The Mu3e Tile Detector: From prototype to pre-production

HighRR Seminar

December 09, 2020

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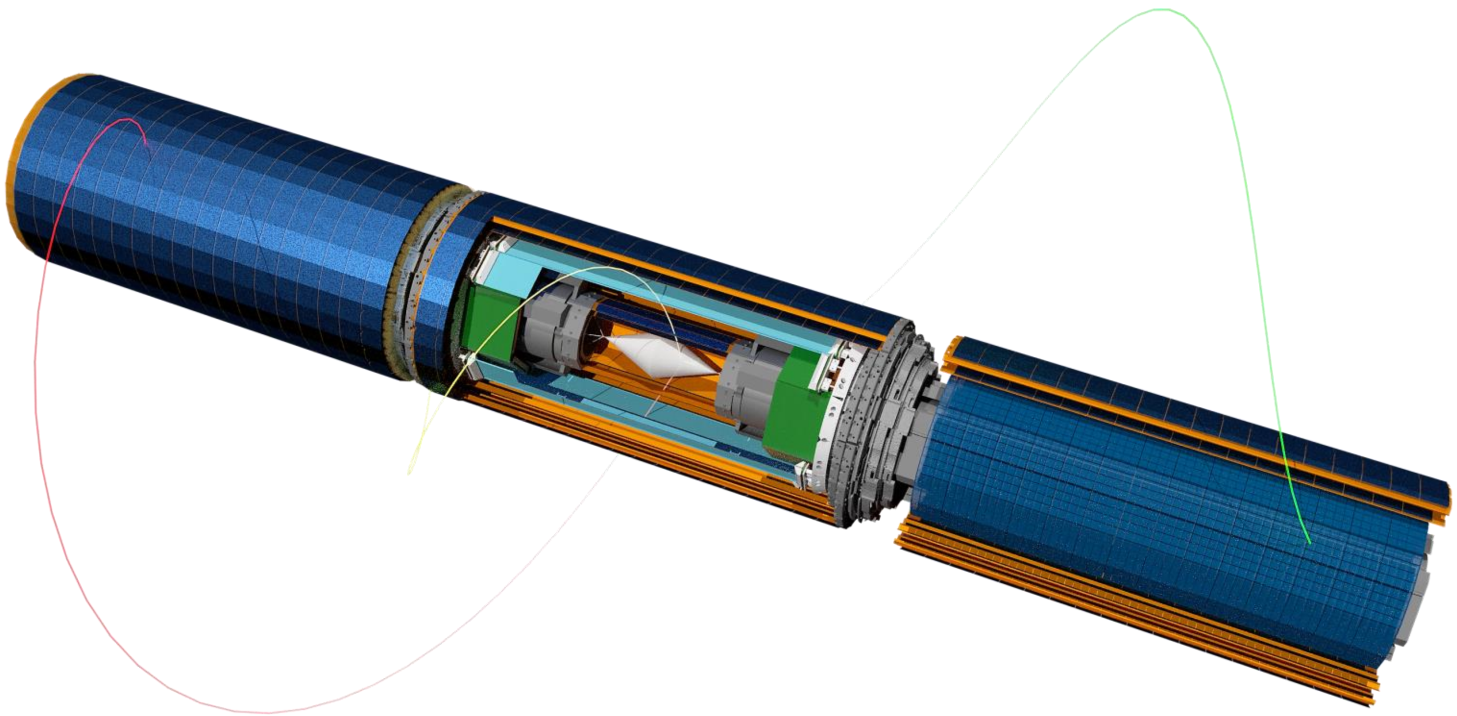
Overview

- Introduction to the Mu3e experiment
- The tile detector: technical prototype and new design
- Production steps and methods
- Validation of new design
- Pre-production setup and plans

Introduction to the Mu3e experiment

The Mu3e experiment

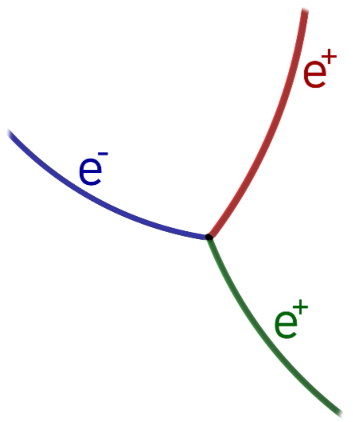
- search for cLFV decay $\mu^+ \rightarrow e^+e^+e^-$
  - SM (including ν mixing): $B_{\mu\rightarrow 3e} \approx 10^{-54}$
- current upper limit: $B_{\mu\rightarrow 3e} < 10^{-12}$ (SINDRUM, 1988)
  → aim of Mu3e: $\mathbf{B_{\mu\rightarrow 3e} < 10^{-16}}$
- stopping target experiment at PSI in Switzerland
  → muon beam rate: 10^8 μ/s
- first commissioning run in 2021



Background sources and rejection

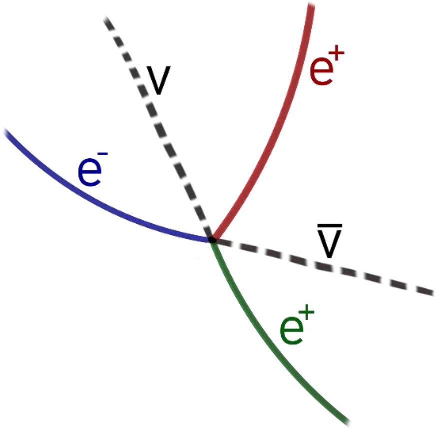
- background sources for $\mu \rightarrow eee$:
  - internal conversion $\mu \rightarrow ee e\nu\nu$ ⇒ reject via precise momentum measurements
  - combinatorial background ⇒ reject via precise time and vertex determination

signal



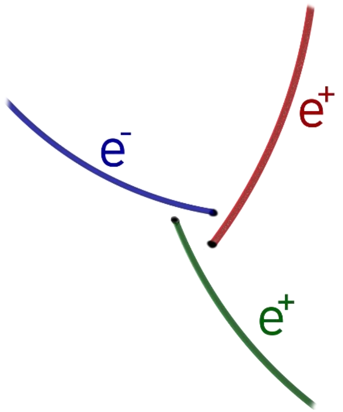
$\sum E_e = m_\mu,\ \sum \vec{p}_e = \vec{0}$

internal conversion decay



$\sum E_e < m_\mu,\ \sum \vec{p}_e \neq \vec{0}$

combinatorial background



$\sum E_e \neq m_\mu,\ \sum \vec{p}_e \neq \vec{0},$
$t_1 \neq t_2 \neq t_3$

Background sources and rejection

- background sources for μ → eee:
  - internal conversion μ → eeνν ⟹ reject via precise momentum measurements
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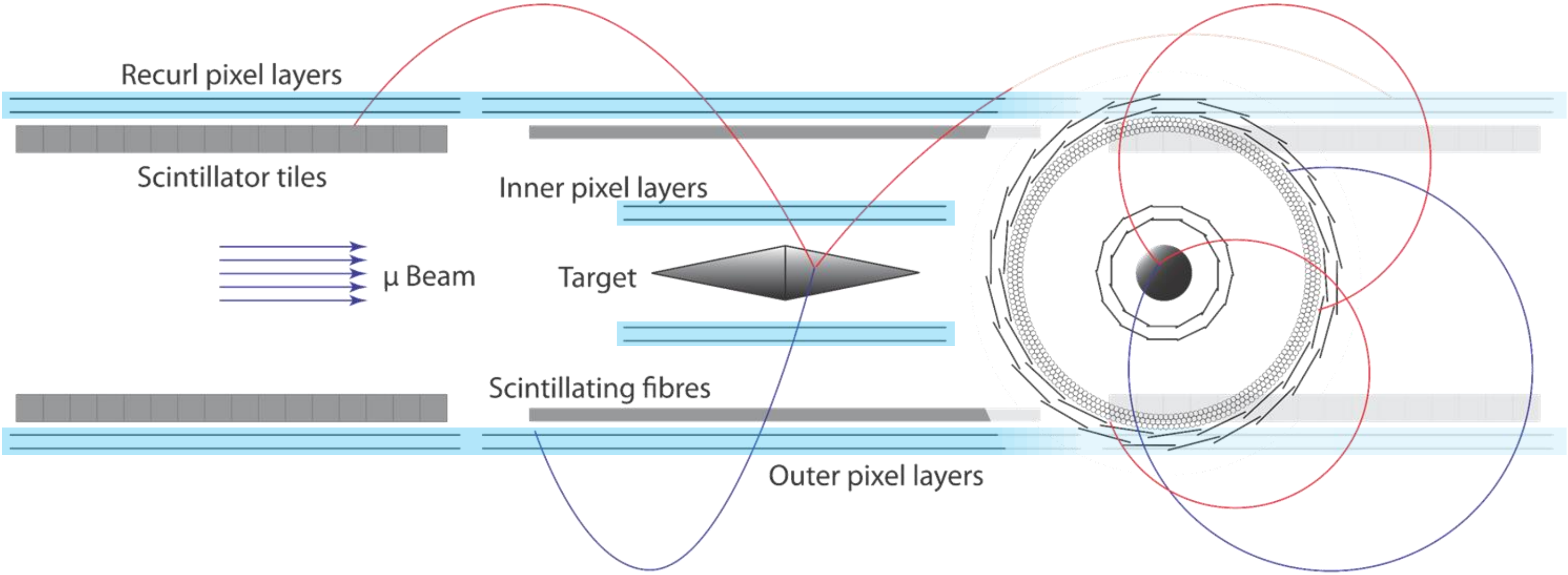
→ pixelated tracking detectors + scintillating fibre/**tile detector**

$\vec{B} = 1\mathrm{T}$



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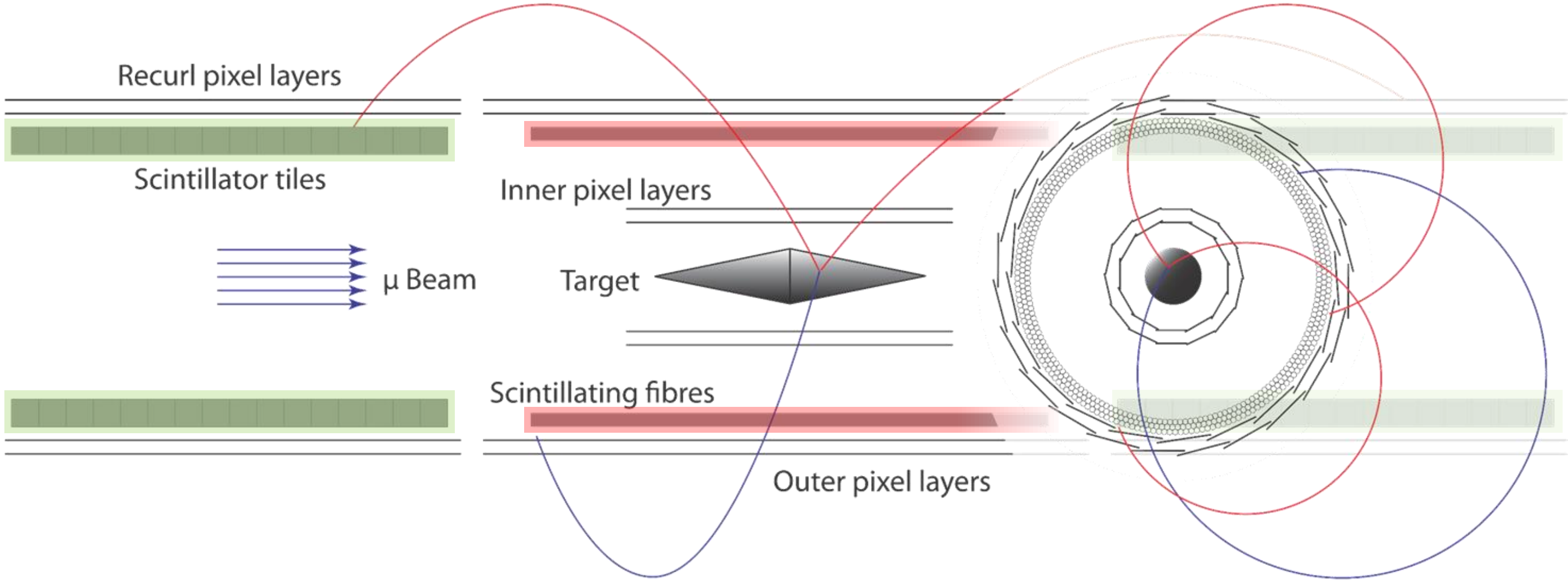

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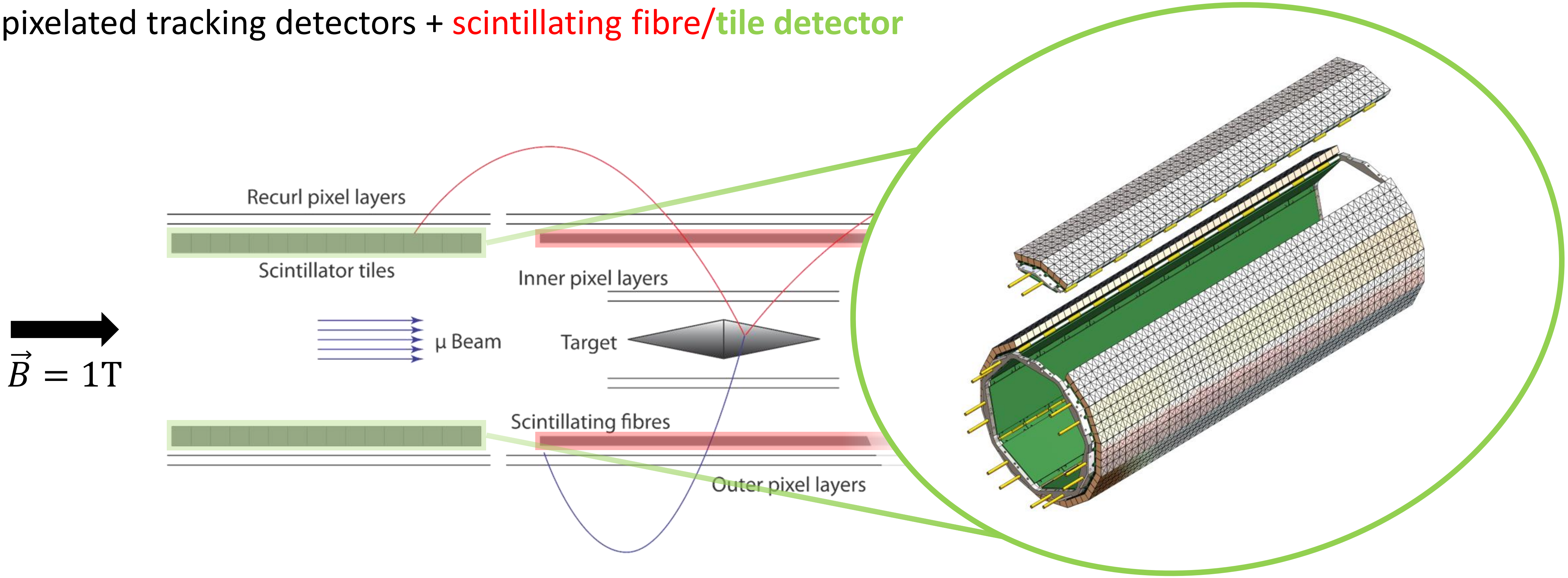
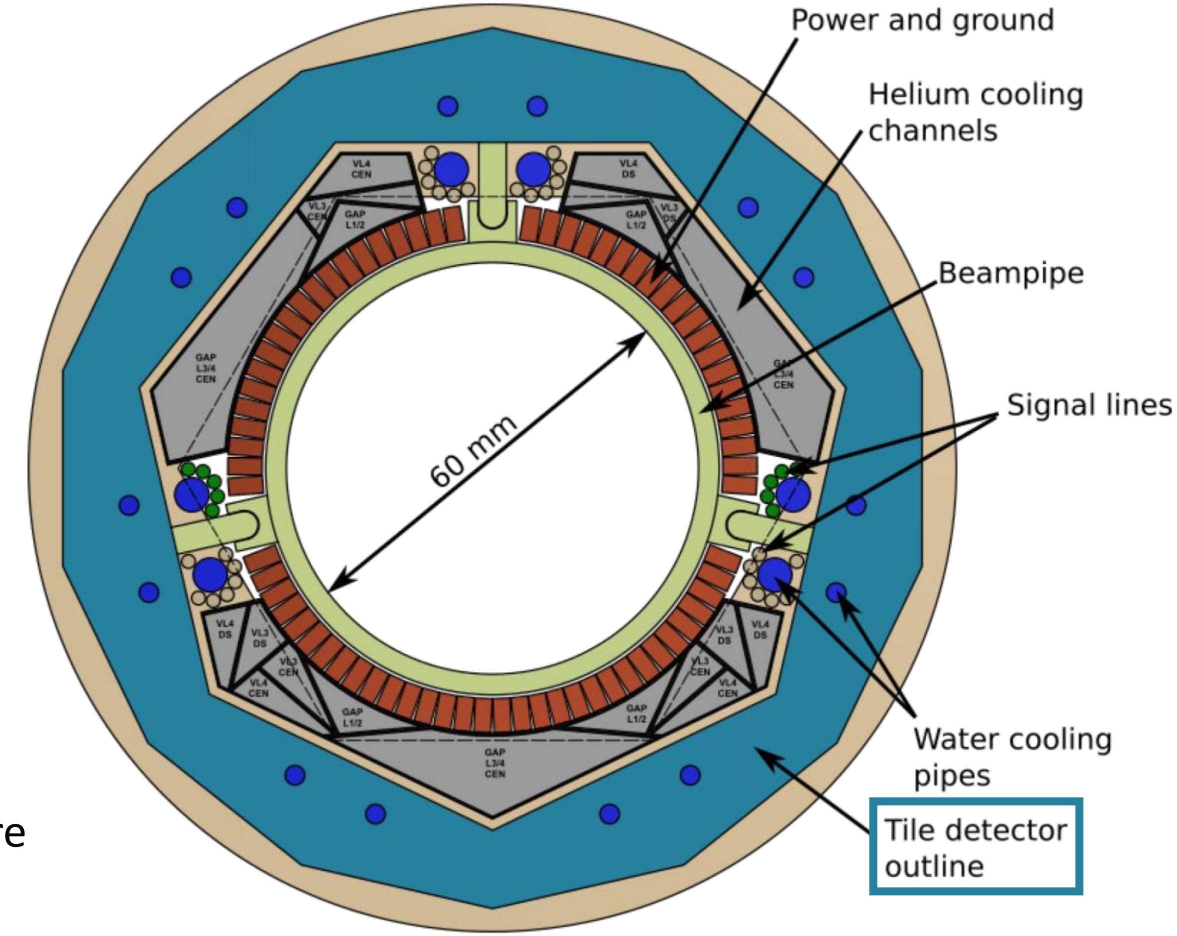


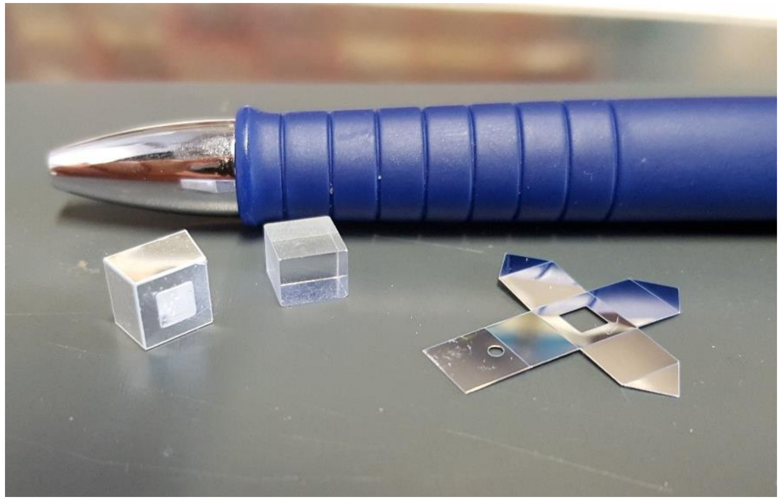
Tile detector overview

- main challenges for detector design:
  - continuous read-out at high rates (10^8 μ/s)
  - compact experiment layout → **limited space**
- tile detector requirements and implications:
  - timing resolution ≤ 100 ps
  - high granularity
  - up to 80 kHz per channel
  - limited space for electronics, services, …
  - operate in high magnetic field and helium atmosphere

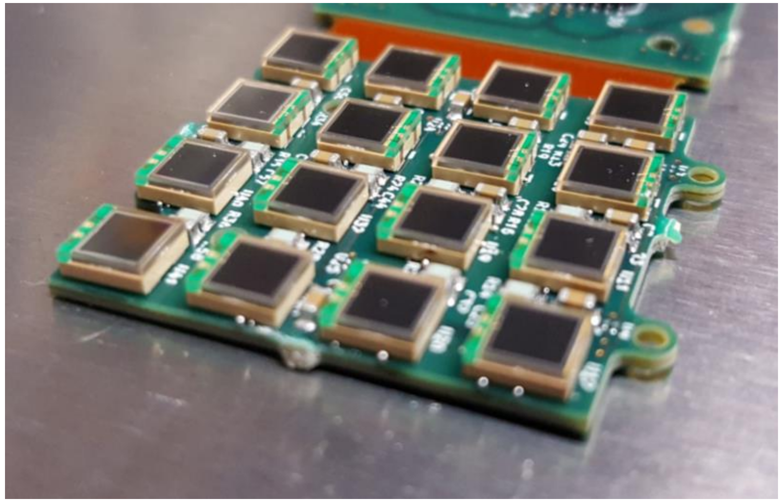


Detector structure I

- basic detector components:
  - plastic scintillator tiles
  - silicon photomultipliers (SiPMs)
  - MuTRiG: custom-designed ASIC developed in Heidelberg



→ resulting base-unit: **submodule**
  - 32 channels (tiles + SiPMs)
  - one MuTRiG
  - custom-designed PCB with flex-print

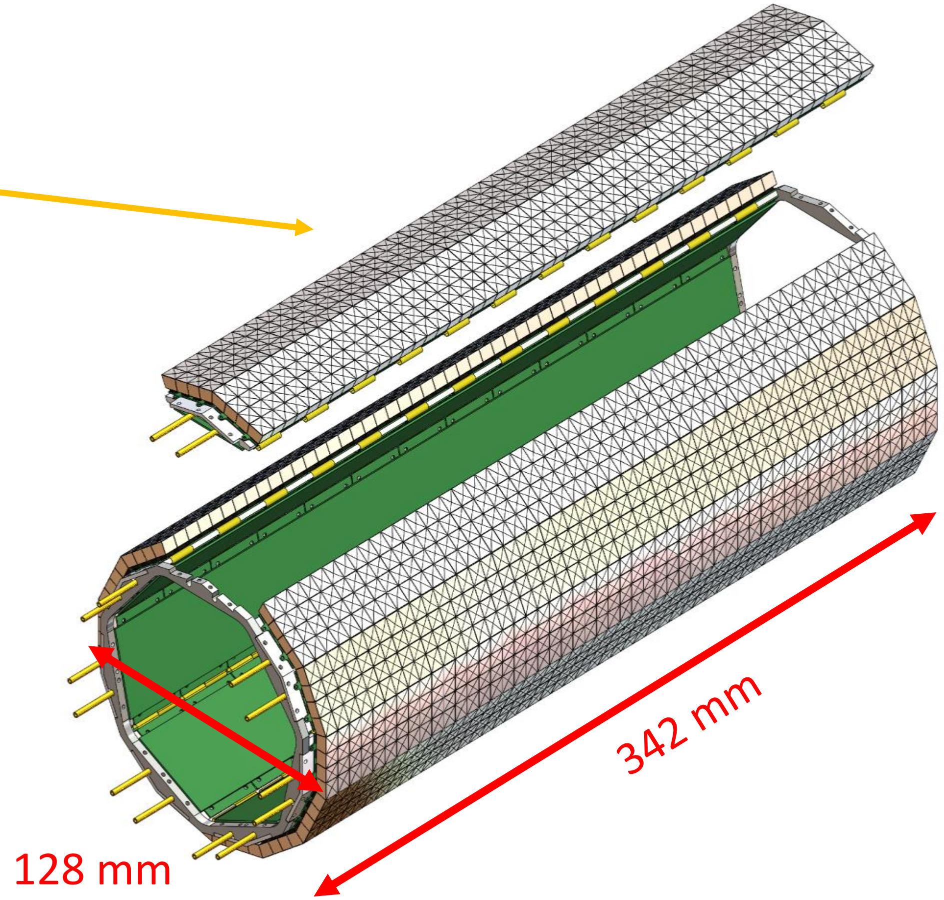


Detector structure II

- **module:**
  - 13 submodules → 416 channels
  - aluminium support and cooling structure
  - aluminium pipes (water cooling)
  - one read-out board

- **recurl station:**
  - 7 modules
  - one pair of endrings (PEI or similar material)

→ two recurls stations = **full tile detector**

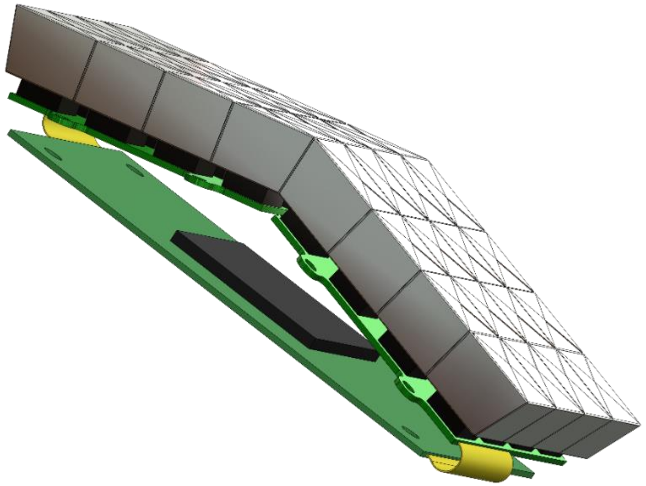


The tile detector

Technical prototype and new design

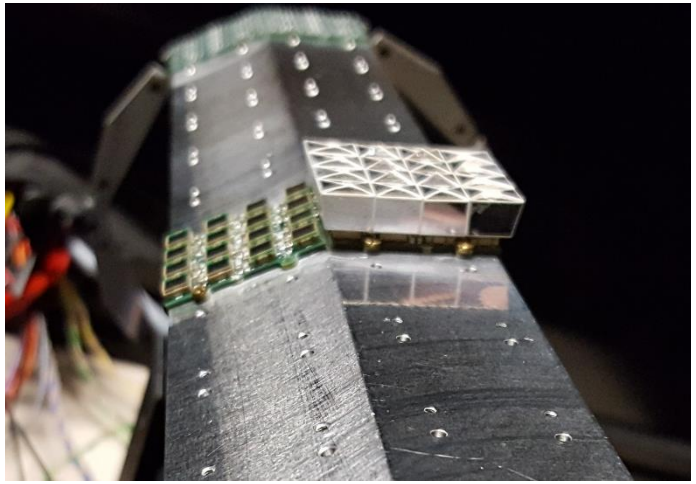
First technical prototype

- first technical prototype: 3 submodules
  - development of production and assembly procedures
  - cooling system test



- succesful testbeam campaigns @ DESY in February and June 2018
  - prototype fully functional
  - time resolution clearly below 100 ps

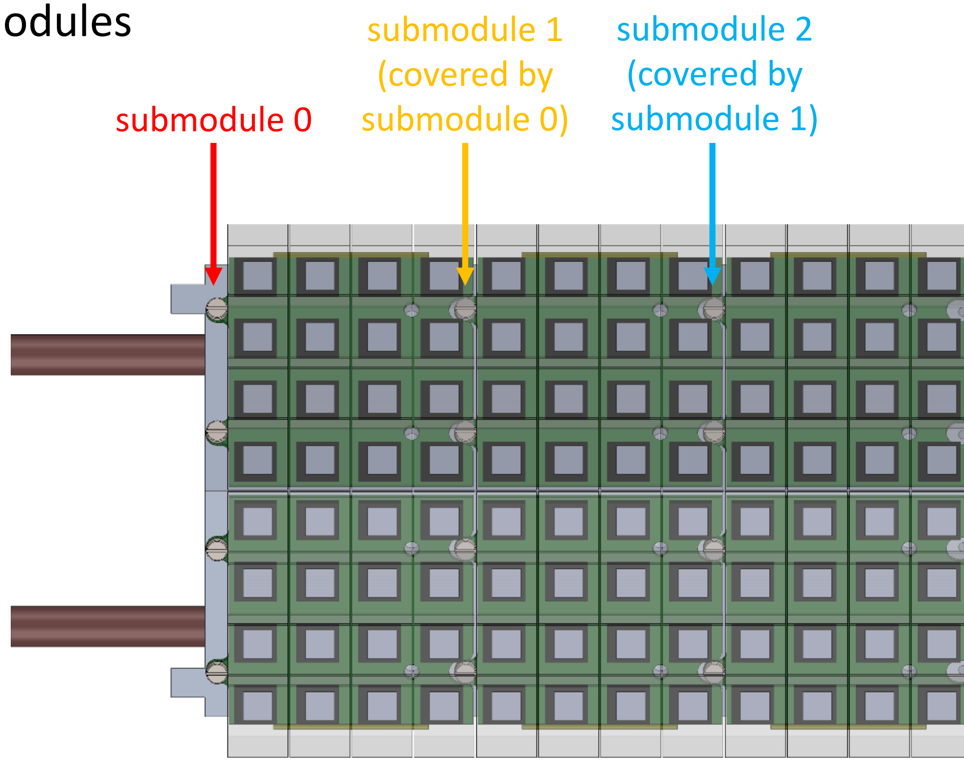
see HighRR talk by Tiancheng Zhong from January 2019



Design modification

- challenges during prototype production:
  - assembly screws are covered by next submodule
    → submodule failure could require removing large number of submodules
  - assembly to cooling plate difficult because of flex-print
    → risk of damaging tiles
- change in size required for experiment integration
  - length reduction → integration with pixel detector endrings
  - "slimming" in radial direction

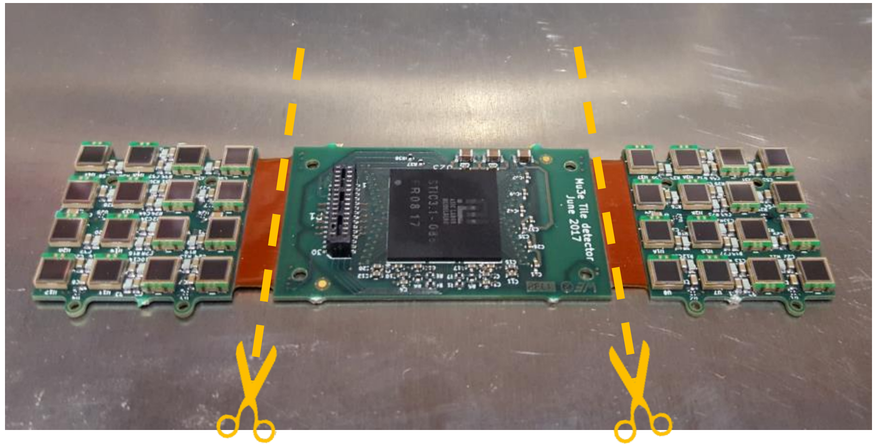
see HighRR talk by HK from March 2019

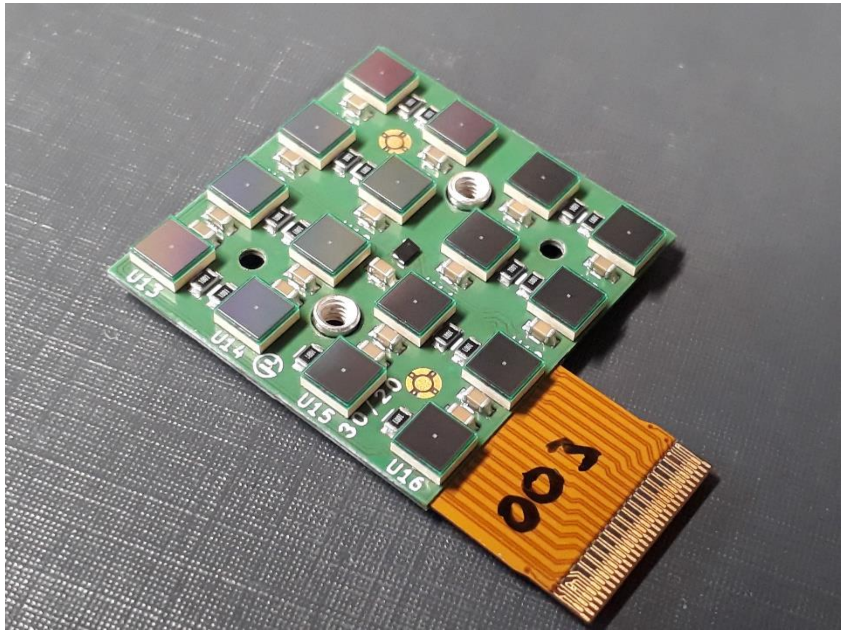


New design

- "cut up" submodule:
  - two separate 4x4 tile matrices
  - MuTRiG moved to read-out board

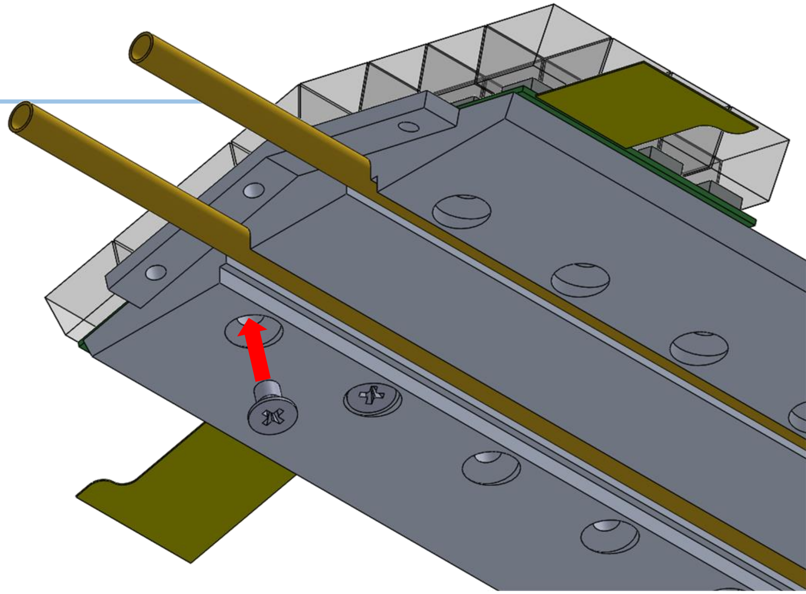
    → replace board in case of ASIC failure without affecting detector parts





board design by Yonathan Munwes

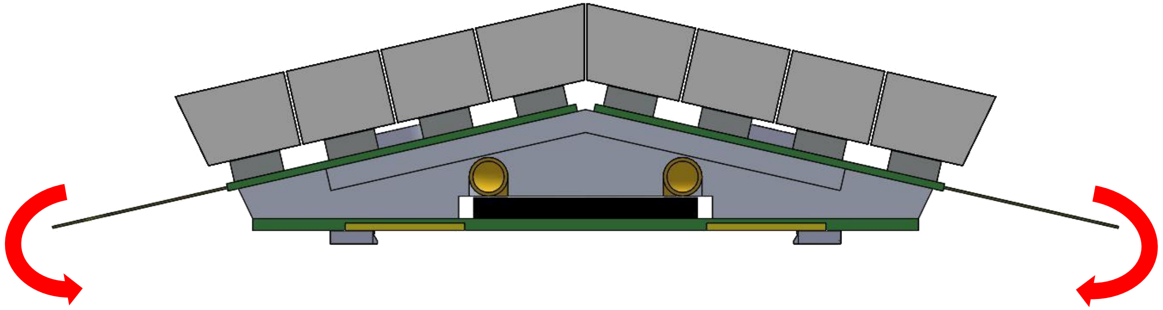
New assembly method

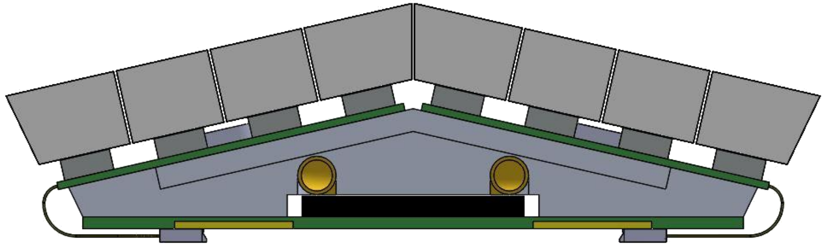


- assembly of tile matrix:
    - threaded spacers assembled to matrix PCB
    - assembly from bottom-side through cooling plate

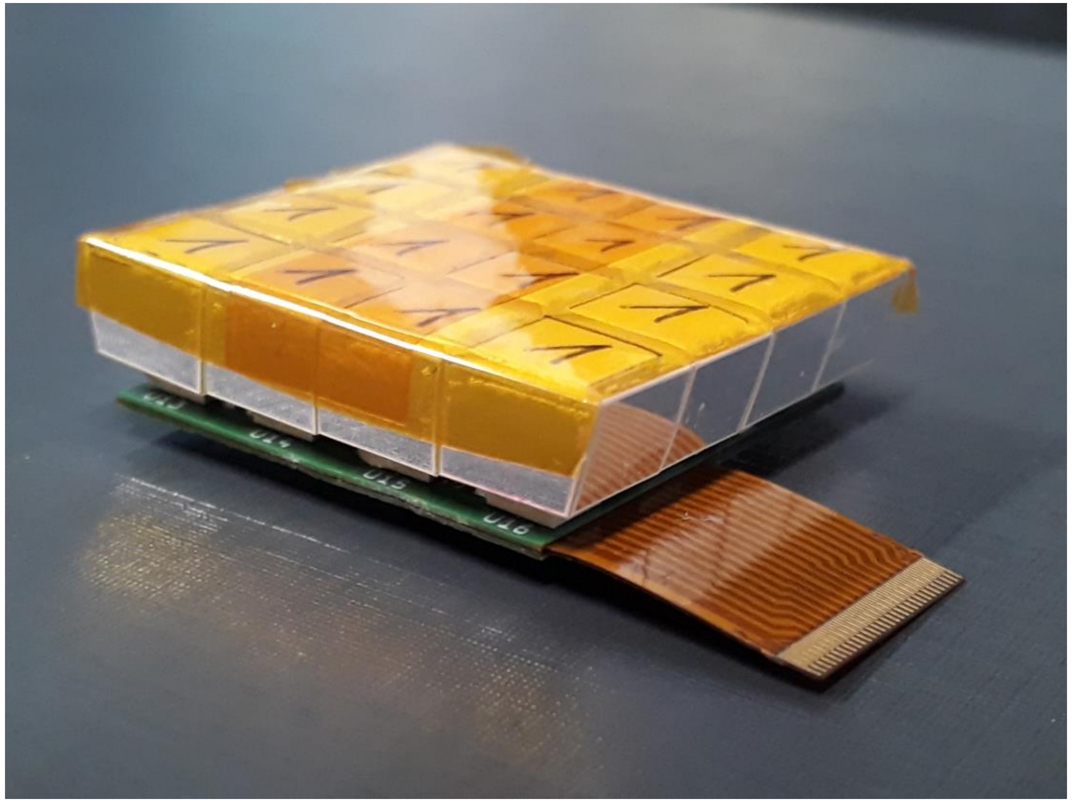
  → **cooling plate re-design**

- new low-profile connector
    - soldered to read-out board
    - directly connect flex-print

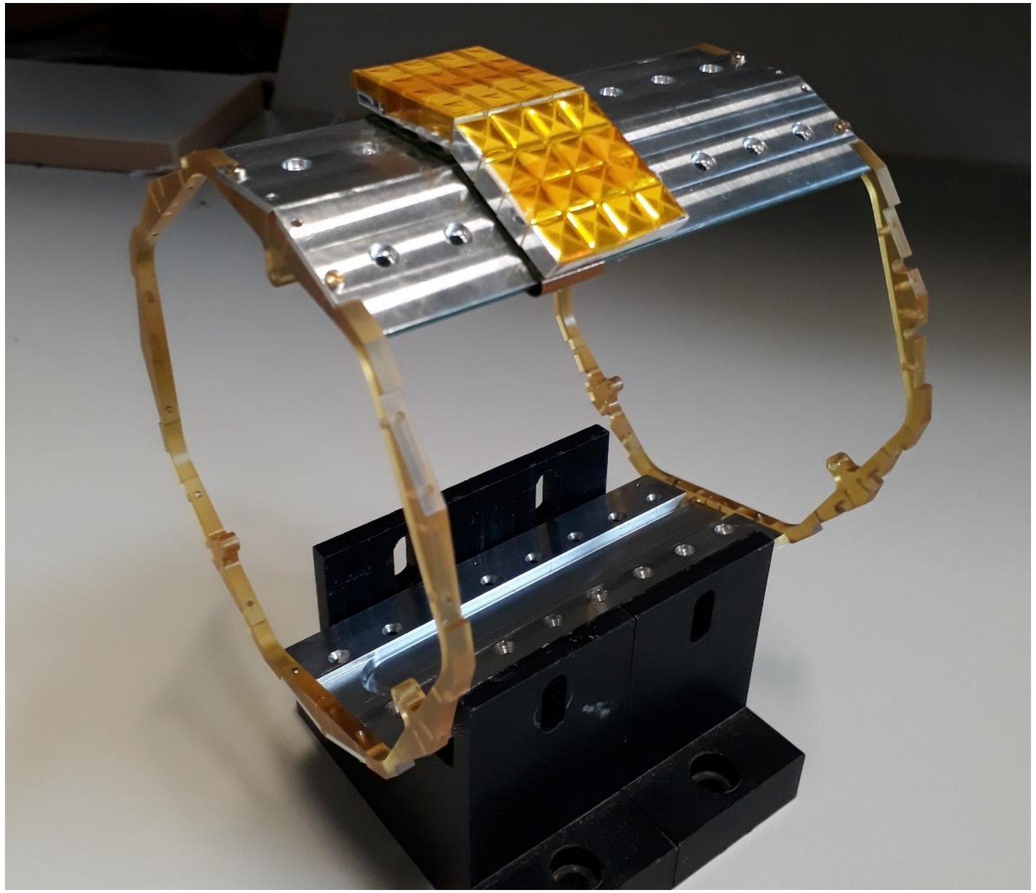




New prototype



4x4 matrix with wrapped tiles and SiPMs,
using new matrix design

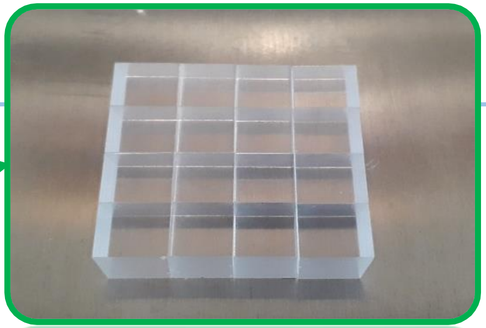


assembly test with PEI endrings and
shortened cooling plate

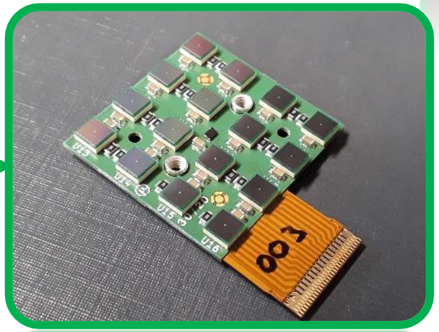
Production steps and methods

Production steps

tile production
@ KIP workshop



SiPM + matrix-flex
board assembly



mechanics
production

tile module
board (TMB)
assembly

Production steps

tile production
@ KIP workshop

→ tile
wrapping

SiPM + matrix-flex
board assembly

mechanics
production

tile module
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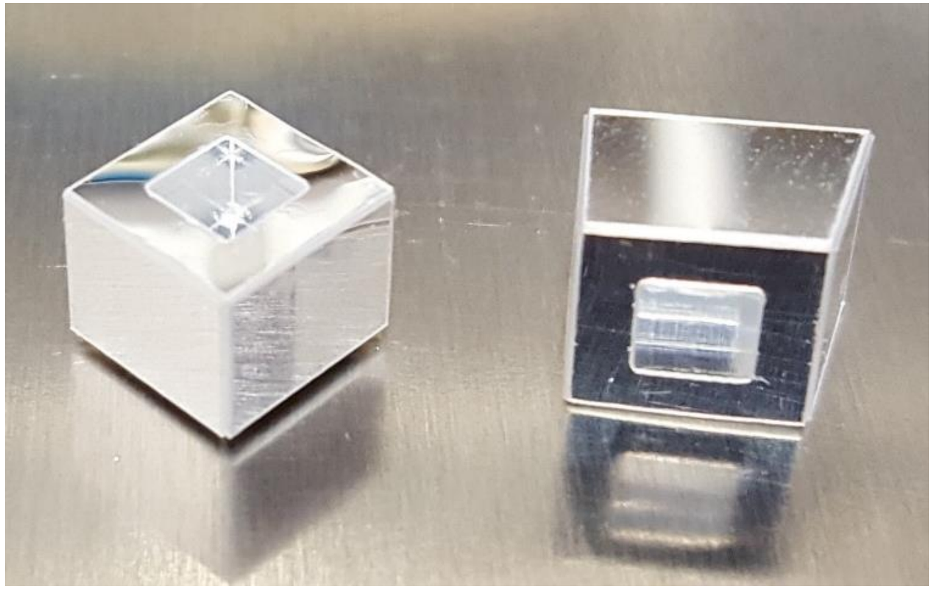
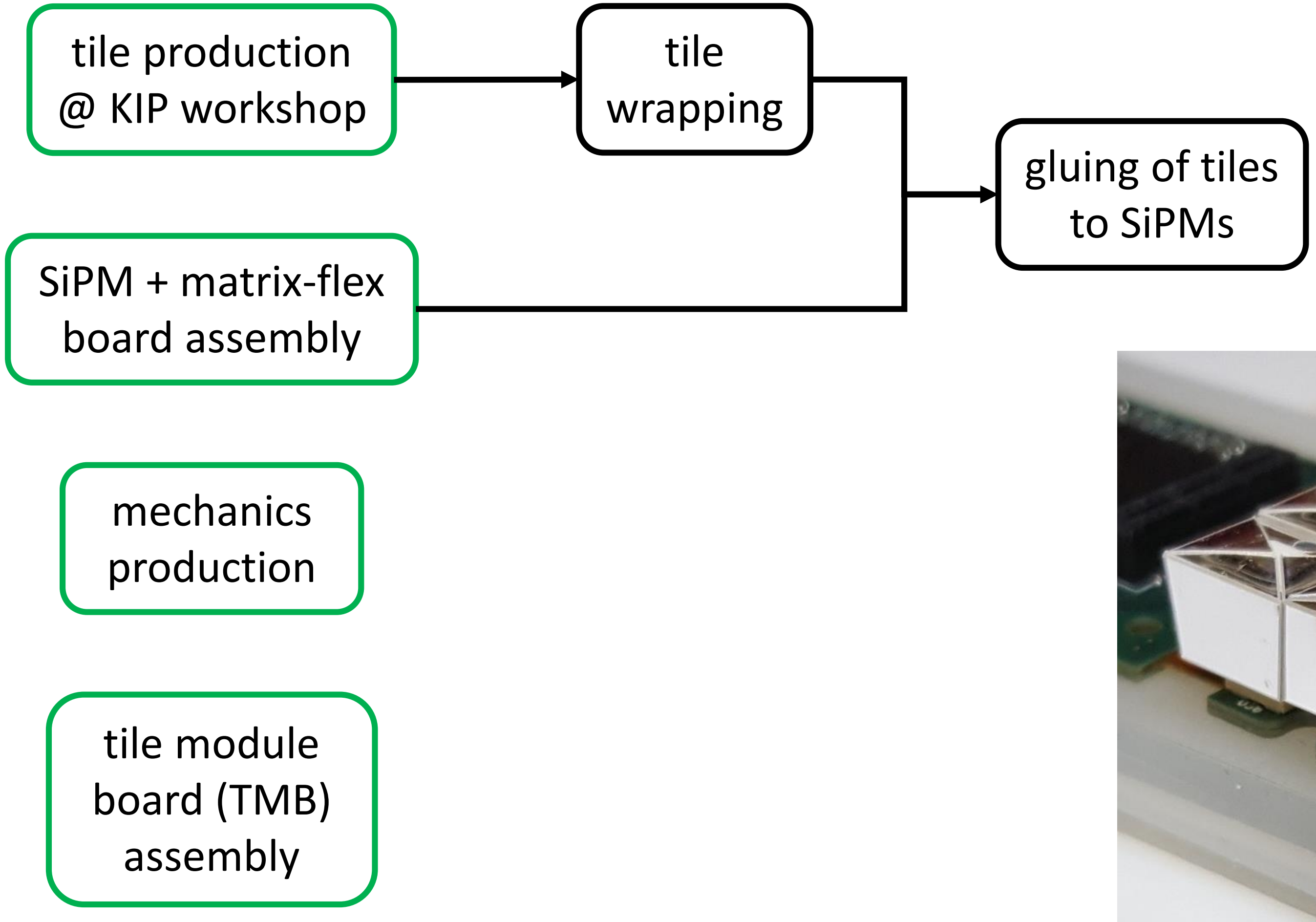
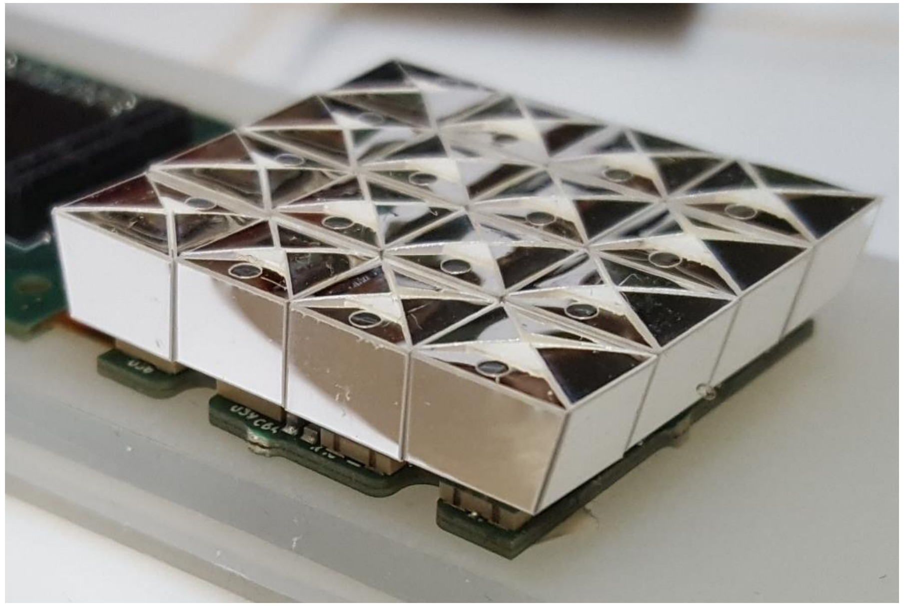
assembly

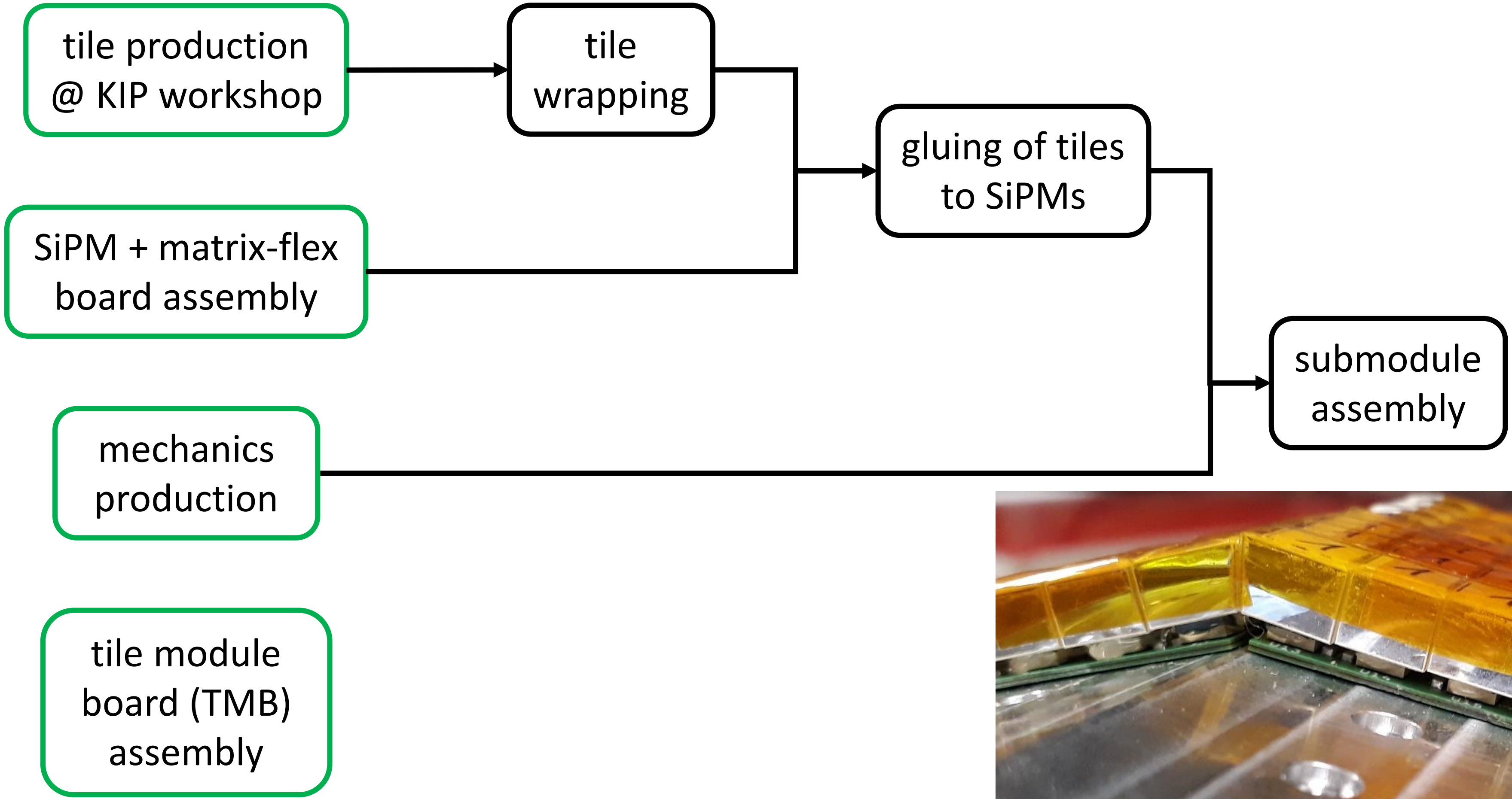


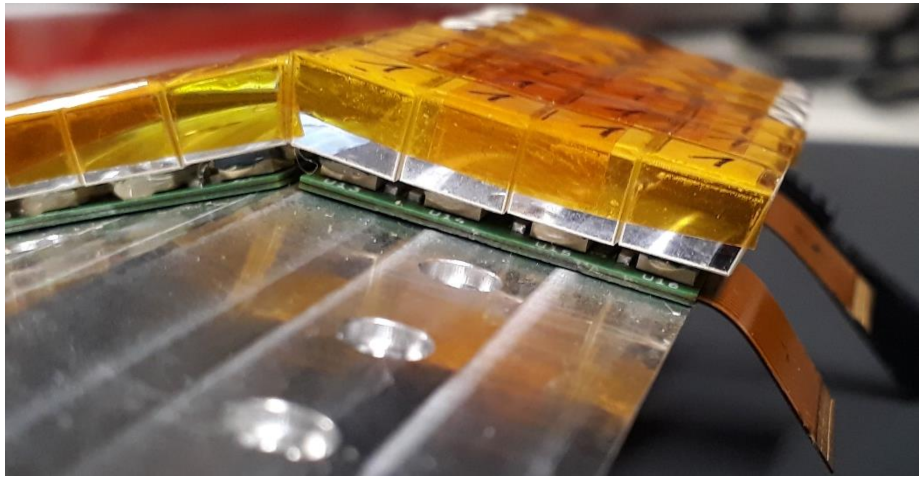
Production steps





Production steps





Production steps

tile production @ KIP workshop

tile wrapping

SiPM + matrix-flex board assembly

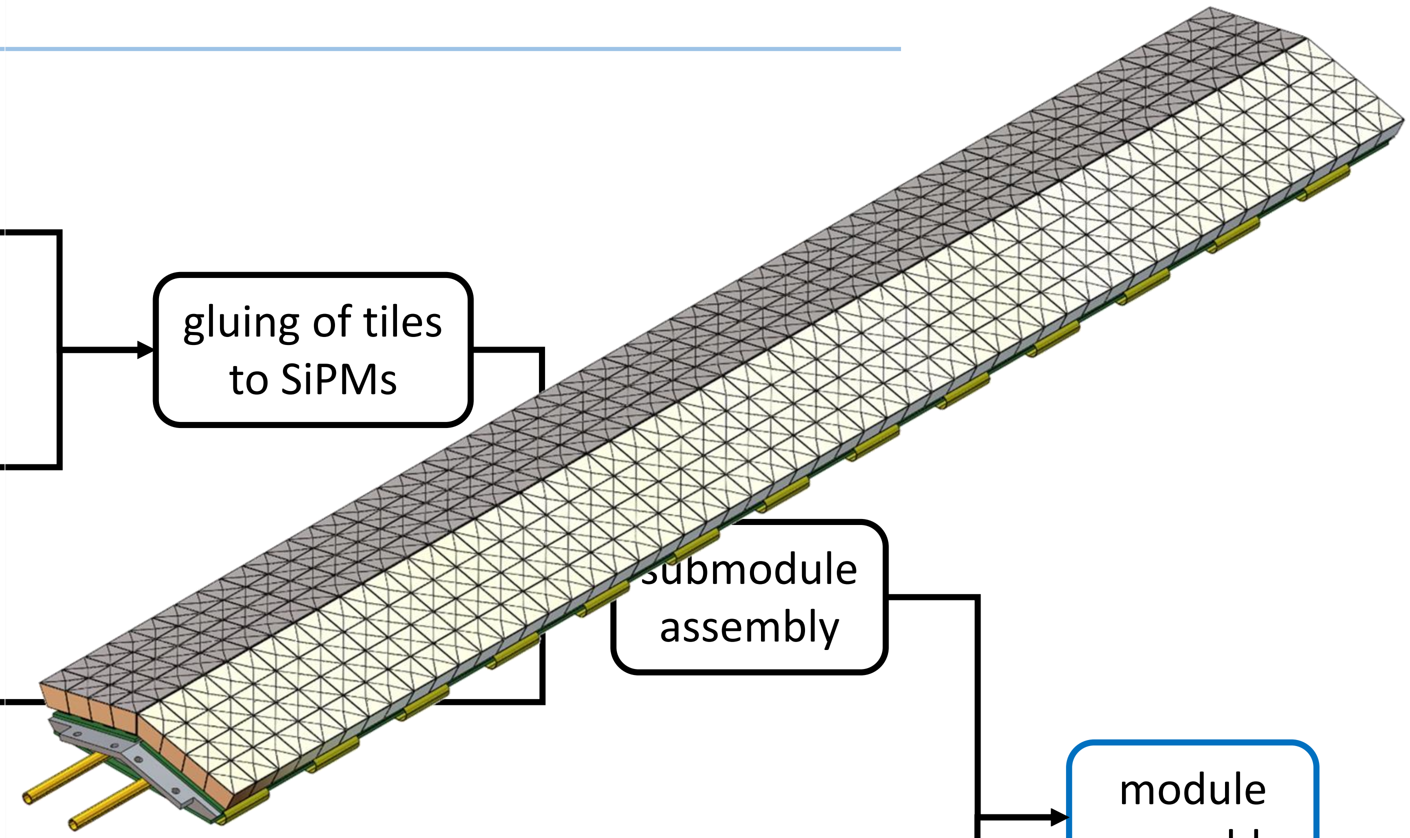
gluing of tiles to SiPMs

mechanics production

submodule assembly

tile module board (TMB) assembly

module assembly



commissioning 2021: two full modules

Tile production status

- number of tiles for two recurl stations: 5 824 tiles → **6.5k tiles**

- first technical prototype: 100 tiles produced in **70 working hours** @ KIP workshop
    - all faces diamond-milled from the top
    - can only work on two tiles at the same time

→ effort to improve production time @ KIP workshop

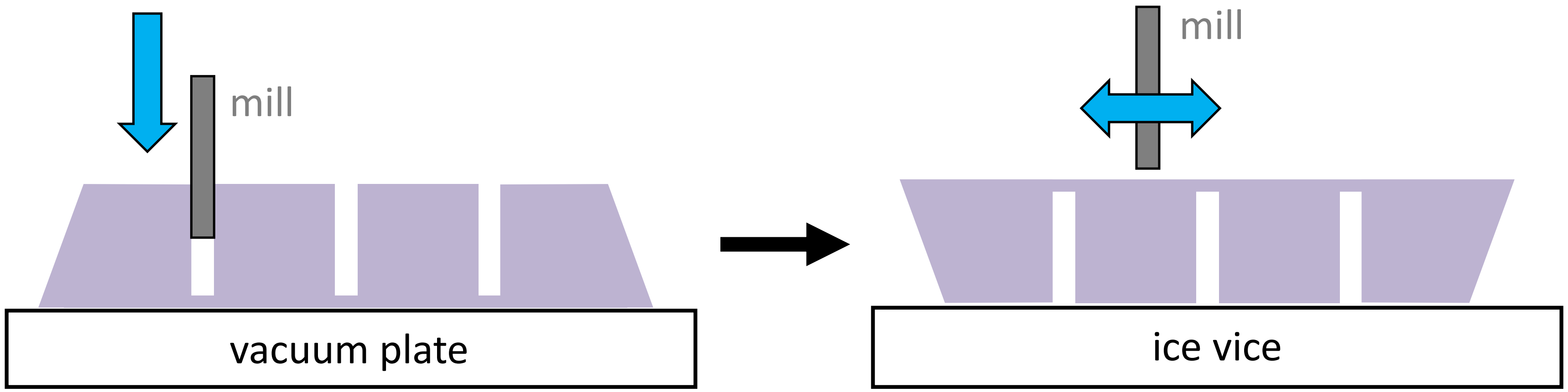
- idea: use "ice vice" ("Gefrierspanner") system

    → mill many tiles at once

The ice vice

- basic idea: freeze small parts to a plate to hold them in place during machining (-10°C)
- plate size: 200 mm x 300 mm
  → could clamp down ~ 100 tiles at once

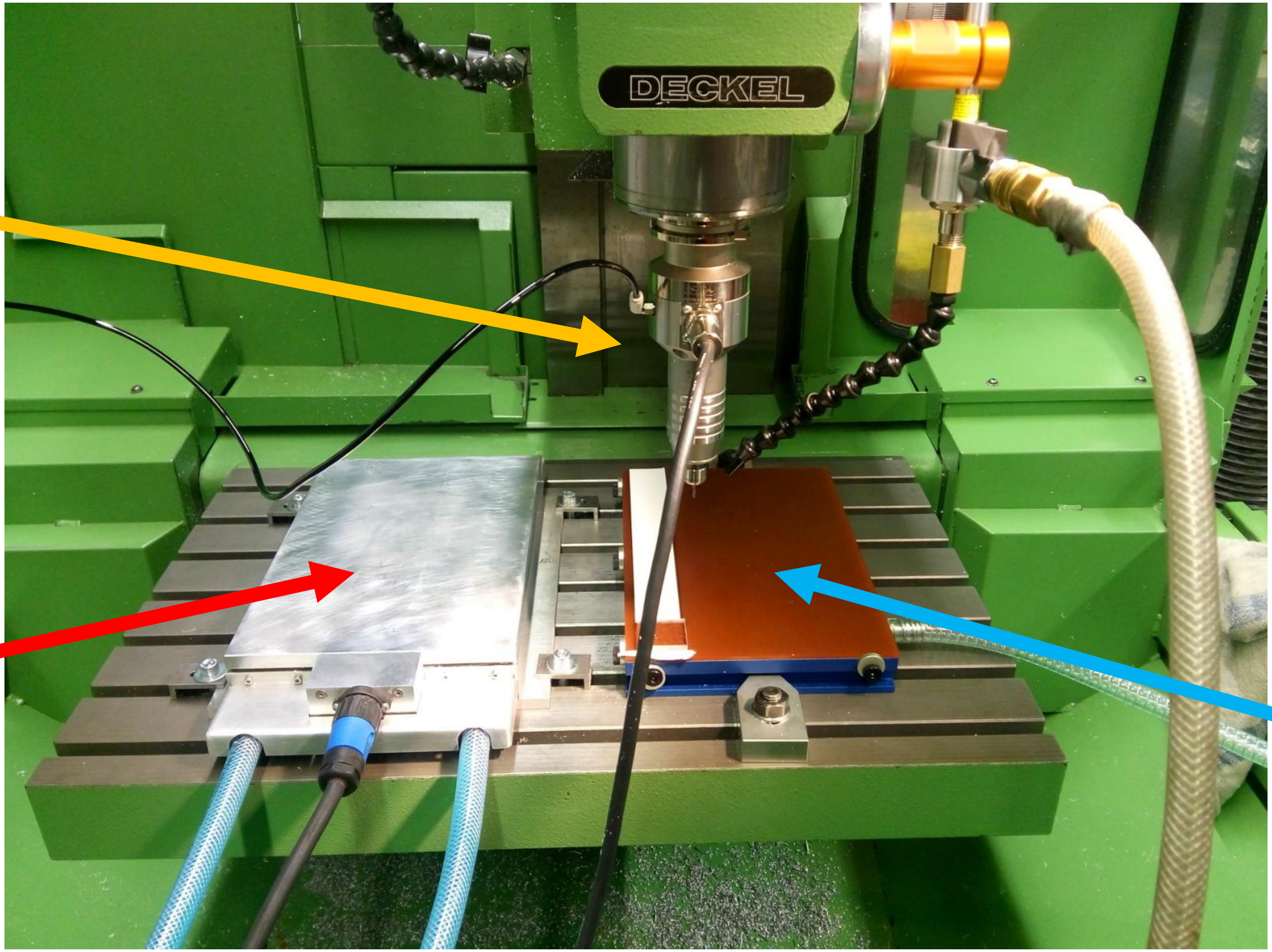
- one step further: cut out a full matrix from scintillator plate



Tile production setup @ KIP workshop

pictures by David Jansen

CNC mill



ice vice
(Gefrierspanner)

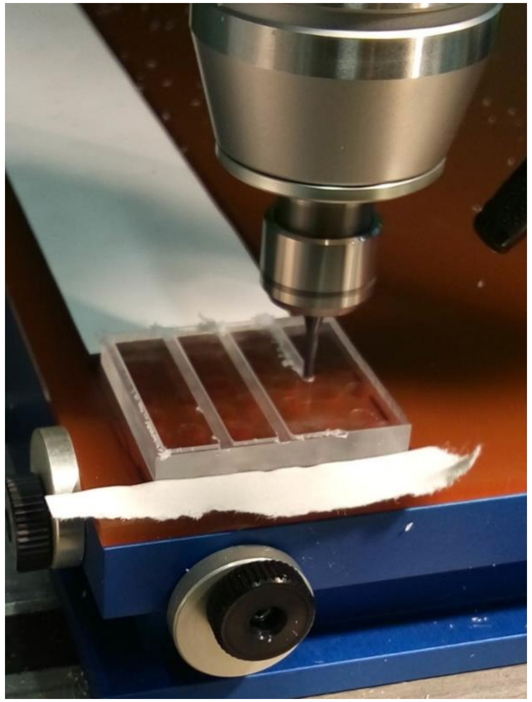
vaccum plate

Vacuum plate milling

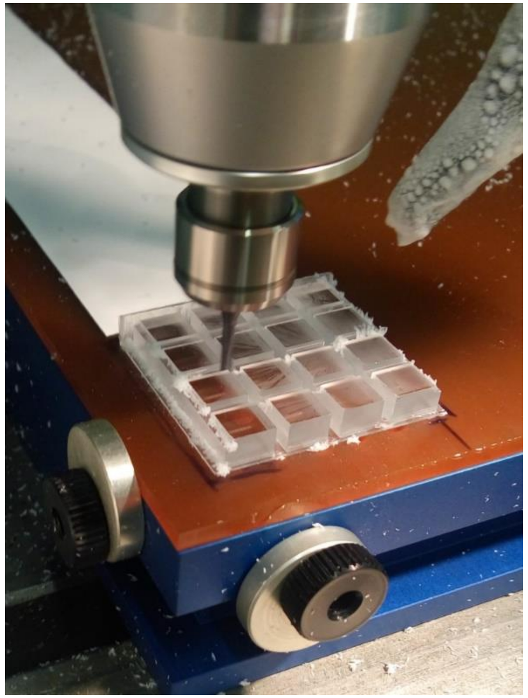
pictures by David Jansen

- milling of edge tiles:
  - step-wise milling with regular mill head
  - final milling with custom-made conical mill head

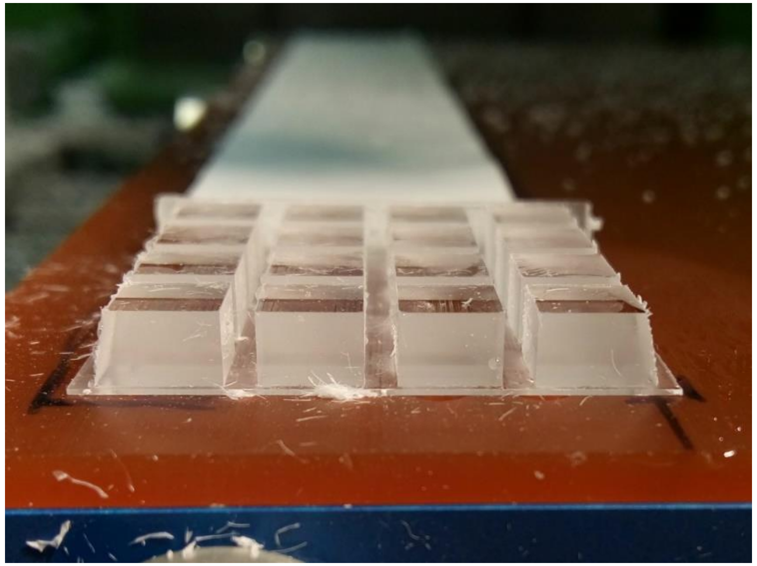
vertical milling



horizontal milling



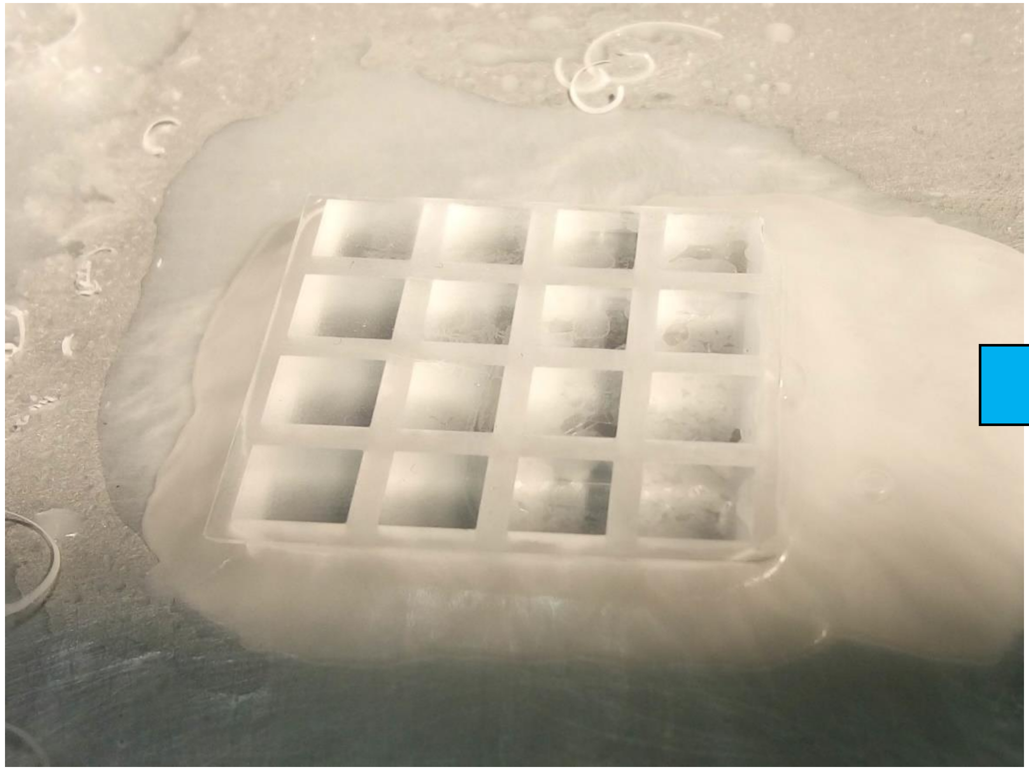
milled matrix with 0.5 mm leftover material



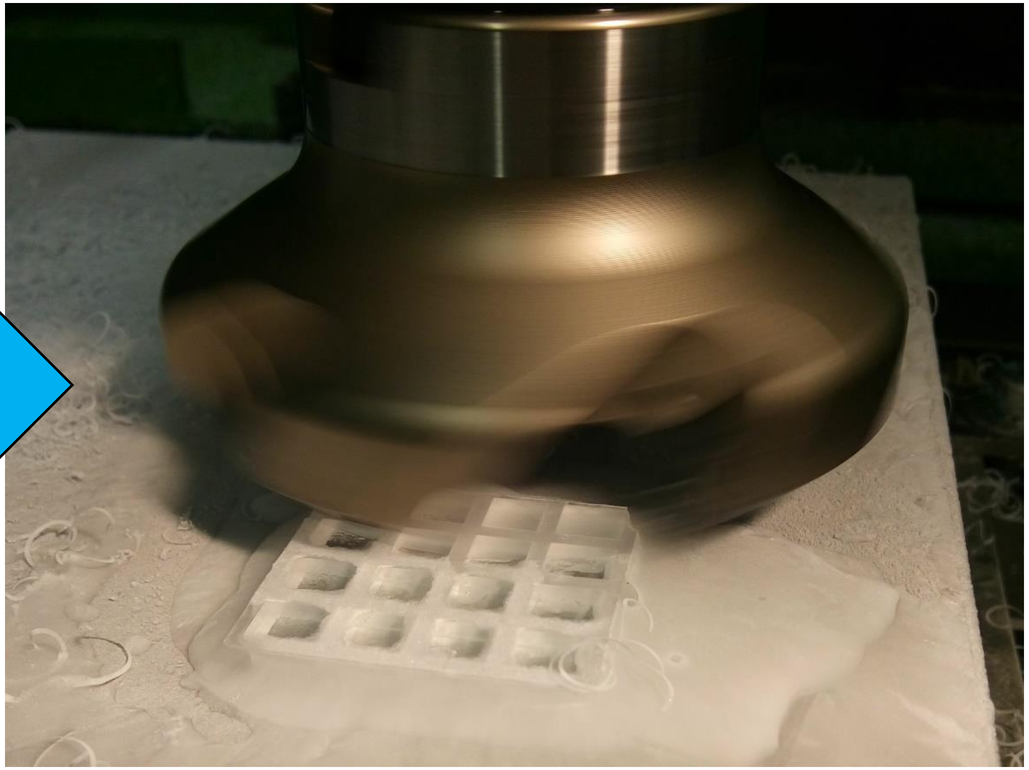
Ice vice milling

pictures by David Jansen

flip matrix to other side and freeze



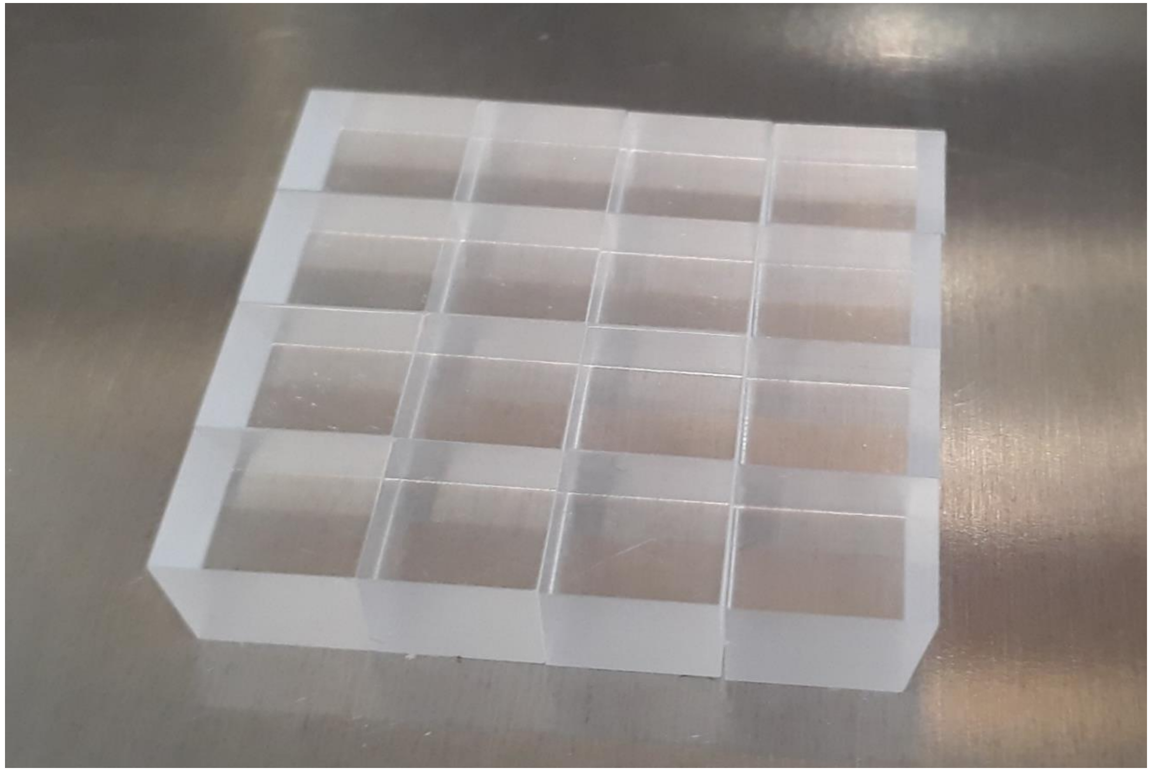
mill away leftover material from the top



Final matrix

- production time per matrix **< 30 minutes**
- reminder: we need 26*7*2 = 364 matrices for Mu3e Phase I

  → **2-3 months production time** ✓

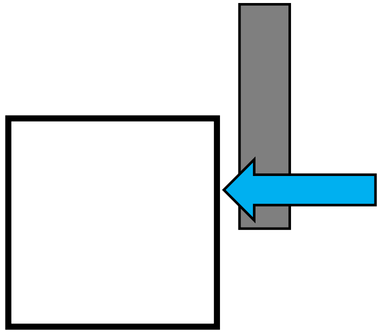


Open questions

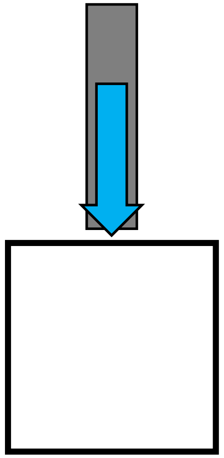
- price to pay for fast milling: "dull" side faces
  → effect on light yield and timing?

- idea: compare clear-surface matrix with dull-surface matrix
  → **testbeam at DESY**

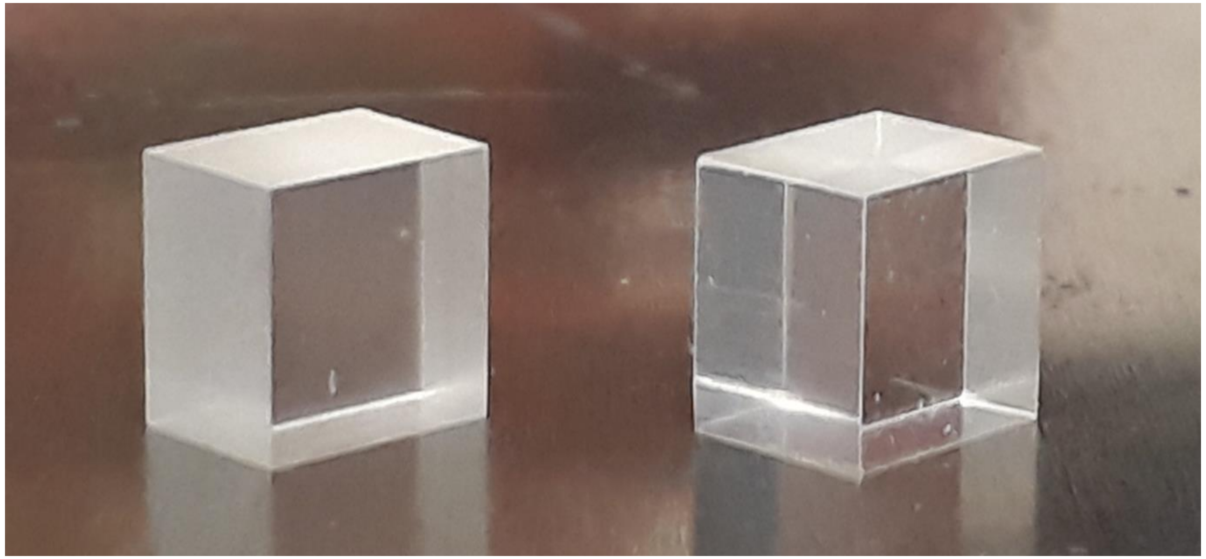
- alternative: mill all faces from the top
  → slower, but still realistic time frame (6 months)



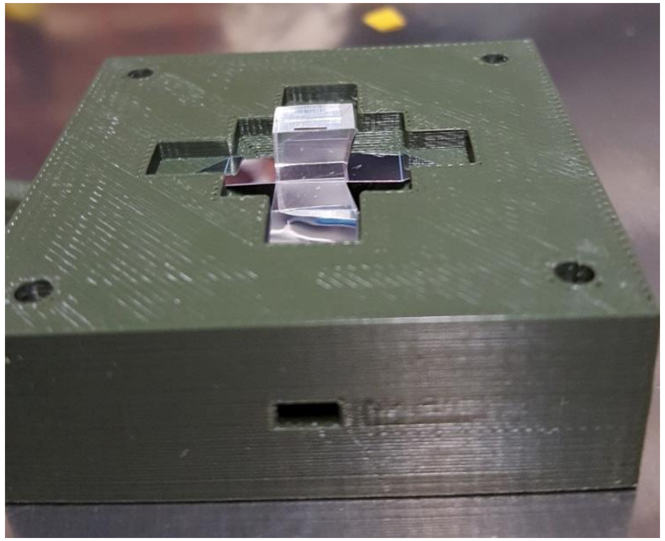
milling from the side (walzen)



milling from the top (stirnen)



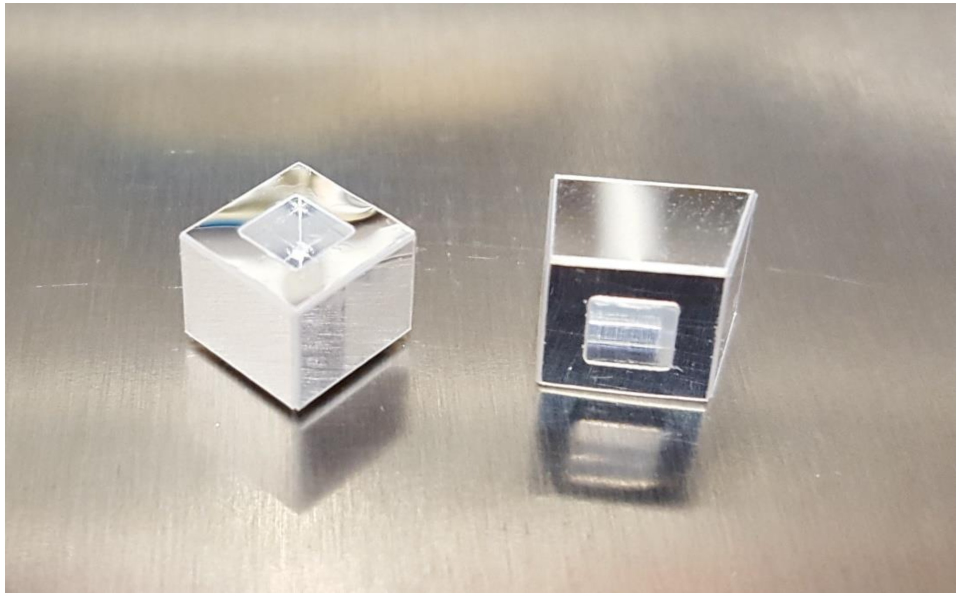
Tile wrapping

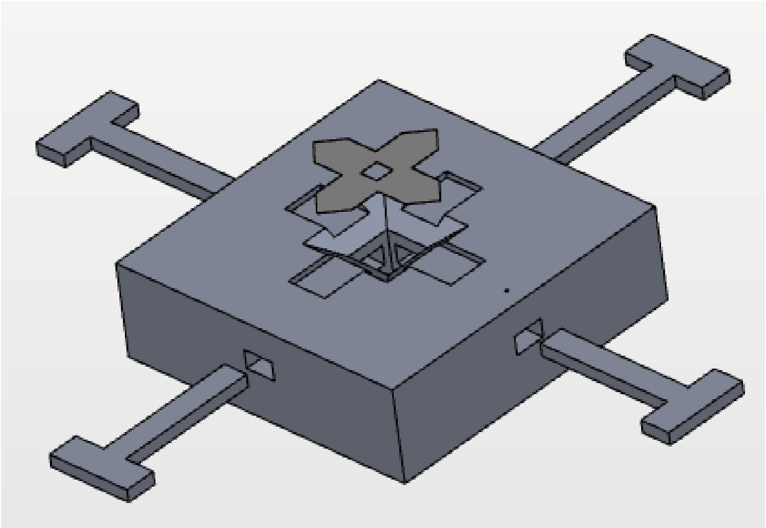


- wrapping of tiles with reflective foil to reduce optical cross-talk
- origignal wrapping tool design using CAD software

  → 3D-printed prototype

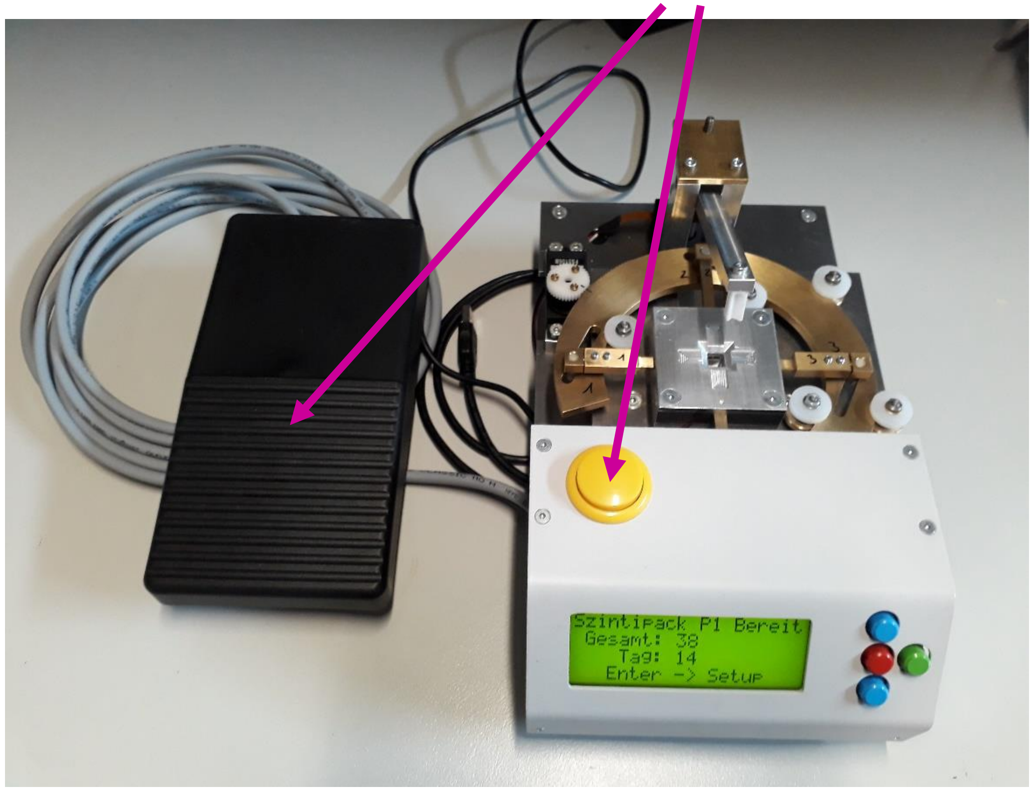
  → "upgrade" to (semi-)automatic solution for easier handling and faster production

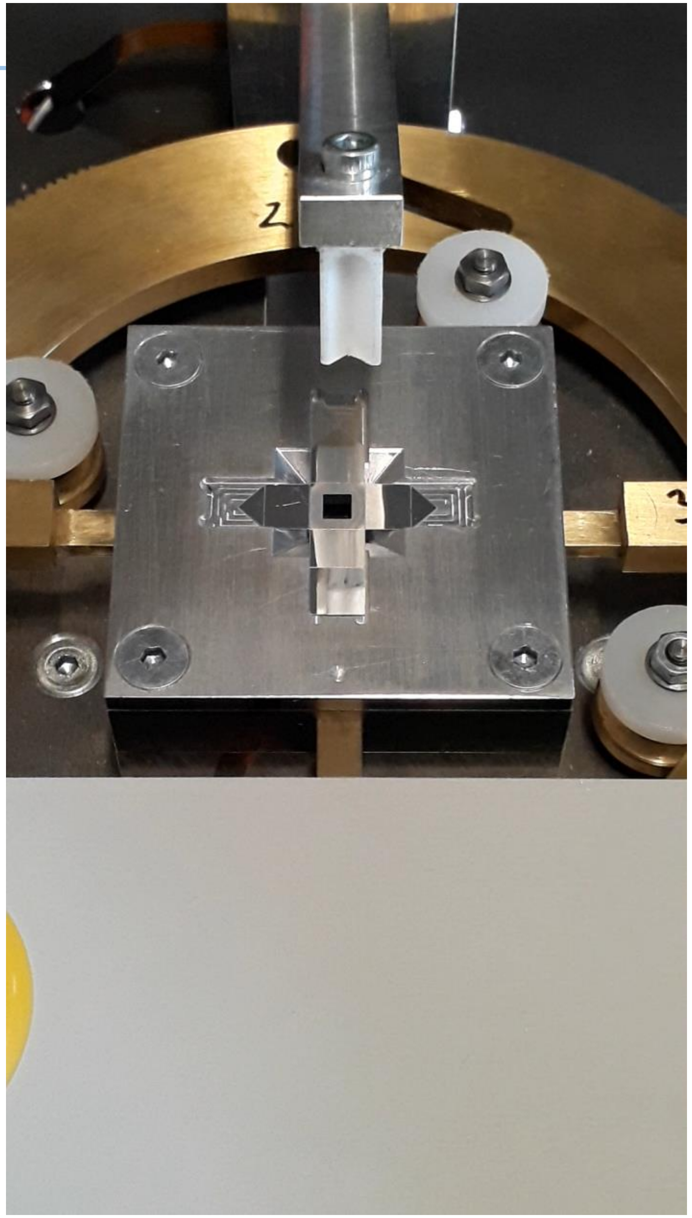




Semi-automatic wrapping tool

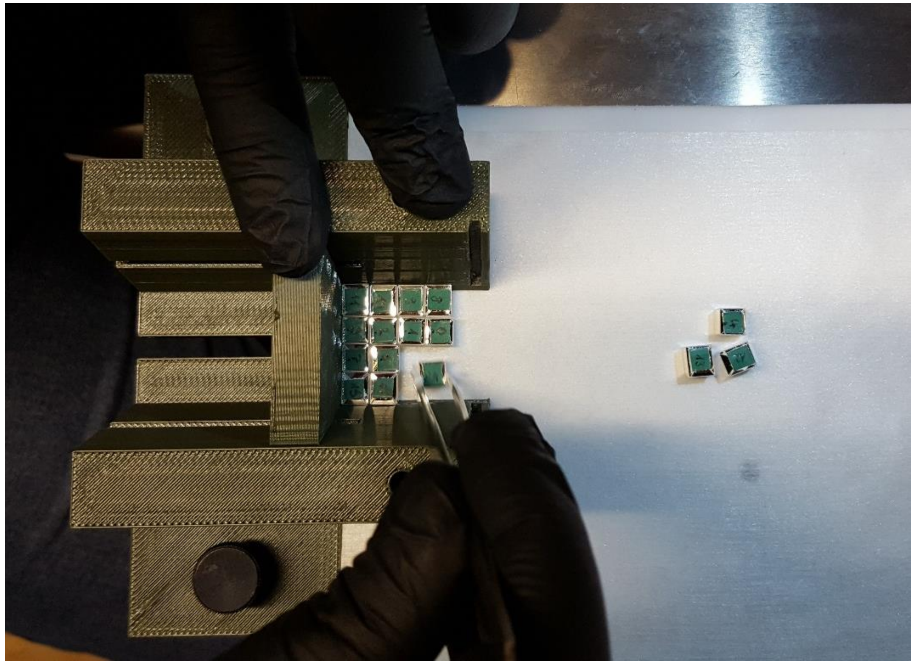
- constructed by Knut Azeroth (electronics workshop) and Christian Herdt (mechanical workshop)
- wrapping sequence controlled by Arduino
    - move through sequence by pressing "Enter"

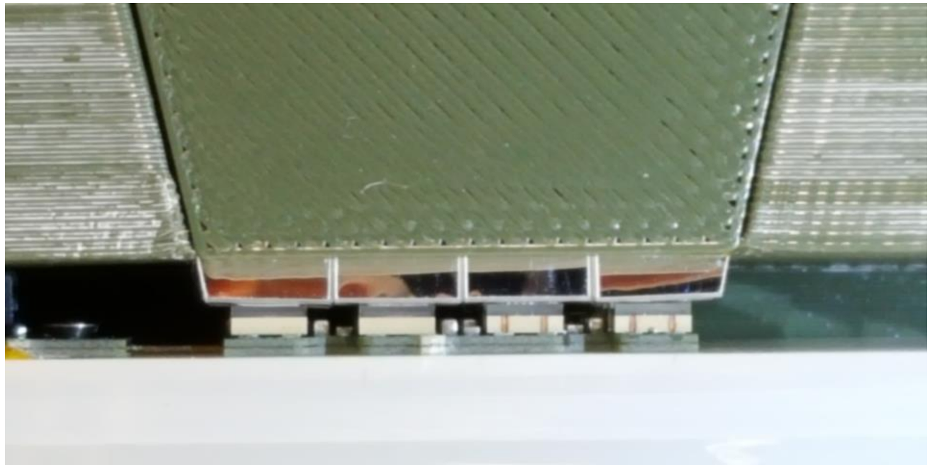




Tile gluing

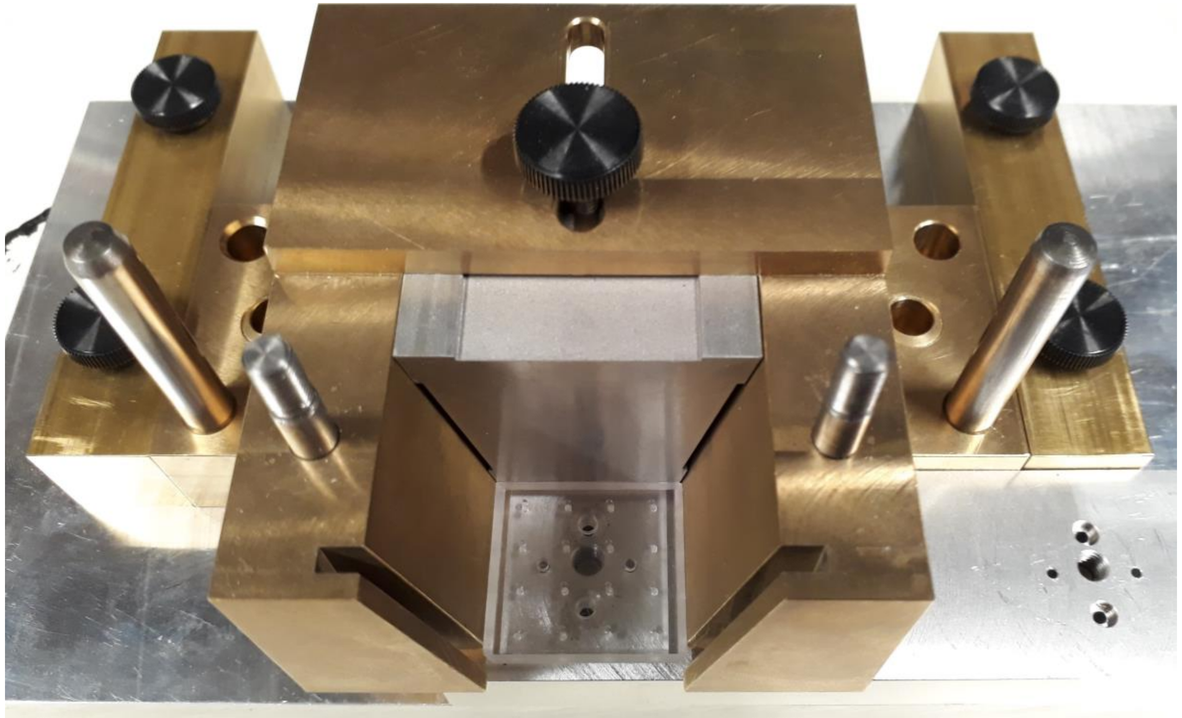
- attach tiles to SiPMs using light-transmitting glue
- glue full tile matrix (4 x 4 tiles) all at once
- 3D-printed prototype
  → production of final tools @ KIP workshop

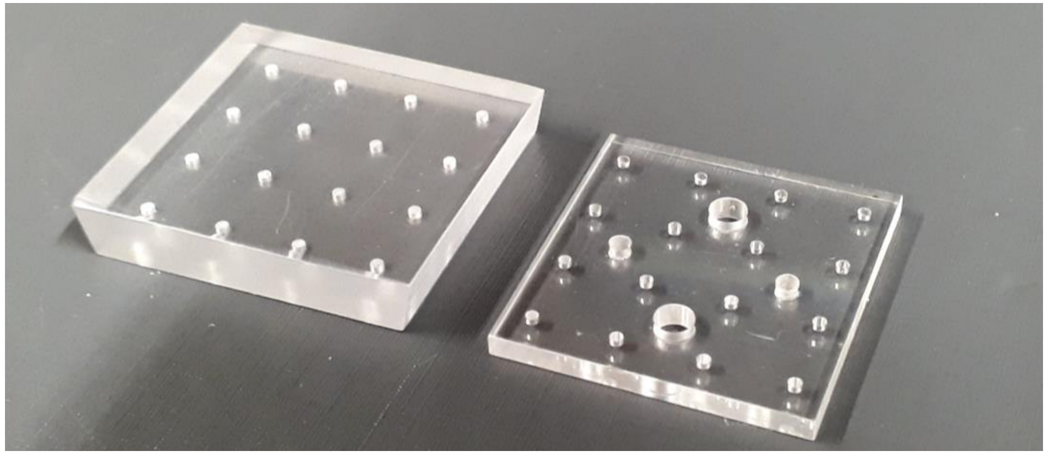




Final gluing tool

- four gluing tool stations produced @ KIP workshop
  → used for new matrix prototype
- alignment of tool to pedestal using tile matrix and SiPM mock-ups (plexiglass)
  - circles mark centres of tiles and SiPMs, respectively
  - align under microscope
  - to ensure alignment of foil window to SiPM





Validation of new design

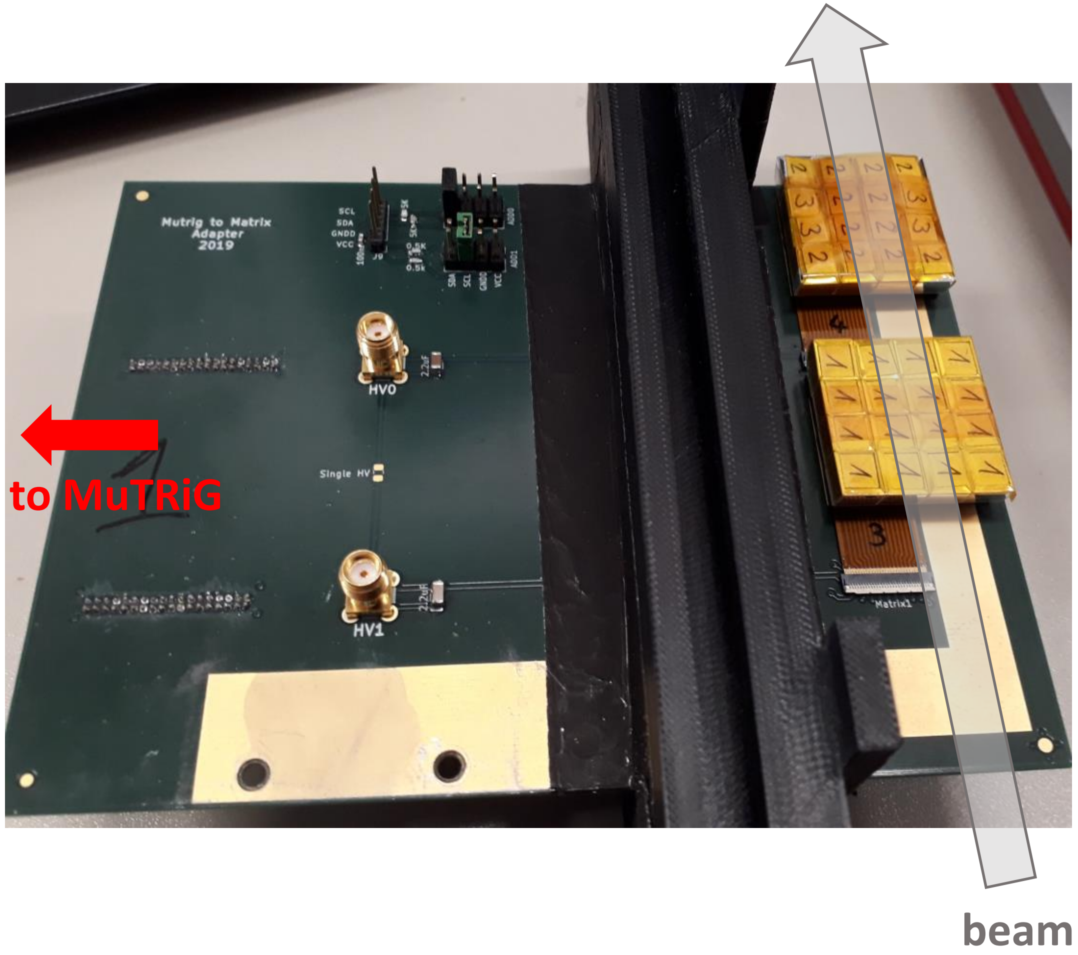
Timing measurements at DESY testbeam

- produced four matrices using new design
  - different tile surface qualities
  - different tile heights (5.0 mm and 4.5 mm)

→ investigate effect on timing

- SiPM read-out using standalone MuTRiG setup
  - only 2 matrices (32 channels) at once

  → matrices switched during testbeam



Timing calculation

- coincidence time resolution (CTR):

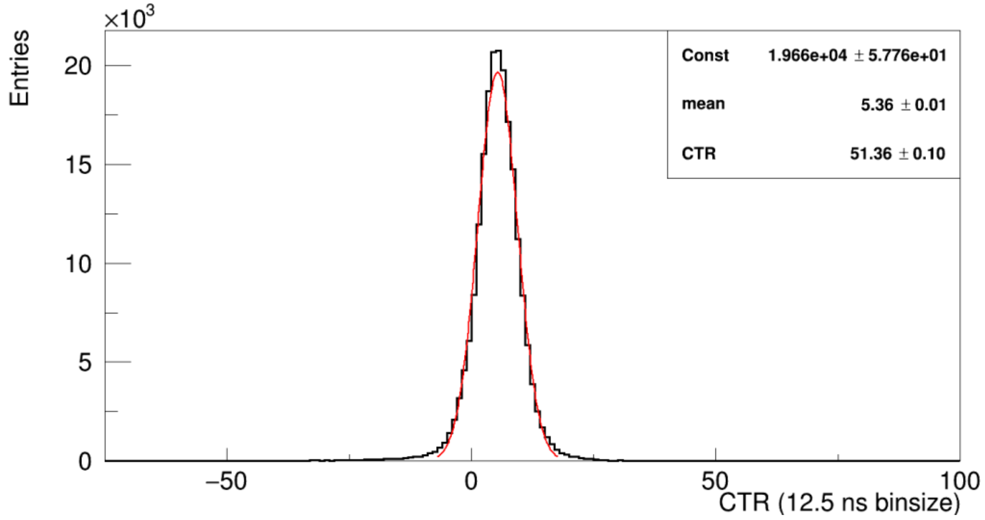
  $\sigma^2_{ij} = \sigma^2_i + \sigma^2_j$

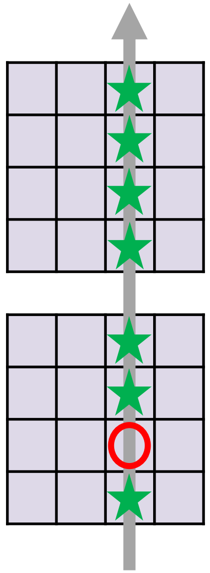
- single channel resolution using three channels 1, 2, 3:

  $\sigma_1 = \frac{1}{\sqrt{2}}\sqrt{\sigma^2{}_{12} + \sigma^2{}_{13} - \sigma^2{}_{23}}$

- single channel resolution using both matrices
  - 8 channels in one column
  - no cuts on energy spectra
  - using timewalk correction

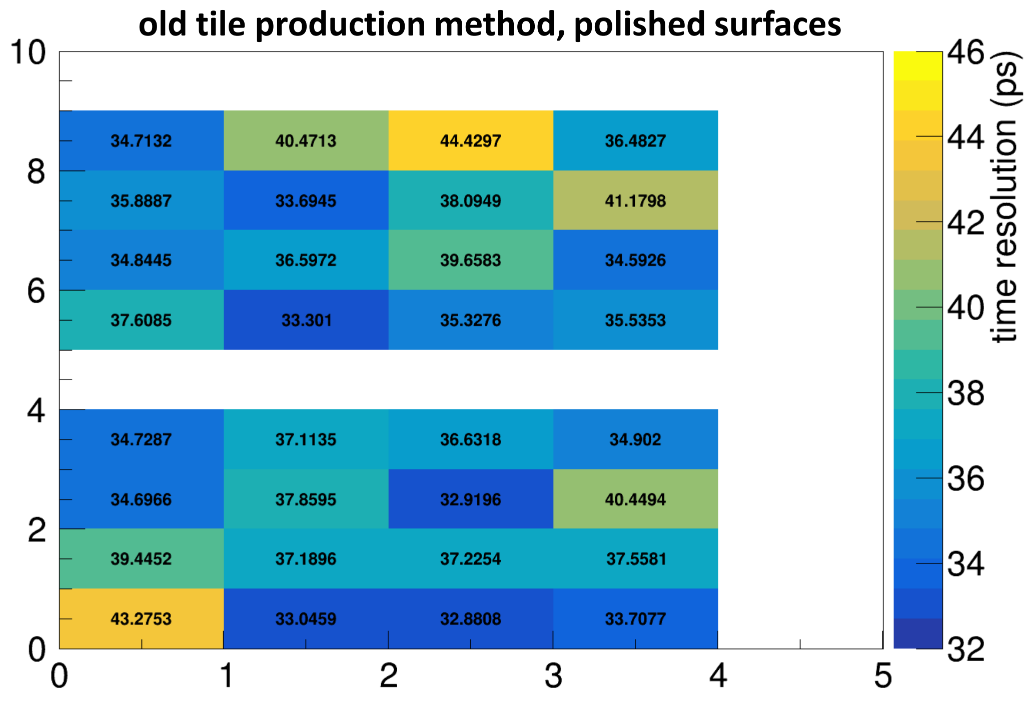
  → extract individual channel resolution

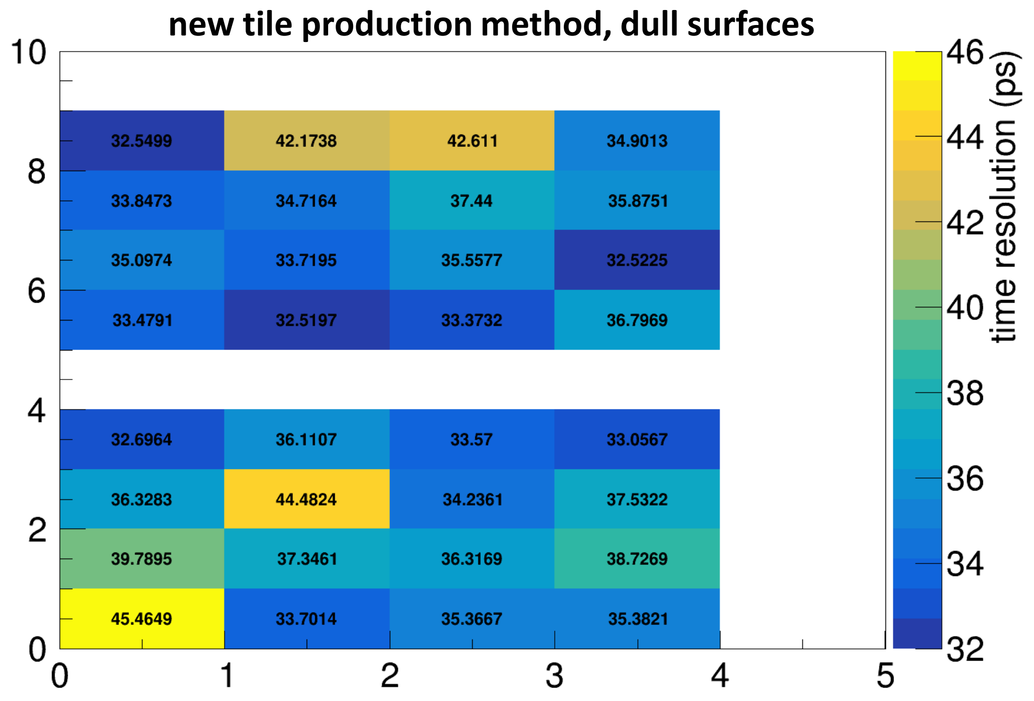




Timing results

- single channel resolution of all four matrices
  - **excellent uniformity** of time resolution
  - some "outliers" due to MuTRiG channel variations
    - remember: same MuTRiG used for left and right plot





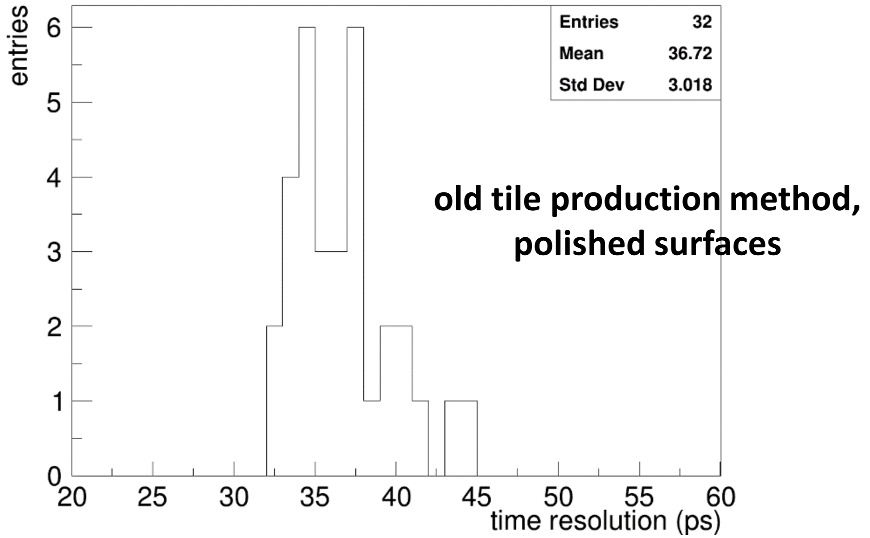
Conclusions

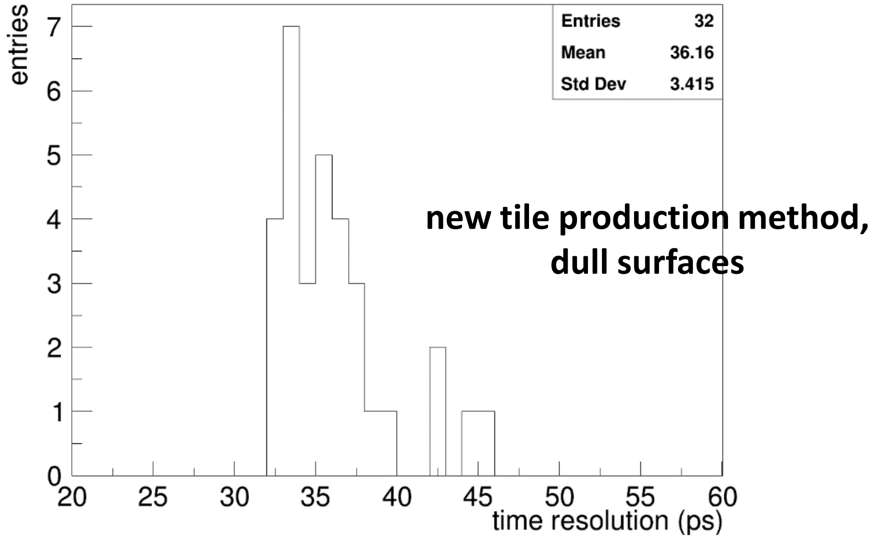
- excellent uniformity of single channel resolution
  - within and between matrices

- excellent timing performance
  - average resolution (old method): **(36.7 ± 3.0) ps**
  - average resolution (new method): **(36.2 ± 3.4) ps**

- no difference in time resolution between old and new tile production methods

→ **functionality and timing performance of new design validated**





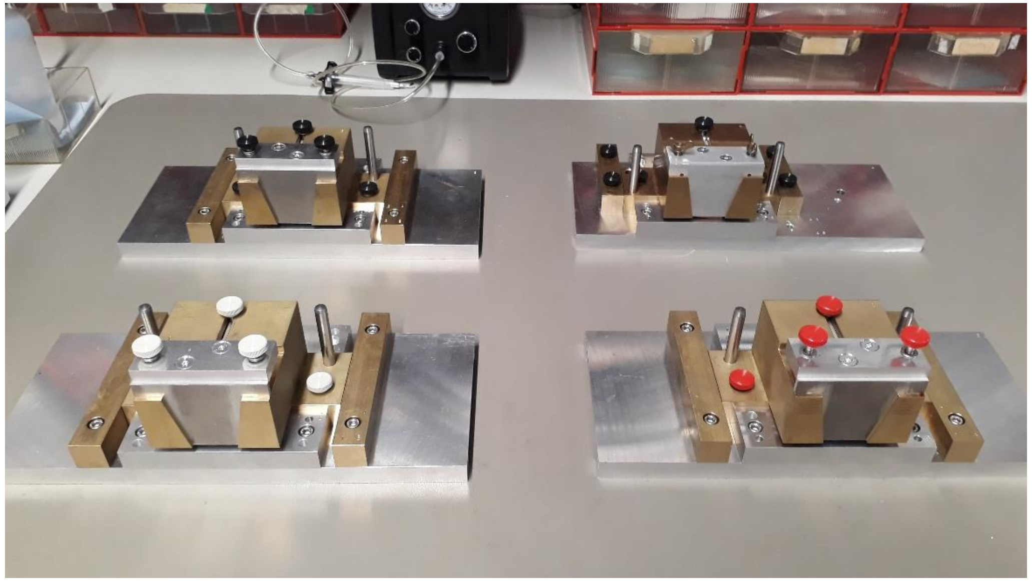
Pre-production setup and plans

Pre-production status

Pre-production has started!

- reminder: goal are two modules for commissioning in spring 2021
  - we have all the material needed (> 1000 tiles, 1000 SiPMs, two cooling plates, …)
- production & assembly:
  - first round of matrix PCBs assembled with SiPMs
  - wrapping tools: centre tiles ready, edge tiles needs some fine-tuning
  - gluing tools are ready
- Quality Assurance tests:
  - QA for matrix PCB is ready
    - general functionality of electronics
    - SiPM DCR
  - tile matrix QA is under development
    - SiPM gain
    - tile light yield

} Tiancheng's work



Outlook

- first round of assembly before Christmas
  - SiPM QA
  - tile wrapping & gluing
  - tile matrix QA

→ validate and optimise production & QA procedures

→ beginning for next year: start full module production

- still missing: read-out board with MuTRiGs
  - under development @ KIP electronics workshop ← based on MALIBU design by Konrad Briggl
  - aim at submission before Christmas

  → start board QA at end of Q1 2021

- commissioning of two modules @ DESY and PSI in spring 2021