: tau reconstruction and identification using machine learning technique with Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: M. Murray (U. of Kansas), Y.S. Kim (Sejong Univ.), Y.J. Kwon (Yonsei Univ.)
- Topic 4: Sensitivity study of H->Zgamma with Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: Y. Maravin (Kansas State Univ.), K.W. Nam (Kansas State Univ.)
- Topic 5: Multi-object identification with Dual-Readout Calorimeter at future e+e- colliders (link)
  - Collaborators: P. Chang (UCSD)
- Topic 6: Dual-Readout Calorimeter for the future Electron-Ion Collider (link)
  - Collaborators: S.H. Lim (PNU), H.S. Jo (KNU), Y.S. Kim (Sejong Univ.)
- Topic 7: Fast optical photon transport at GEANT4 with Dual-Readout Calorimeter at future e+e- colliders (link)

Feasibility study of combining a MIP Timing Detector with the Dual-Readout Calorimeter at future e^+e^- colliders

J.H. Yoo[1], S.W. Lee, C.S. Moon[2], S.H. Ko[3], D. Stuart[4], S.H. Lee[5], and J.W. Park, H.D. Yoo *[6]

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August 30, 2020

Heavy flavour tagging using machine learning technique with silicon vertex detector and Dual-Readout Calorimeter at future e^+e^- colliders

J. Huang[1], Q. Hu[2], S.H. Lim[3], S.H. Lee, Y.J. Lee[4], and S.W. Kim, H.D. Yoo *[5]

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[2]Lawrence Livermore National Laboratory, USA
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[5]Yonsei University, Republic of Korea

August 31, 2020

τ reconstruction and identification using machine learning technique with Dual-Readout Calorimeter at future e^+e^- colliders

Y.S. Kim[1], M. Murray[2], and K.H. Kim, Y.J. Kwon, H.D. Yoo *[3]

[1]Sejong University, Republic of Korea
[2]University of Kansas, USA
[3]Yonsei University, Republic of Korea

August 30, 2020

Sensitivity study of $H \to Z\gamma$ with Dual-Readout Calorimeter at future e^+e^- colliders

K.W. Nam, Y. Maravin[1] and H.D. Yoo *[2]

[1]Kansas State University, USA
[2]Yonsei University, Republic of Korea

August 30, 2020

Multi-object identification with Dual-Readout Calorimeter at future e^+e^- colliders

P. Chang[a], S. K. Ha[b], K. Y. Hwang[b], H. D. Yoo[b]

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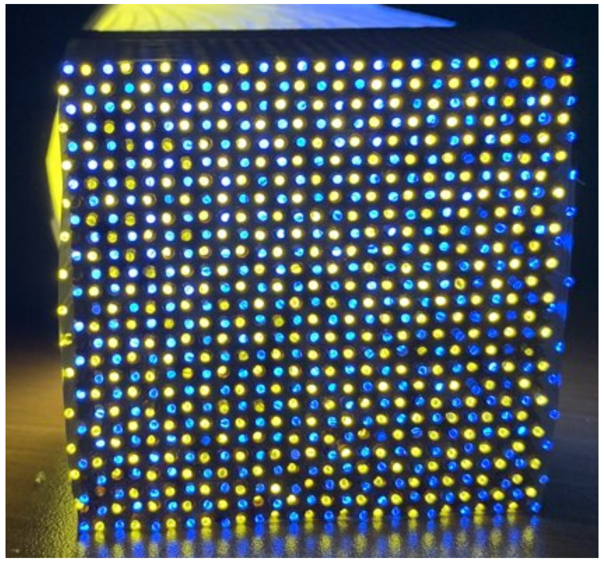
[b]*Yonsei University, Republic of Korea*

Summary

- Dual-Readout Calorimeter R&D project for future e^+e^- collider in Korea is very active
  - Build and test full size prototype DRC detector by 2025
  - HW R&D and simulation studies for performance and ML applications on-going
  - Under preparation for test beam 2021
  - Calorimeter design for EIC project with Korea HI community is also on-going



- Innovative 3D-printing module is on-going
  - Collaborating with world-leading 3D metal printing frontier companies
  - Prototype module design and production are underway
- Various Snowmass 2021 studies are on-going