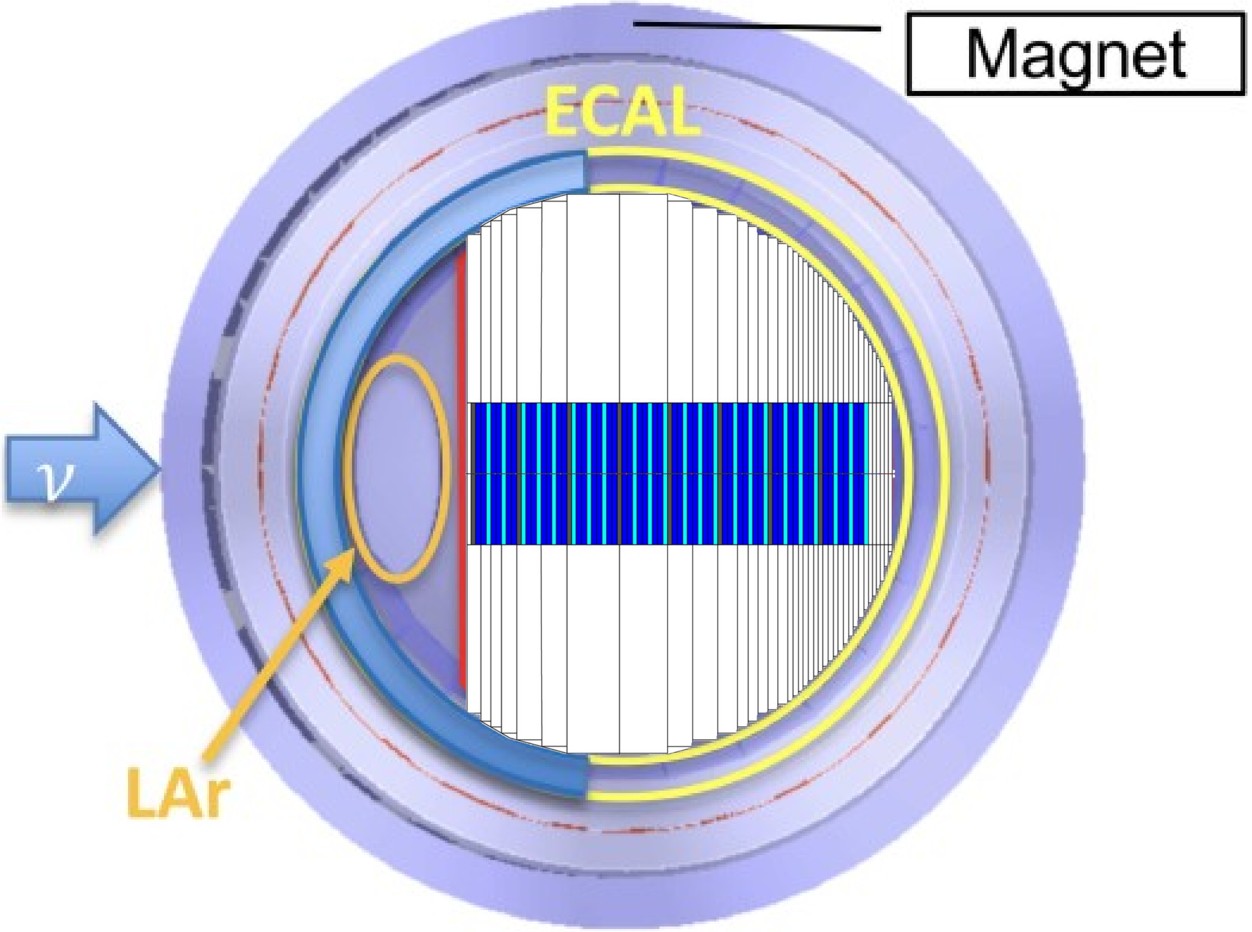


Introduction to SAND Tracker

S. Di Falco and G. Sirri

Dune Italia meeting

October 29, 2024

Outline

- SAND Inner Tracker requirements
- Straw Tube Tracker (STT) design
- First STT prototypes Test Beam
- Gas System
- Readout electronics
- Cooling
- Resources
- Schedule
- Costs

Requirements* for a SAND Inner Tracker

* will drive the technical choice defining the Threshold parameters

ND requirements for neutrino oscillation*

Requirements:

- R0: Predict ν spectrum at FD
- R1: constrain uncertainties on flux, cross sections and detector response
- R2: constrain backgrounds
- R3: study energy dependence of observables (PRISM)
- R4: monitor neutrino beam
- R5: resolve pileup

* From Physics requirements of the Phase I Near Detector, May 2024

ND additional search opportunities*

Search Opportunities:

- X1: Neutral Heavy Leptons
- X2: Light Dark Matter
- X3: Neutrino tridents
- X4: Short baseline oscillations

* From Physics requirements of the Phase I Near Detector, May 2024

ND measurement requirements*

Measurement requirements:

- M0: ν interactions classification → particle identification
- M1: flux normalization (ν_e elastic scattering)
- M2: wrong sign contamination
- M3: ν_e /$\overline{\nu}_e$ contamination
- M5: muon integrated rate changes @1%
- M6: on axis neutrino spectrum
- M7: resolve single ν interactions

* From Physics requirements of the Phase I Near Detector, May 2024

SAND systematics oriented measurements*

Measurements:

- X5: ν-p cross sections
- X6: ν-Ar/ν-H cross section ratios
- X7: cross sections on other targets
- X8: $\nu_\mu, \bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ fluxes
- X9: inverse μ decay
- X10: on-axis beam monitoring

* From Physics requirements of the Phase I Near Detector, May 2024

SAND tracker capabilities*

Capabilities:

- C3.1: low average density (ρ<0.22 g/cm^3)
- C3.2: charged particle momentum resolution < 5% up to ~5 GeV/c
- C3.3: < 1 X_0 from center to ECAL
- C3.4: < 1 λ_I from center to ECAL
- C3.5: solid H by subraction of C and CH targets
- C3.6: other nuclei targets
- C3.7: Ar target (GRAIN)

* From Physics requirements of the Phase I Near Detector, May 2024

SAND tracker capabilities* (beam monitoring)

Capabilities:

- C4.1.1: Fiducial Volume mass ~5 ton
- C4.1.2: μ momentum resolution < 5% @1 GeV/c, <10% up to 5 GeV/c
- C4.1.3: ν vertex resolution < 5 cm
- C4.1.4: time resolution < 10 ns

* From Physics requirements of the Phase I Near Detector, May 2024

More SAND tracker requirements (to be quantified)

Capabilities:

- **ν energy resolution:** depends on channel
  (→ angular resolution)
- **Particle identification** (with ECAL and Muon detector):
  electrons, pions, muons, protons, neutrons
  (→ vertex and time resolution)

Notes on SAND tracker threshold parameters

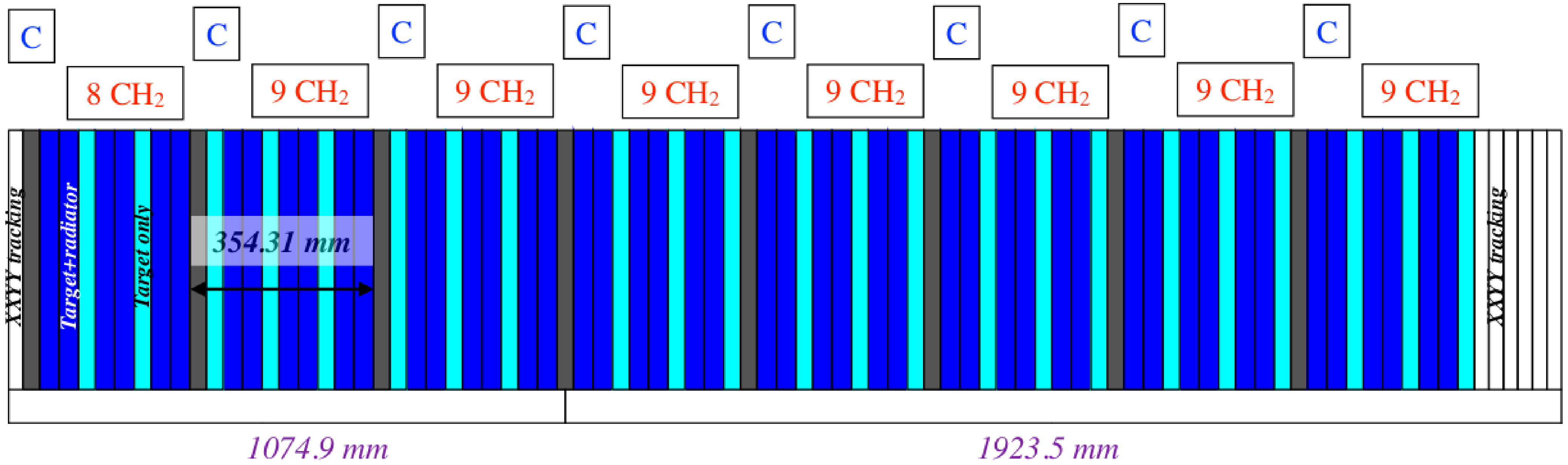
Most numerical values for the threshold parameters in question are based on analyses conducted during the STT design study (see “A Proposal to Enhance the DUNE Near-Detector Complex,” doc-db 13262, March 2021).

Before making a final technical decision, the simplified simulation used in this study requires improvement. Specifically:

- Detector response (digitization) should leverage performance data from **test beams**.
- Results should remain **unbiased** by Monte Carlo (MC) information.
- A **Kalman filter**-based track reconstruction is essential to achieve accurate resolution of 3D particle momenta.

Straw Tube Tracker (STT) design

Default STT configuration



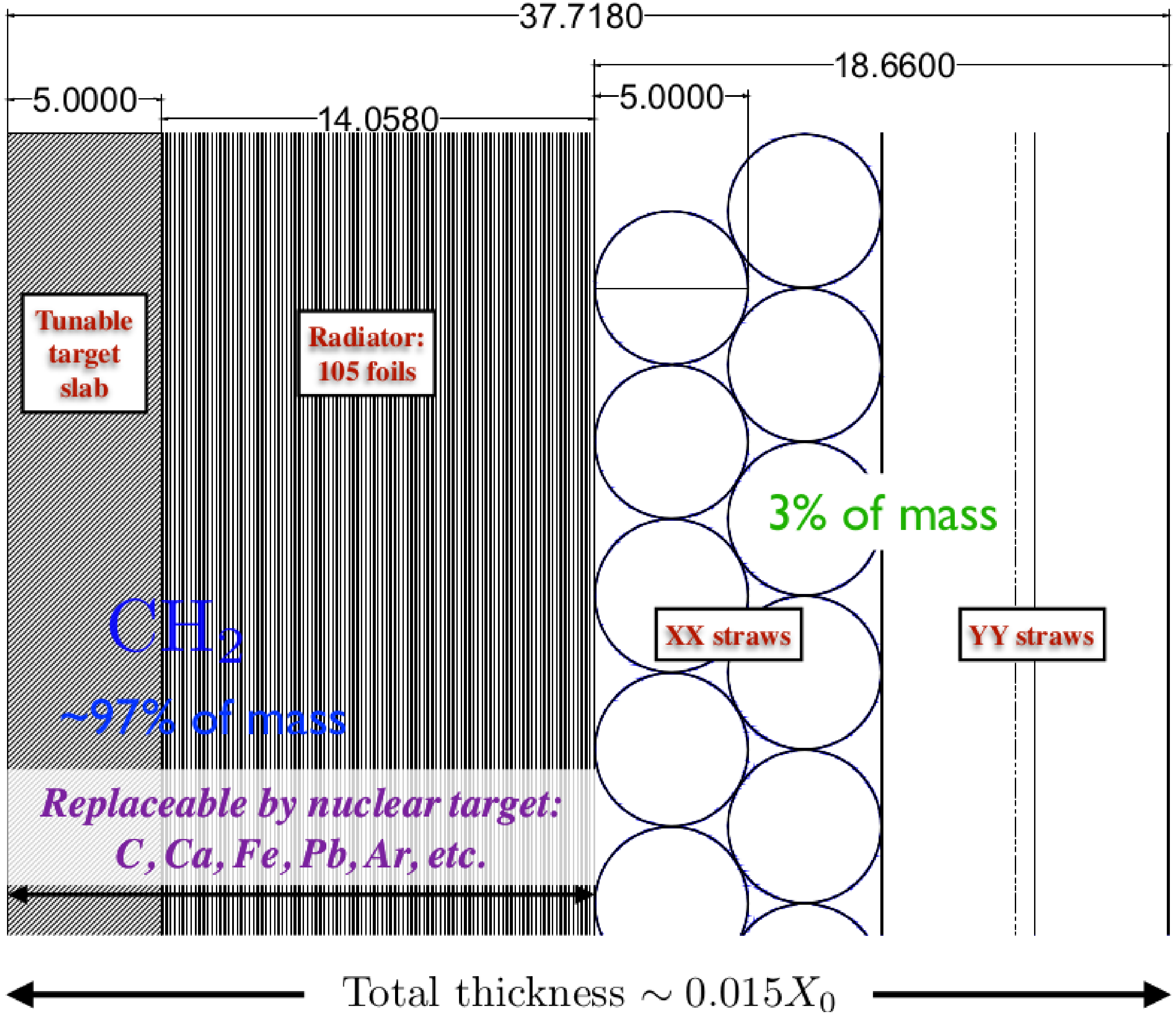
- 925 mm upstream space for GRAIN
- 48 CH_2 (**polypropylene**) modules with target+radiator (37.718 mm)
- 23 CH_2 modules with target only (32 mm)
- 8 C (**graphite**) modules (32 mm)
- 7 tracking only module XXYY (28 mm)

Total: **86 modules**
(8 super-modules of 10 modules,
1 tracker only supermodule with 6 modules)

$<\rho>\sim 0.17$ g/cm^3
$X_0 \sim 3.5$ m
$\perp$ sampling 0.15%X_0
// sampling 0.36%X_0

FV mass 4.4 tons
Thickness ~1 X_0

STT C-H modules



A slab of **polypropylene** (C_3H_6) is used as C-H target

105 polypropylene foils 18 μm thick act as **transition radiator** to improve e/π separation

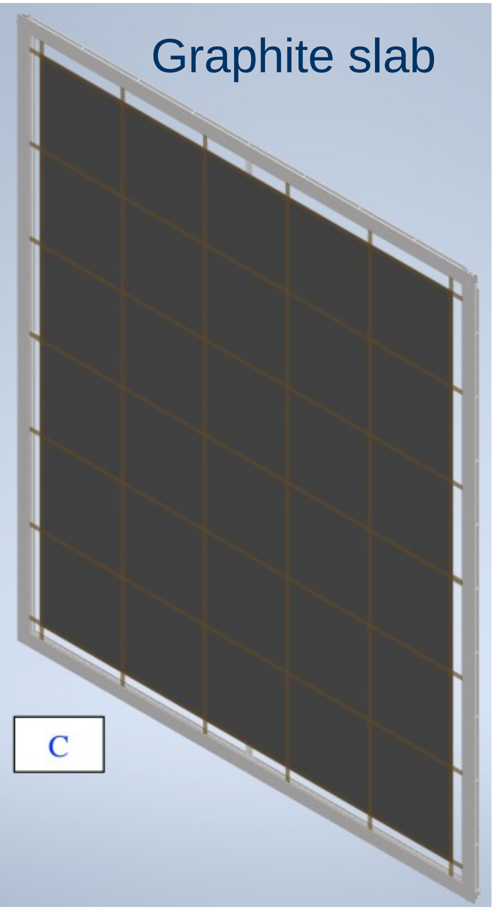
2+2 layers of **5 mm straw tubes** are disposed along the **X and Y** coordinates perpendicular to the beam

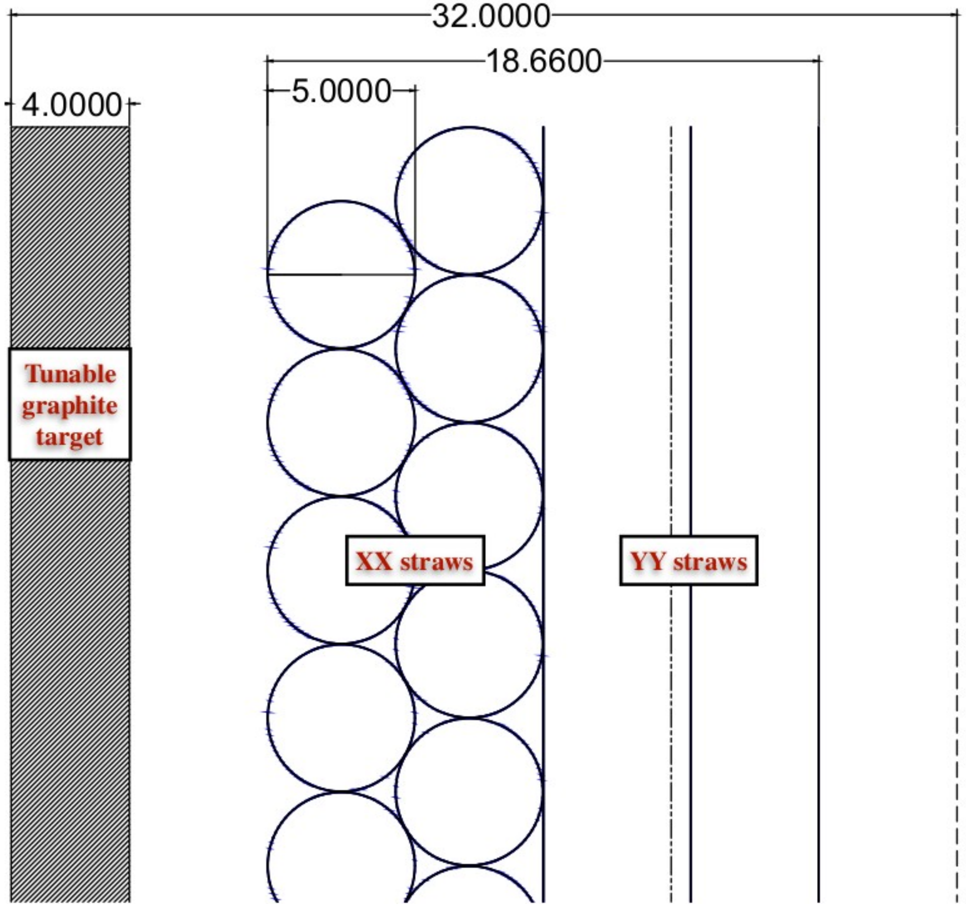
The default gas mixture is **70% Xe 30% $C0_2$**

The overpressure is ~1 atm (2 atm absolute)

Straw tubes length varies from **~1 to 3.8 m**

STT C modules





2+2 layers of **5 mm straws** are disposed along the **X and Y** coordinates perpendicular to the beam

The default gas mixture is **70% Ar 30% C0$_2$**

The overpressure is ~1 atm (2 atm absolute)

Straw tube length varies from ~**1 to 3.8 m**

More details on mechanical design in Fabrizio’s talk

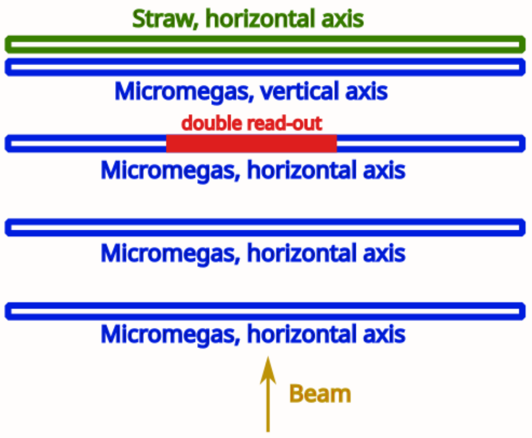
STT design validation

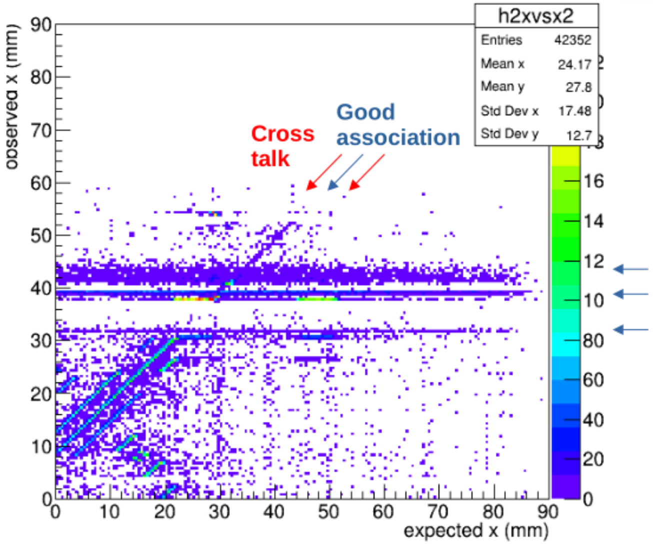
Prototyping activities: CERN 2022 test beams

6 mm double layer straw tube prototype at Cern PS test beam in **June 2022**

Long test beam activity started in 2021 at Cern H4

Recovered electronics mounting **VMM3** ASIC





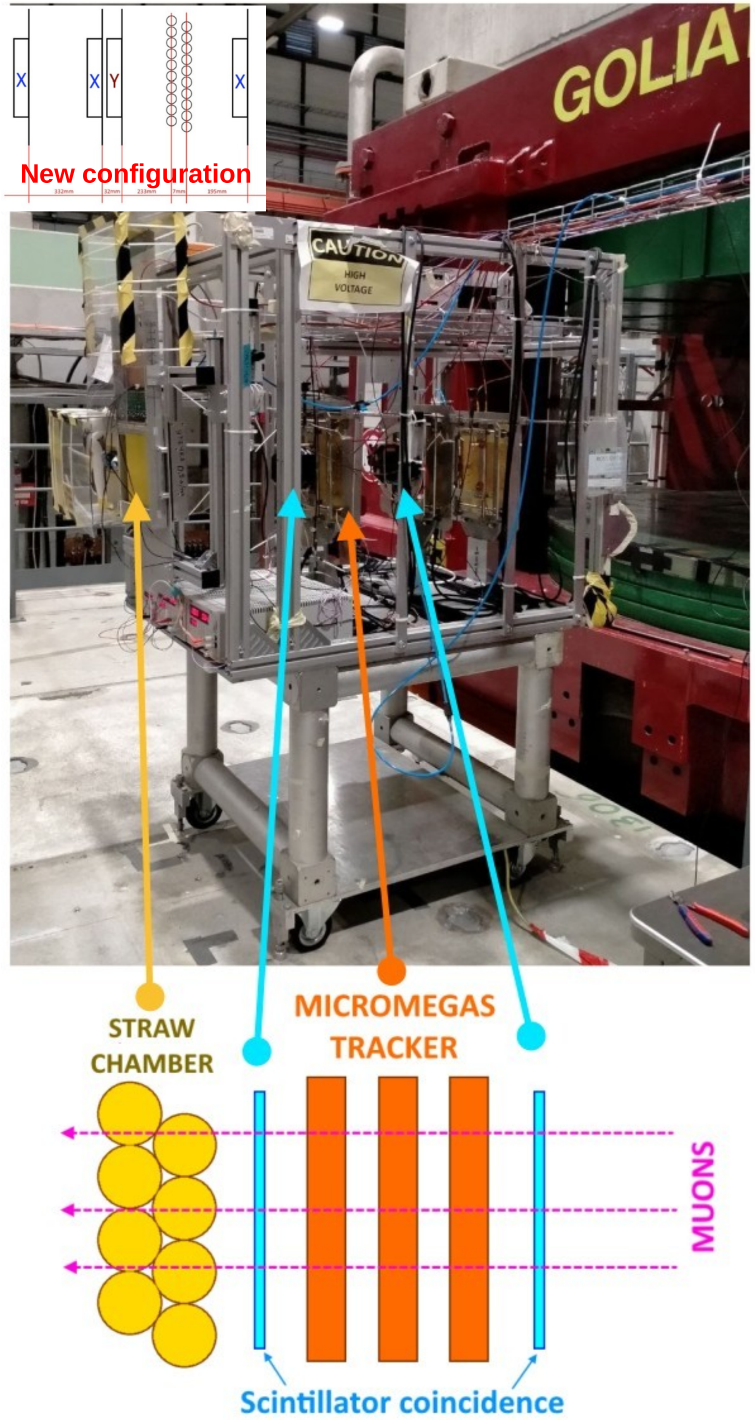
Recovered electronics with **VMM3** ASIC:
Noisy strips
Dead channels

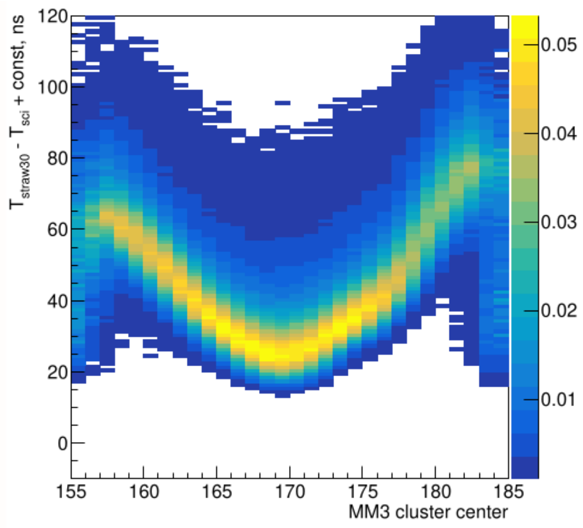
No possibility to synchronize STT and Micromegas readout

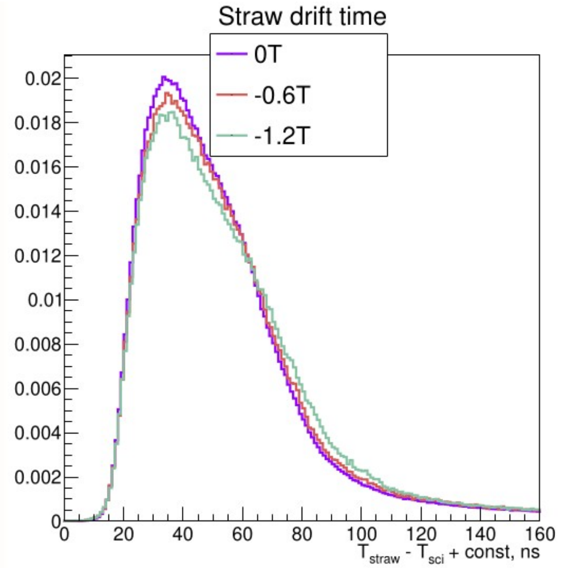
Prototyping activities: CERN 2022 test beams

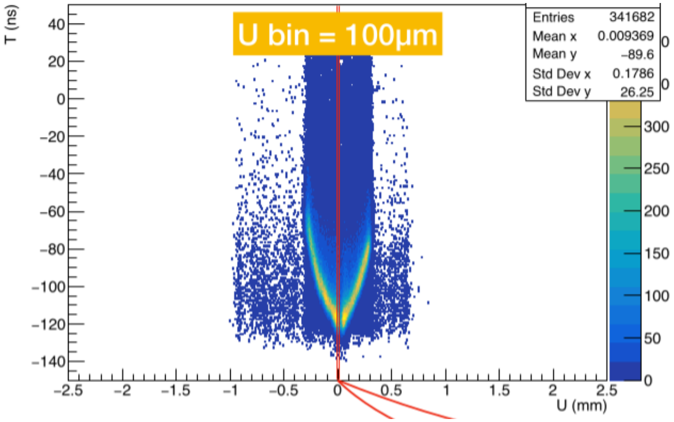
October 2022:
Recovered electronics mounting **TIGER** ASIC

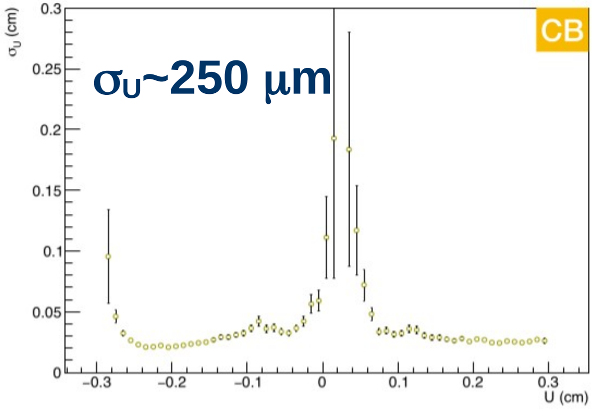
Some Micromega signals sent to STT readout to allow **synchronization**







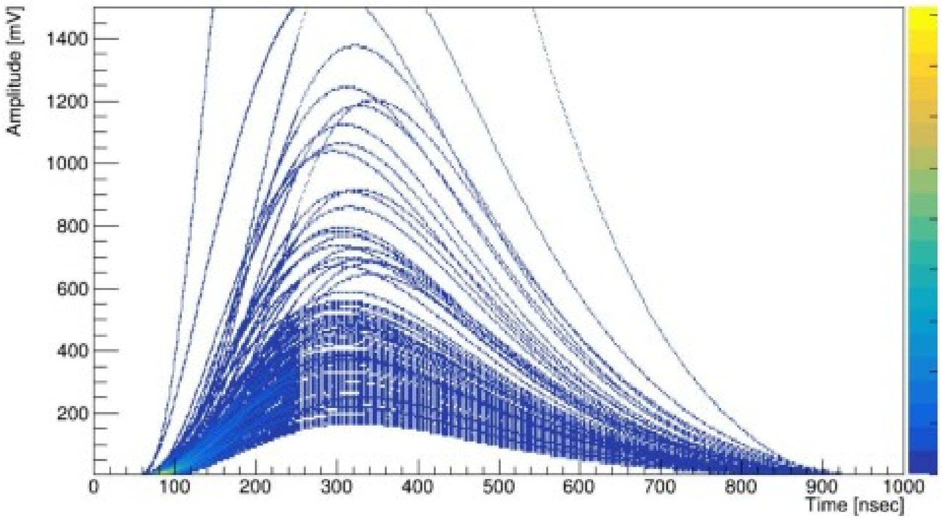




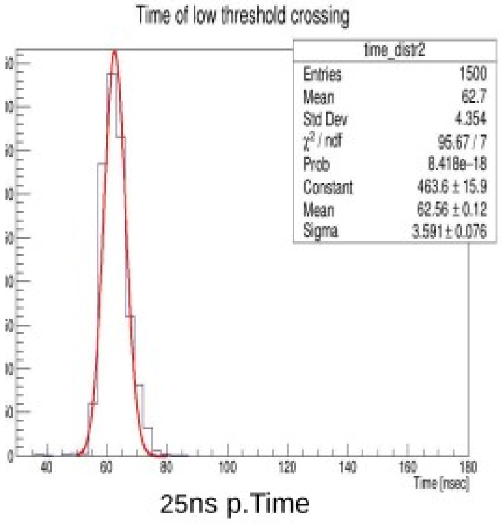
σ_U~250 μm

Prototyping activities: Readout simulation*

Garfield + LTSpice (VMM3)

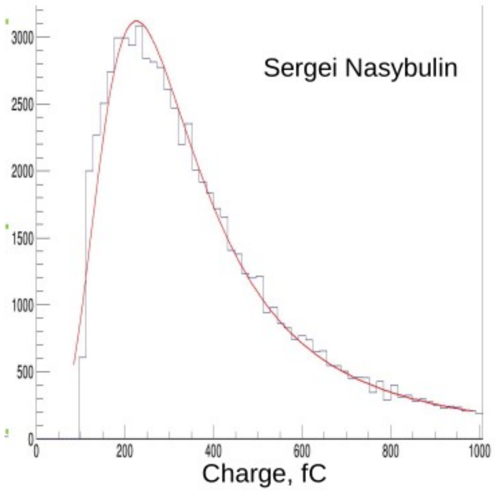


σ_t vs peaking time

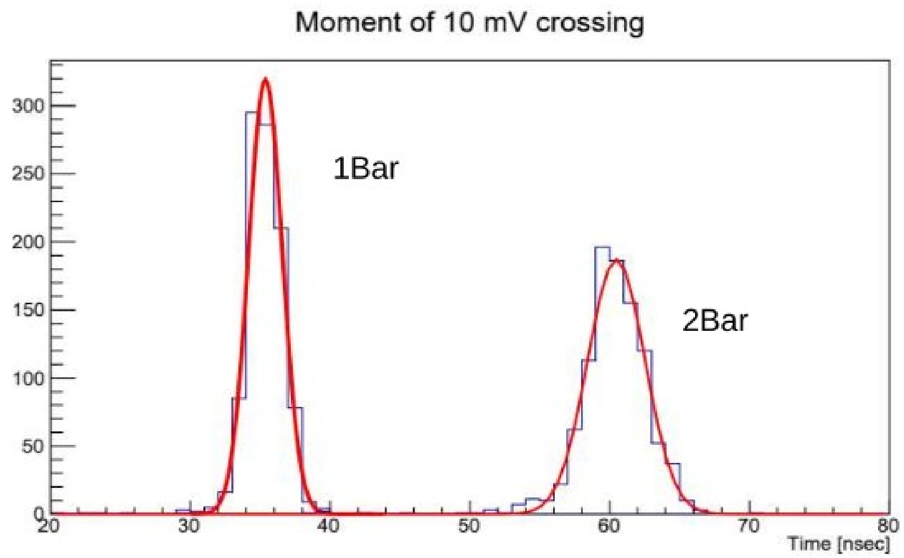


25ns p.Time
10mV THL

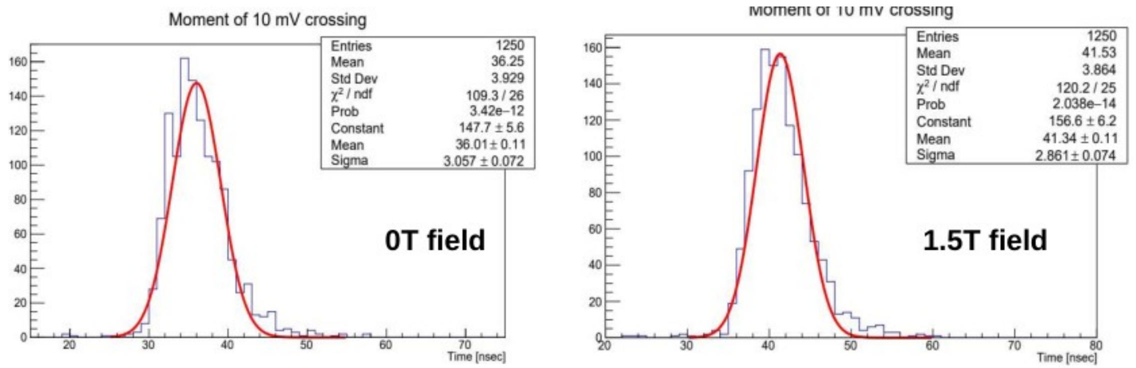
Collected charge (TIGER)



Drift time vs gas pressure



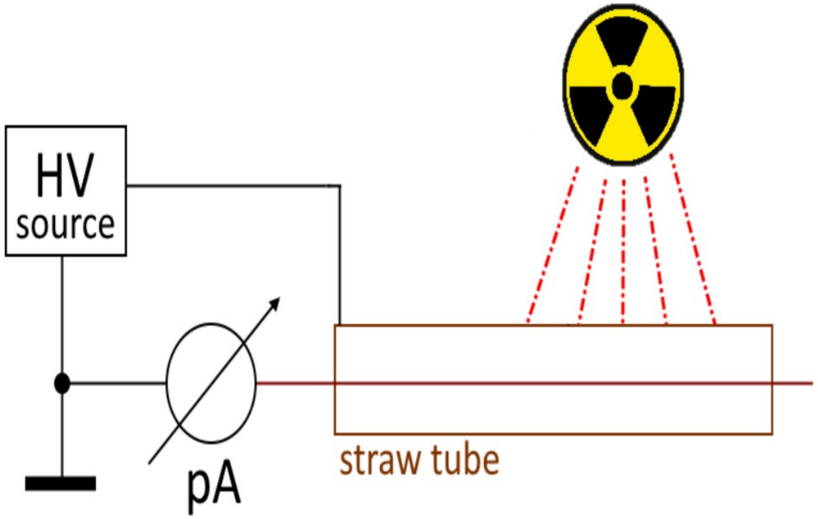
Effect of magnetic field on drift time

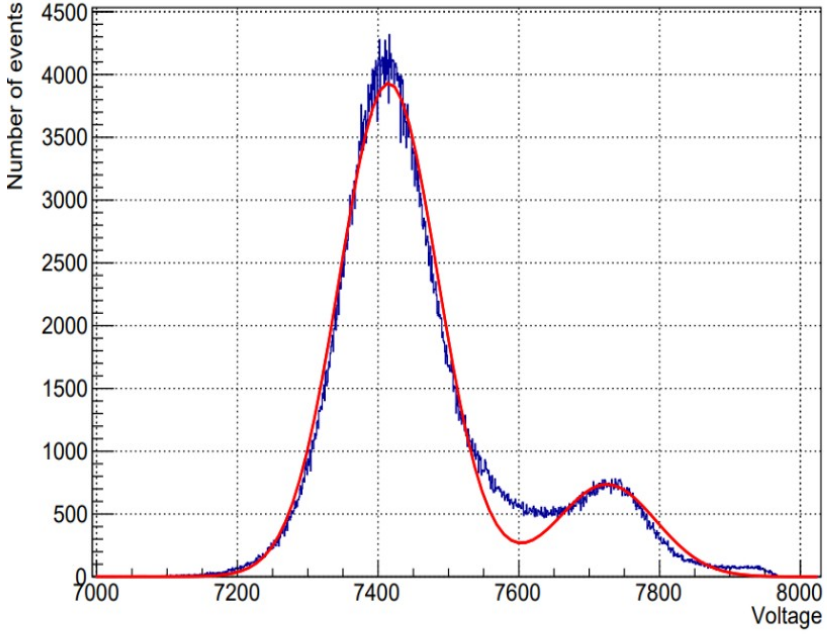


*Most simulations refer to 10 mm straw tubes

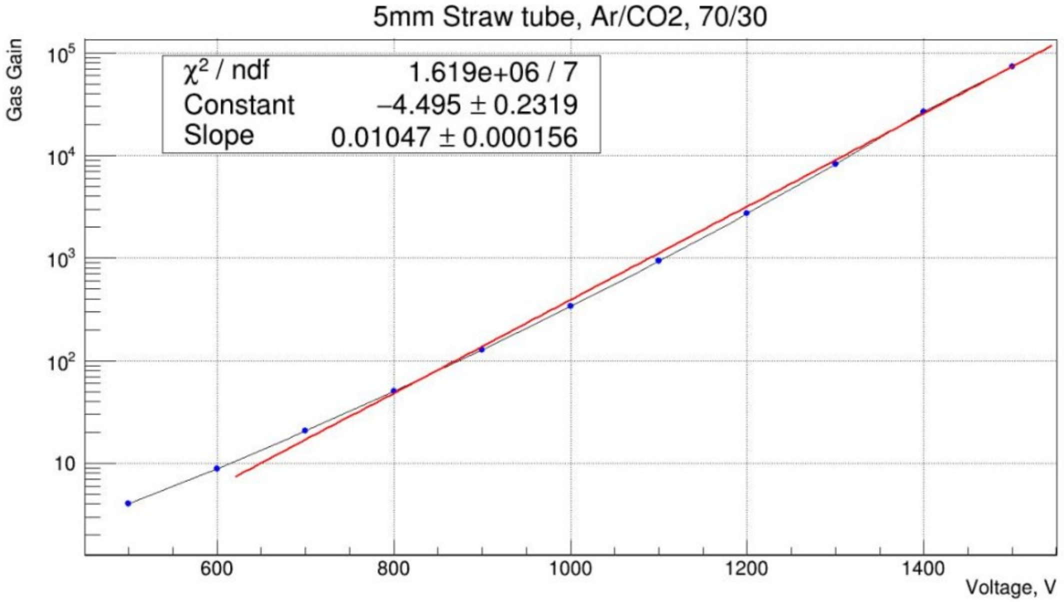
Garfield prediction on gas gain must be checked...

Prototyping activities: gas gain vs HV



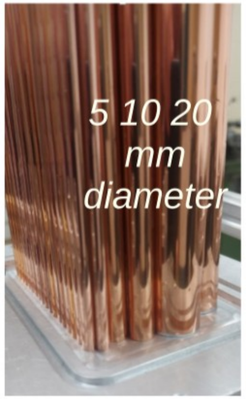


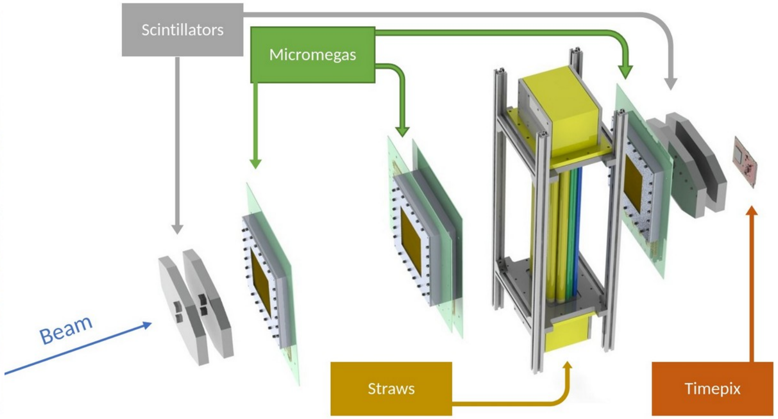
Rate: ~2.7 kHz
Current: ~90 fA

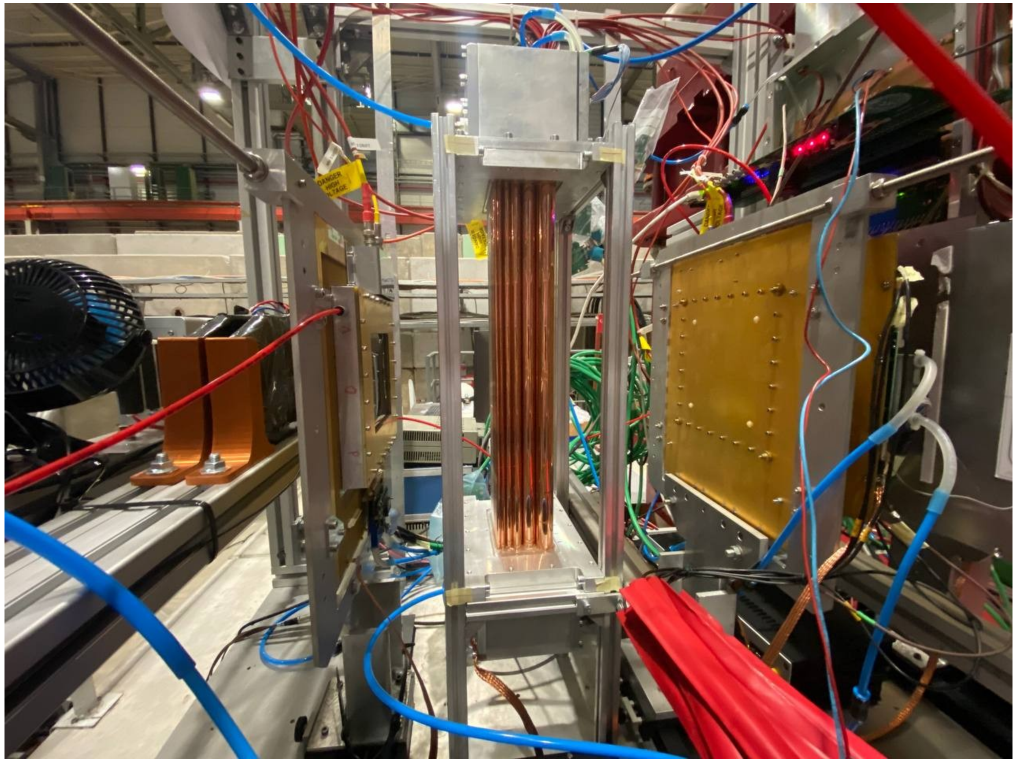


A gain higher than 10^4 is sufficient

Prototyping activities: CERN 2023 test beams



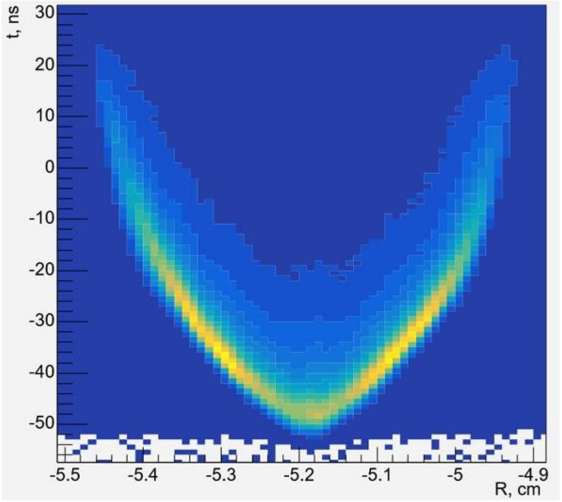


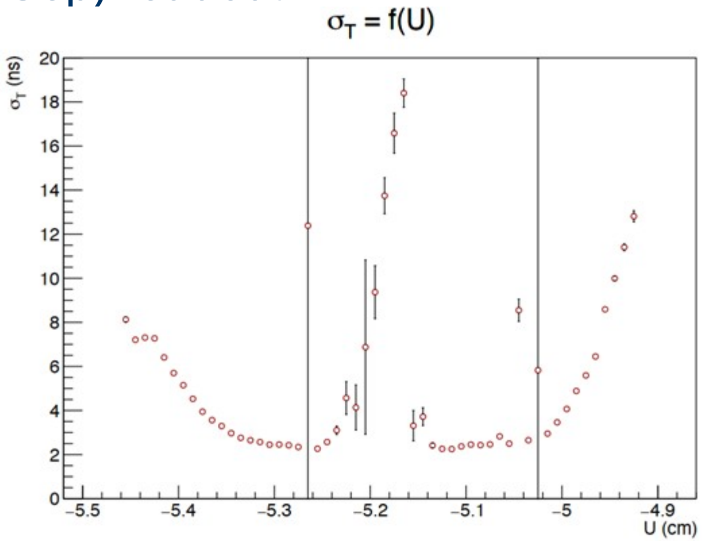


Mixed prototype with two layers of 5mm diameter straw tubes tested at H4 line at Cern

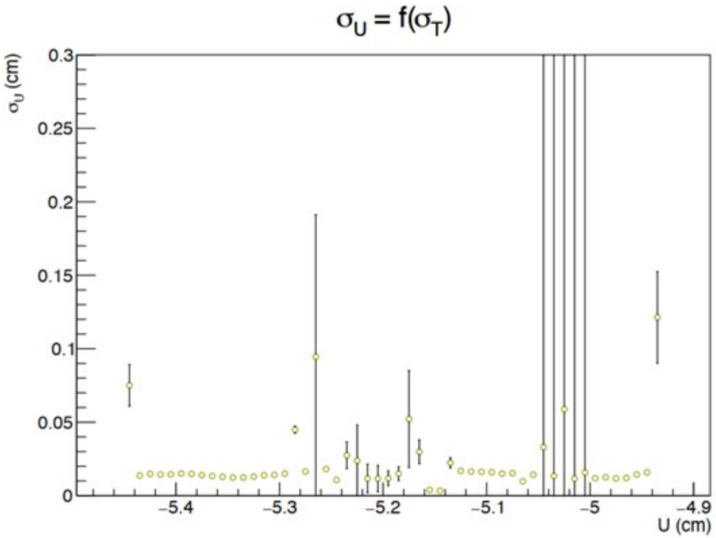
MicroMega position resolution < 70 μm
Time resolution from scintillators ~ 140 ps

TIGER (Apr-Jul) or VMM3 (Jul-Sep) readout



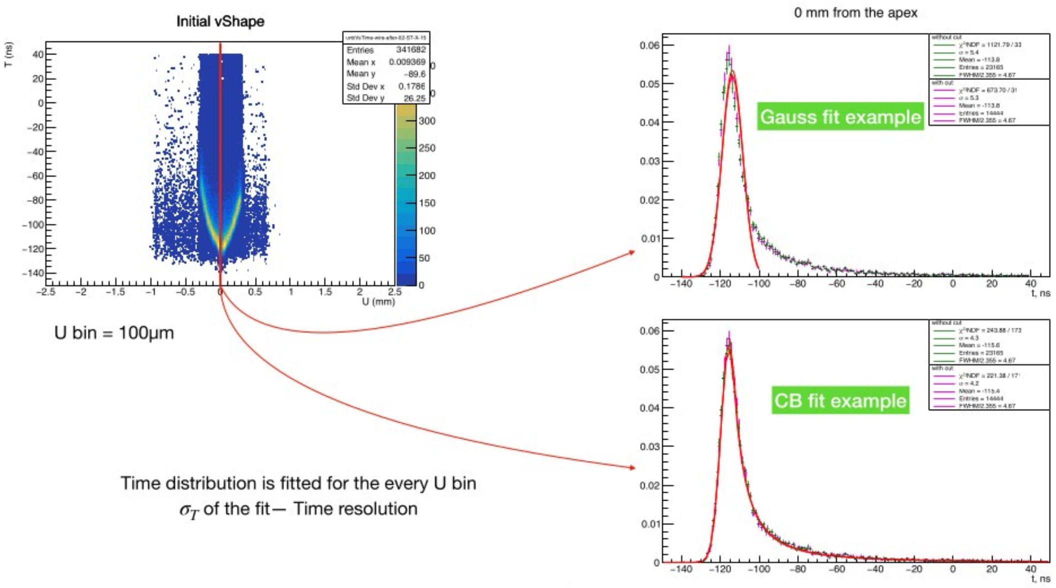


Crystal Ball fit: Best $\sigma(t)$~2 ns



Weighted $\langle\sigma_U\rangle$ = 136 μm

Prototyping activities: CERN 2023 test beams

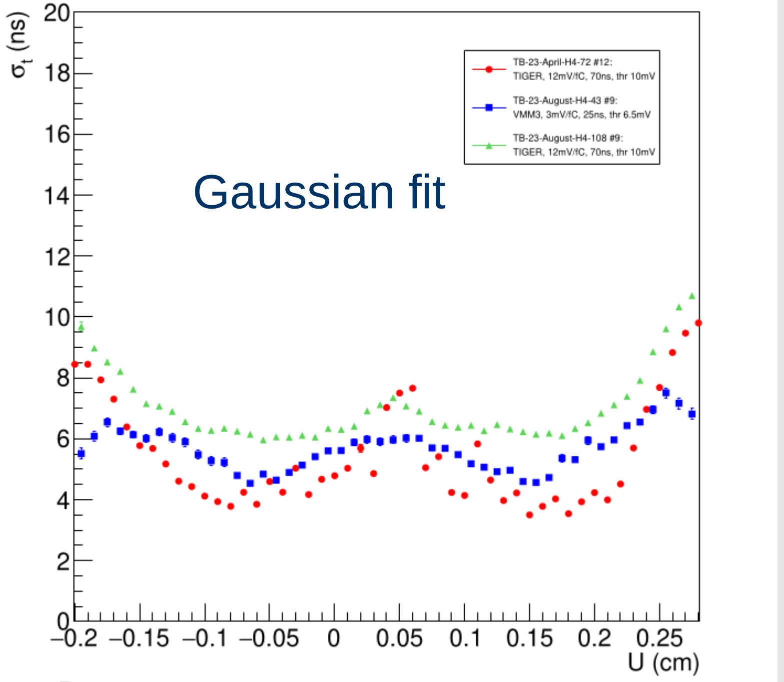


Gauss fit example

CB fit example

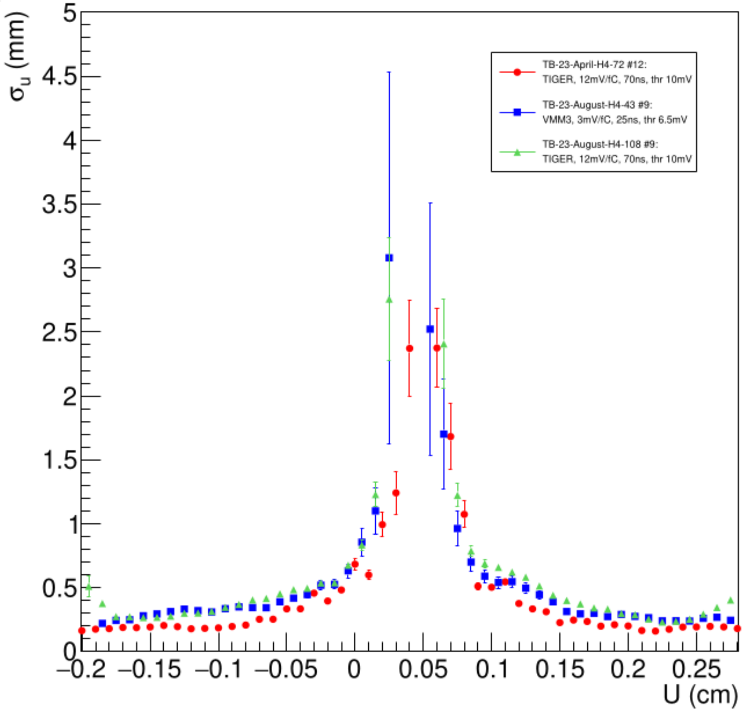
U bin = 100µm

Time distribution is fitted for the every U bin
σ_T of the fit— Time resolution



Gaussian fit

Crystal Ball σ_t fit paramater corresponds to Gaussian fit σ_t-2 ns



TIGER data, April TB: 190 µm

VMM3 data, August TB: 280 µm

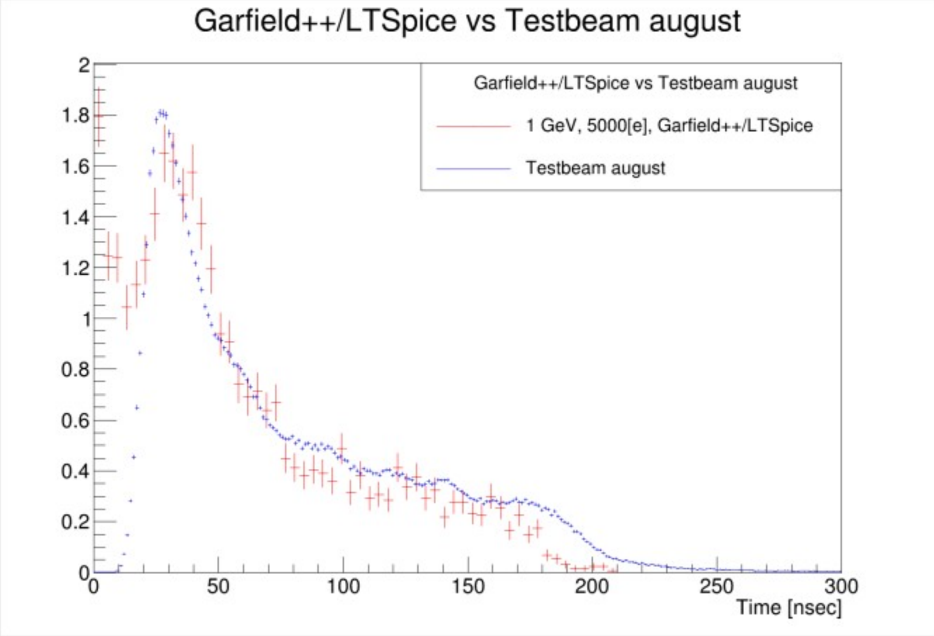
TIGER data, August TB: 300 µm

$$\sigma_u = \sqrt{\sigma_{straw}^2 + \sigma_{track}^2 + \sigma_{bin}^2 + \sigma_{t0}^2 + \sigma_{noise}^2}$$

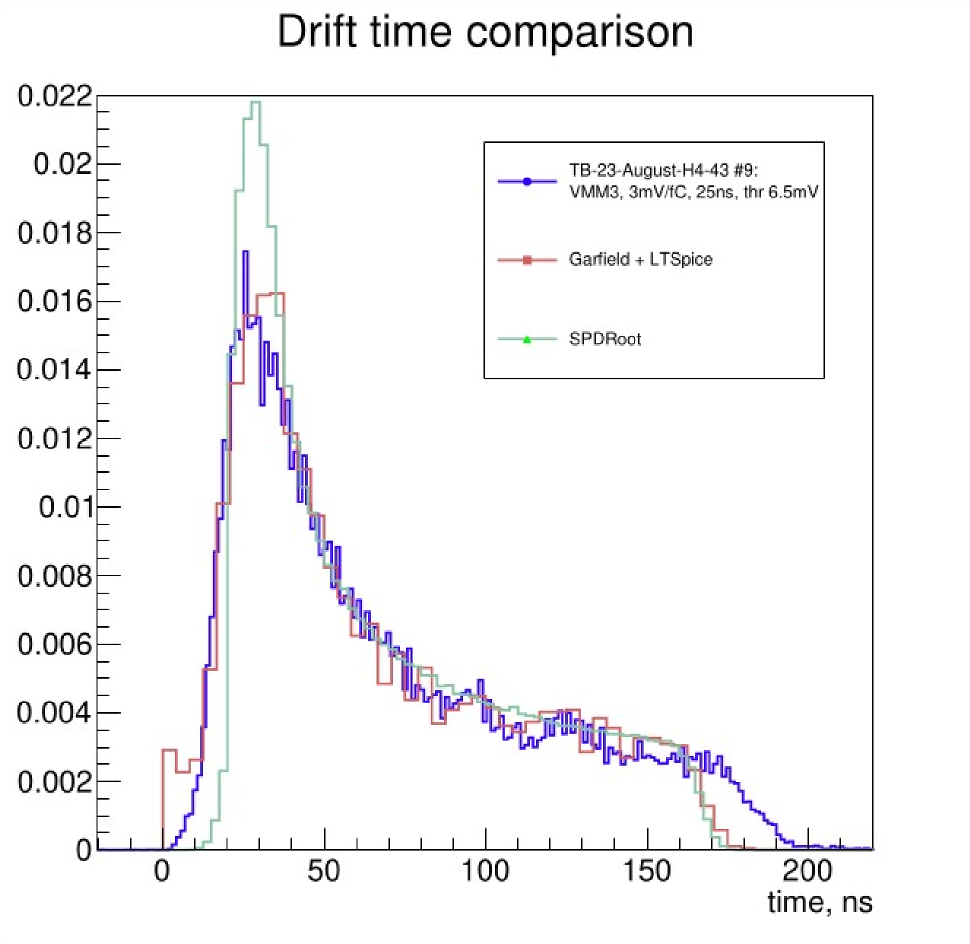
Worse August resolution due to higher noise

Prototyping activities: validation of simulation

TIGER LTSpice model



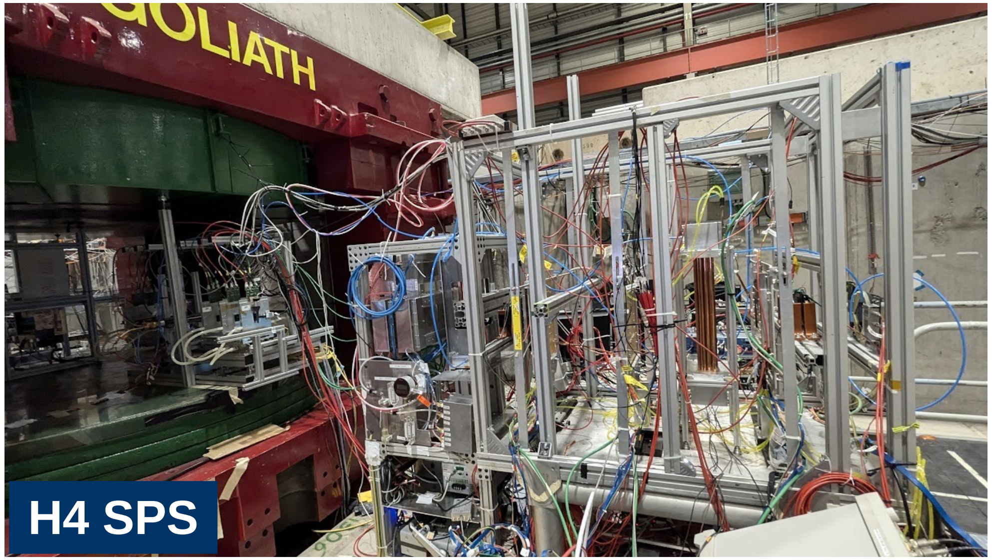
VMM3 LTSpice mode

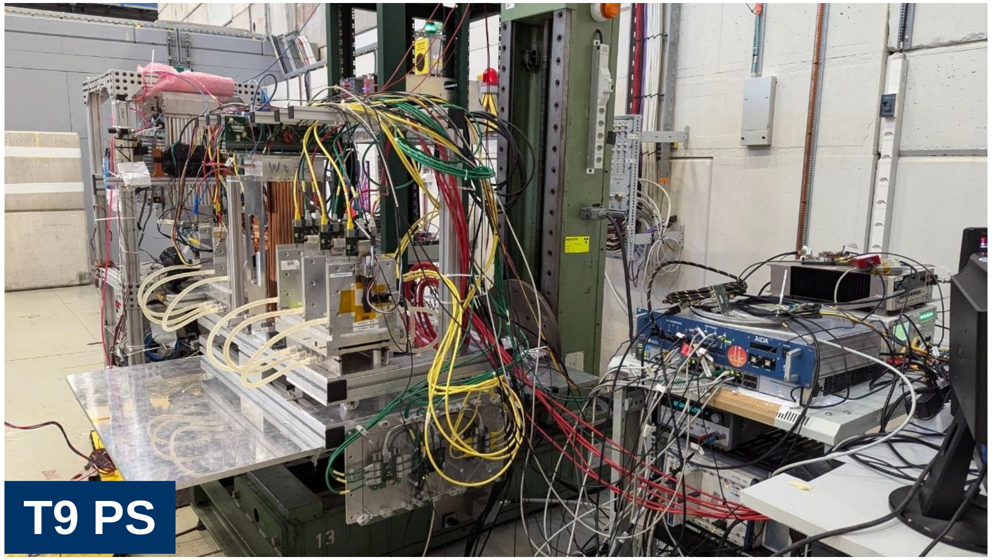


For 10 mm diameter straw tubes
the drift time distribution is well reproduced!

Prototyping activities: CERN 2024 test beams

T9 PS		08/05-15/05				09/10-16/10
H4 SPS	10/04-24/04		26/06-10/07		18/09-02/10	
H8 SPS dump	10/04-26/10					





The UM sMDT telescope
8-layers in x and y directions

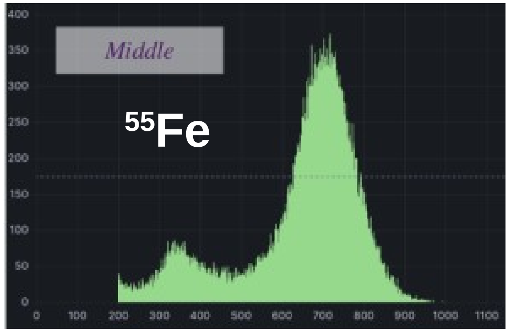
PS setup (low energy hadrons and muons):

- Muon tag (low P runs)
- Precise tracking with AZALEA telescope (6 Mimosa pixel sensors): σ_U~5 μm
- Timing from scintillators: ~200 ps
- Devices Under test:
  - **Mixed prototype** (VMM3 and MDT readout)
  - single straw (20 mm)
  - sMDT drift tubes
  - TimePix4

Analysis in progess…

The Cern 80x120 cm^2 prototype

- ~800 straws from GTU @ JINR using Russian procured double metalization film
- 20 μm Tungsten wire
- ATLAS pins
- No spacers
- Mounting table, support frame and carbon fiber frame from from Pisa
- Single view sealed for gas flow and readout
- 64 (XX)+64(YY) straws wired

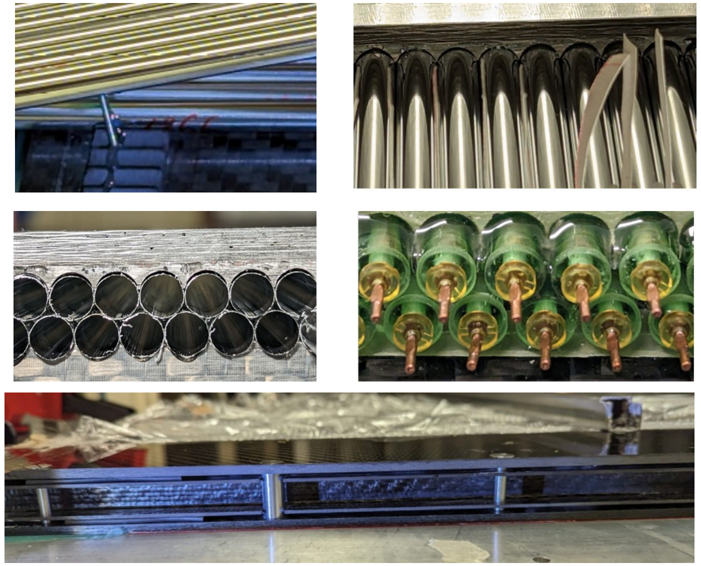


Very successfull assembly!

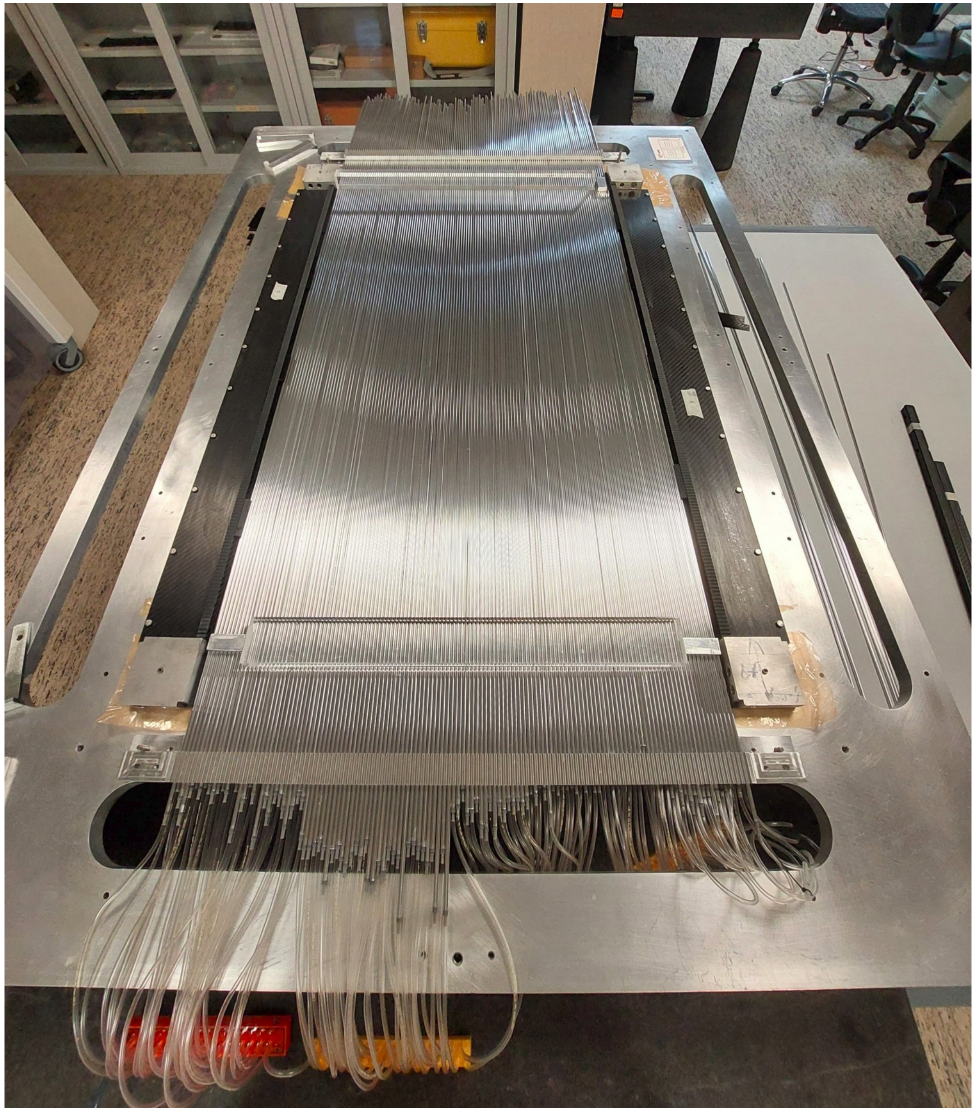
~2 months, ~ 4 people
(many lessons learned)

Full validation of assembly procedure requires to use:

- 3.8 m straws with final film,
- final pins and endplugs,
- spacers



The Pisa 80x120 cm^2 prototype



New features:

- Both views instrumented (not completely)
- New pins and endplugs + spacers available
- Kapton readout board

Assembly status:

Waiting for straw tubes with new Fraunhofer double metalization film

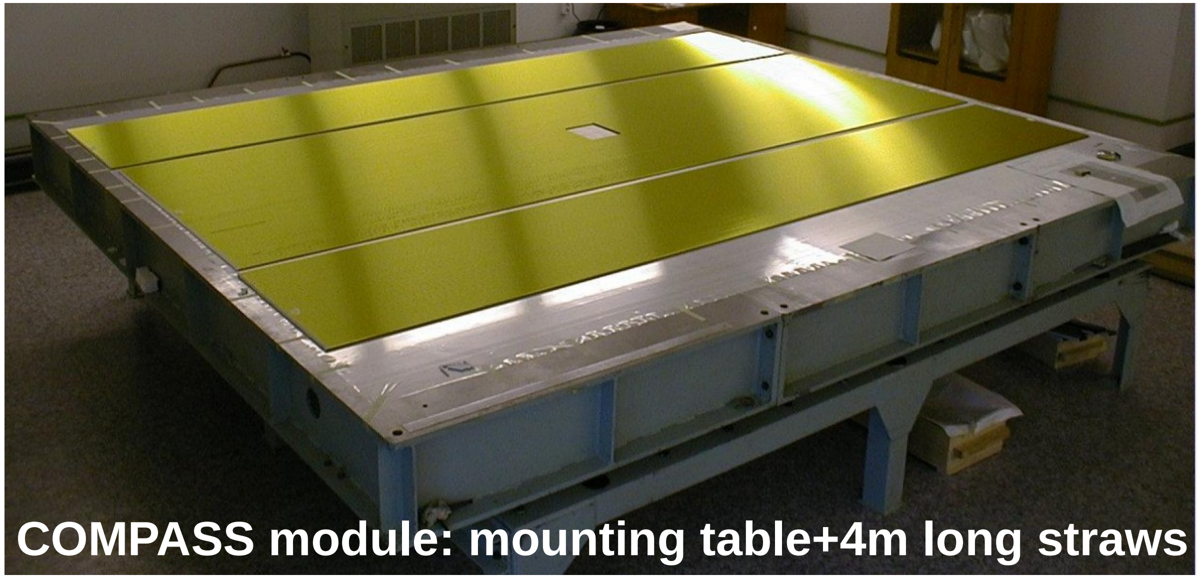
Problems with ultrasonic welding double metalization film at 20 kHz: Titanium head gets consumed after few 5m long straws!

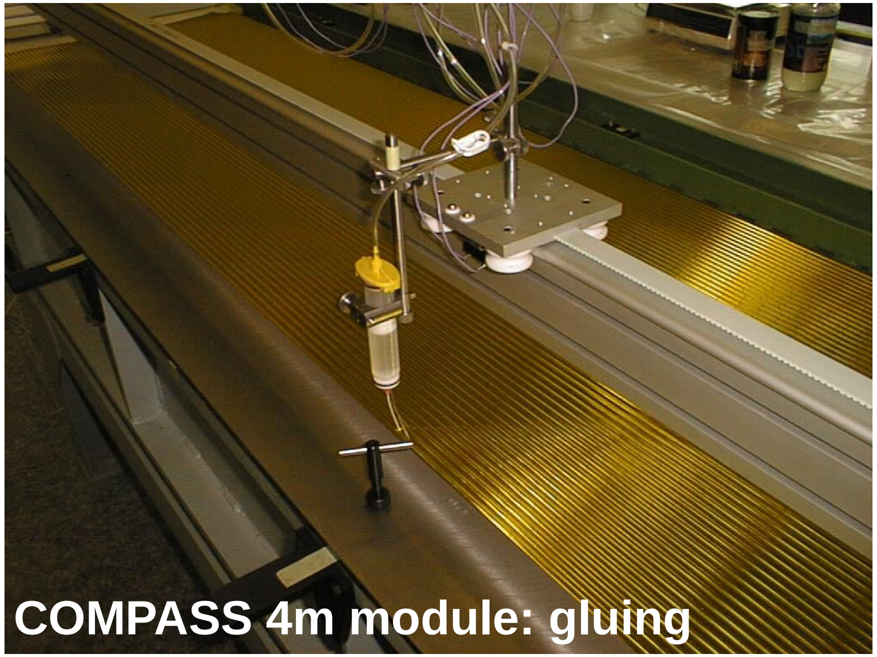
Not observed in the production of the ~800 straws of Cern prototype using 40 kHz welding head

New line with 60kHz in construction,
Al oxide removal with laser or acetilene under investigation.

Assembly completion expected by March 2025 (see Fabrizio’s presentation)

The full scale prototype (320x380 cm^2)


COMPASS module: mounting table+4m long straws


COMPASS 4m module: gluing

New features:

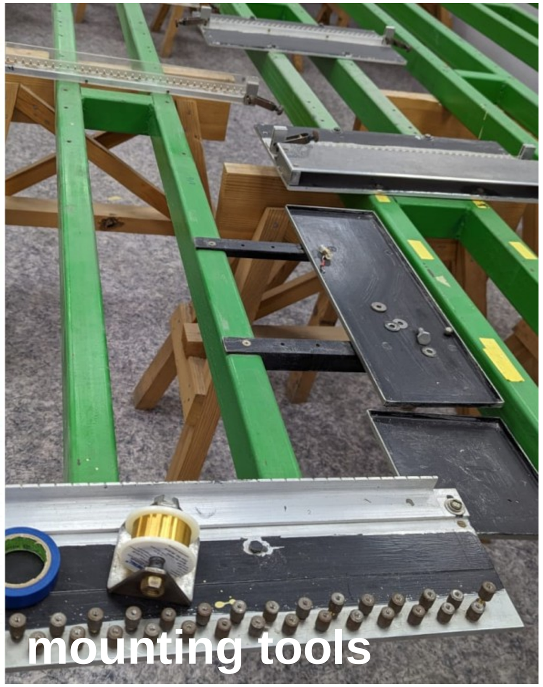
- Both views completely instrumented
- New pins and endplugs + spacers available
- Longest straws

Same assembly tool used for COMPASS

Waiting for straw tubes with new Fraunhofer double metalization film

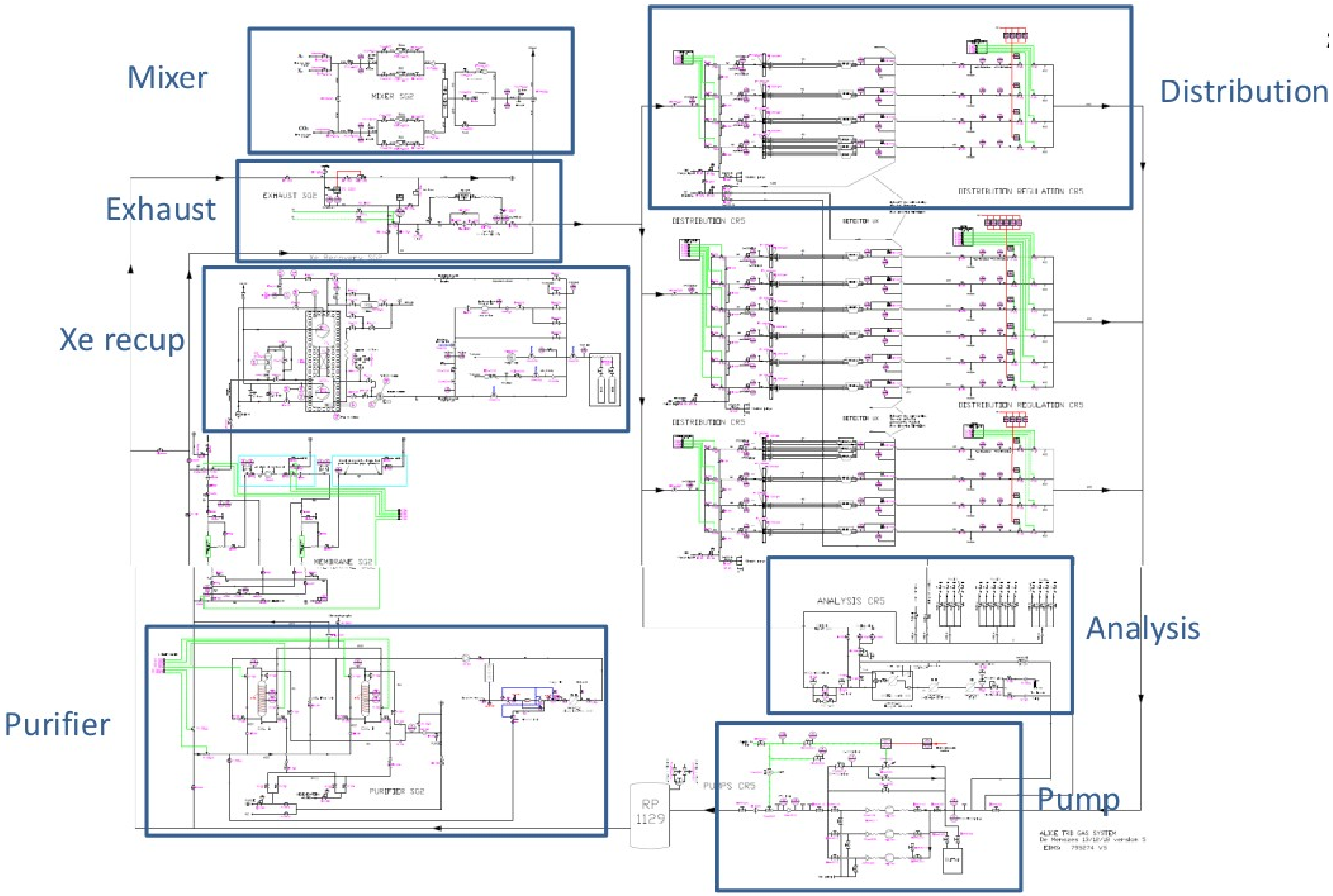
Assembly at JINR expected to be completed by May 2025 (+delays in straw tubes production)


COMPASS


mounting tools

Gas system

Gas system



Complete gas system for STT based on functional modules from ALICE -TRD

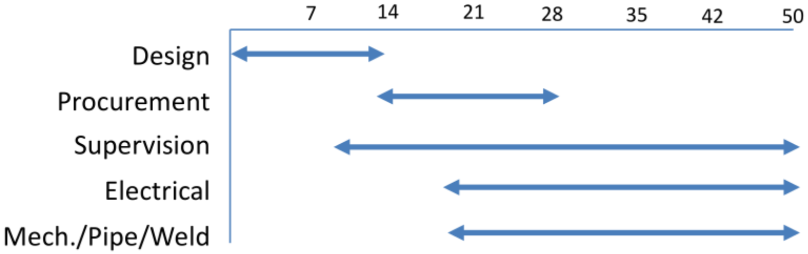
Design similar to other CERN experiments (ATLAS,ALICE)

Total detector volume: 14 m^3

Ar/CO$_2$: 38 modules
volume 5.7 m^3
7 distribution circuits
(one for 6 detector modules)

Xe/CO$_2$: 48 modules
volume 8 m^3
5 nl/min/module
Total Xe/CO2 flow:
~ 15 nm^3/h
per detector module ~ 300 nl/h
8 distribution circuits
(each for 6 detector modules)
flow per circuit ~ 1.9 nm^3/h

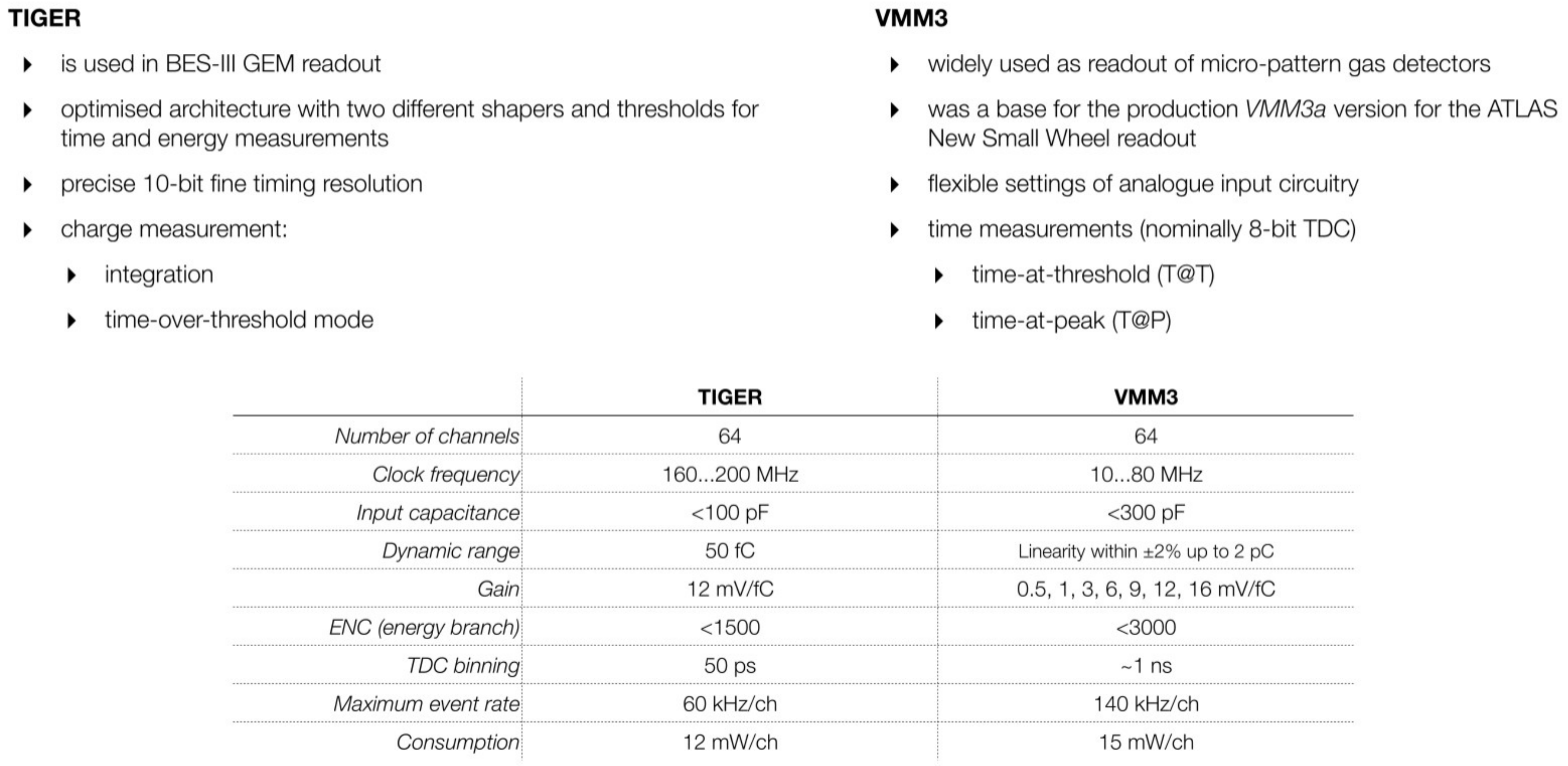
Delivery time:
~50 weeks



Cost at 2021: ~500 kCHF

Readout electronics

Tiger vs VMM3



TIGER

- is used in BES-III GEM readout
- optimised architecture with two different shapers and thresholds for time and energy measurements
- precise 10-bit fine timing resolution
- charge measurement:
  - integration
  - time-over-threshold mode

VMM3

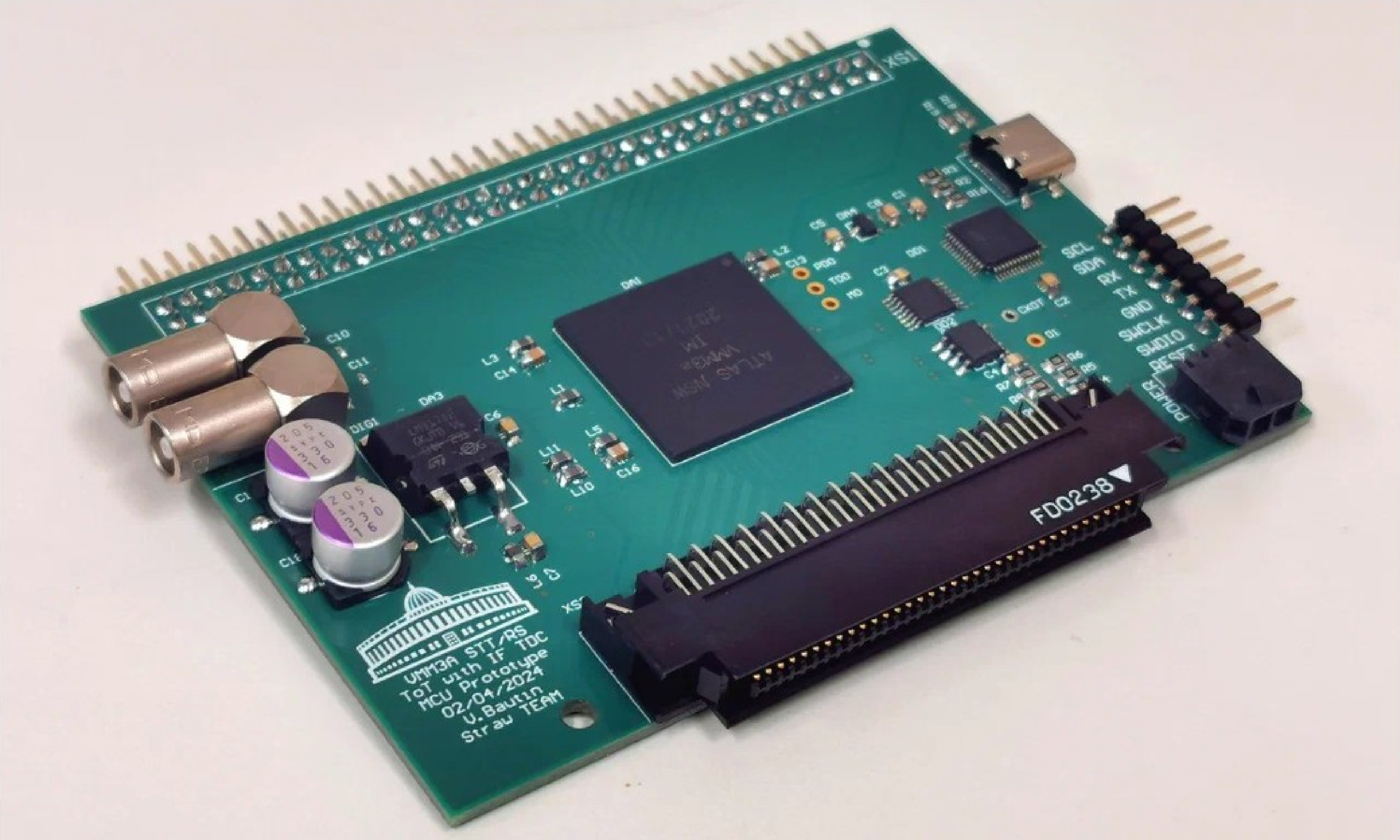
- widely used as readout of micro-pattern gas detectors
- was a base for the production *VMM3a* version for the ATLAS New Small Wheel readout
- flexible settings of analogue input circuitry
- time measurements (nominally 8-bit TDC)
  - time-at-threshold (T@T)
  - time-at-peak (T@P)

	TIGER	VMM3
Number of channels	64	64
Clock frequency	160...200 MHz	10...80 MHz
Input capacitance	<100 pF	<300 pF
Dynamic range	50 fC	Linearity within ±2% up to 2 pC
Gain	12 mV/fC	0.5, 1, 3, 6, 9, 12, 16 mV/fC
ENC (energy branch)	<1500	<3000
TDC binning	50 ps	~1 ns
Maximum event rate	60 kHz/ch	140 kHz/ch
Consumption	12 mW/ch	15 mW/ch

Both circuits need to be updated: **potential cost and schedule issues**
Backup solution: VMM3a saturation issue, channel latching problem and ADC resolution can be bypassed using the **external ADC mode**

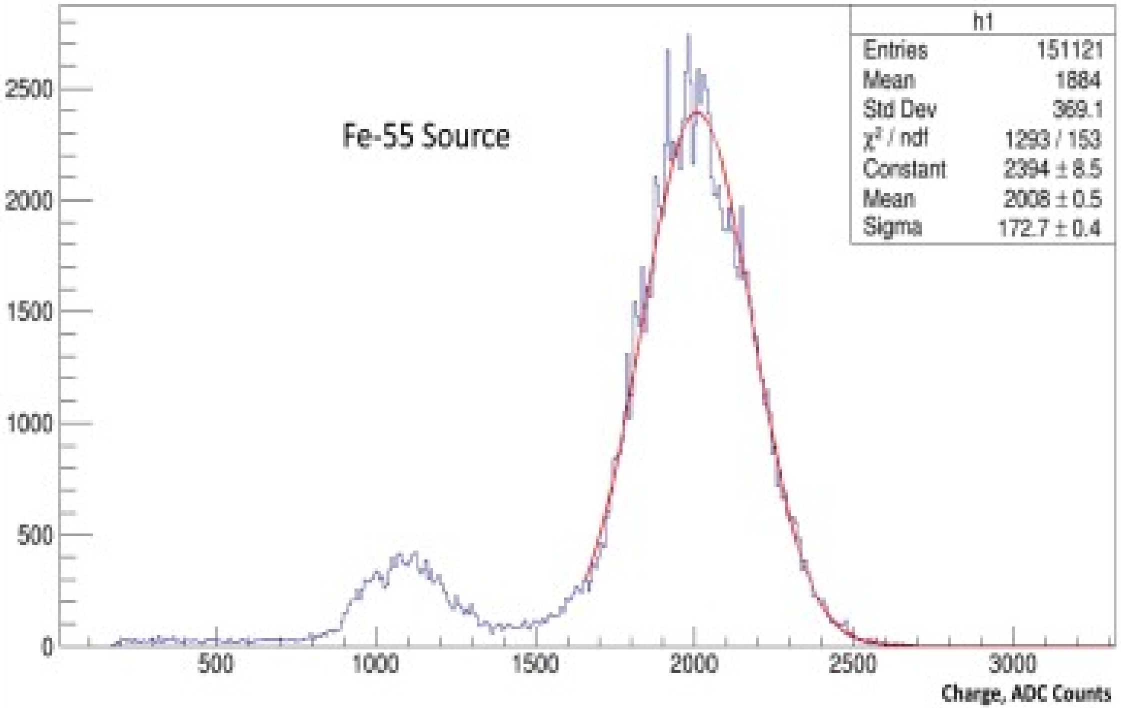
VMM3 with external ADC

A **new FEB** based on **VMM3A** has been developed and assembled. It uses «new» external ADC Mode with **12-bit 4MSPS ADC**. First results on next slides. Testing is ongoing.

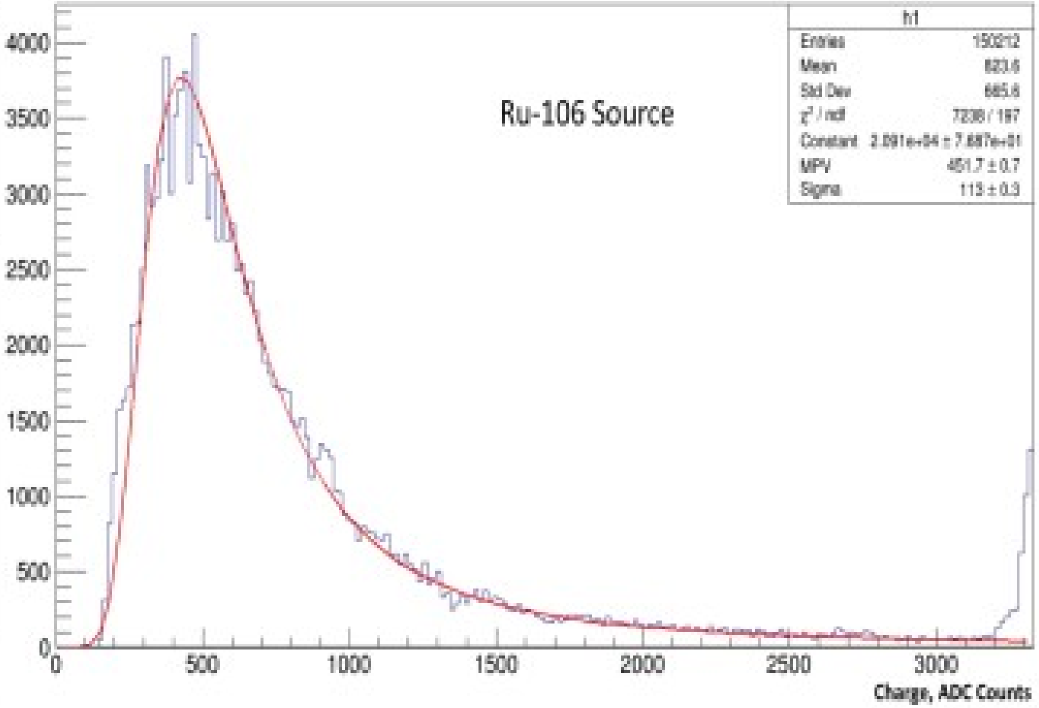


Readout electronics

VMM3/3A has well known bad **ADC/TDC** perfomance in standard **Continuous Mode**

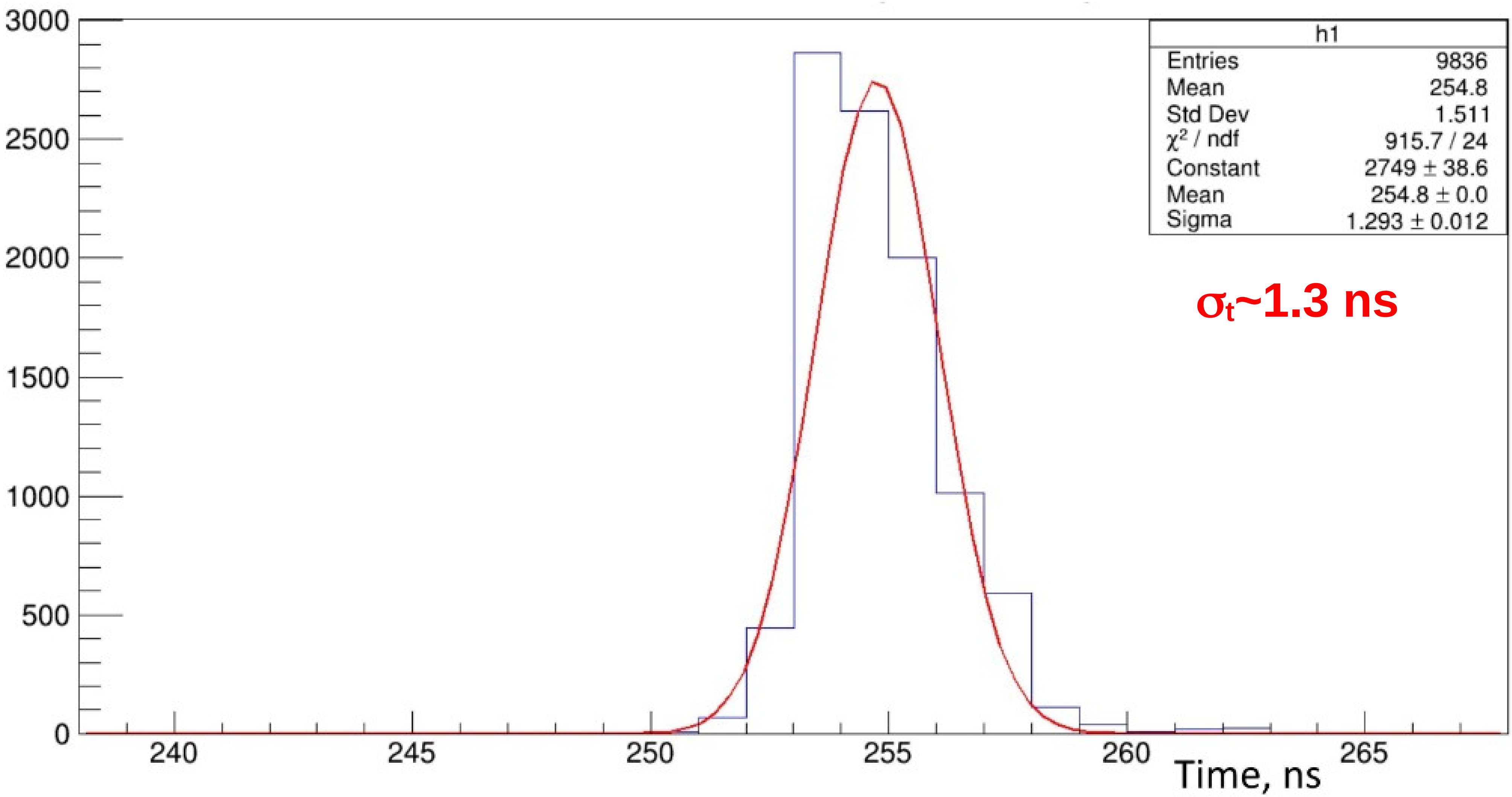


Fe55 Spectra, external ADC
Much better resolution



Ru106 Spectra, external ADC
Much better resolution

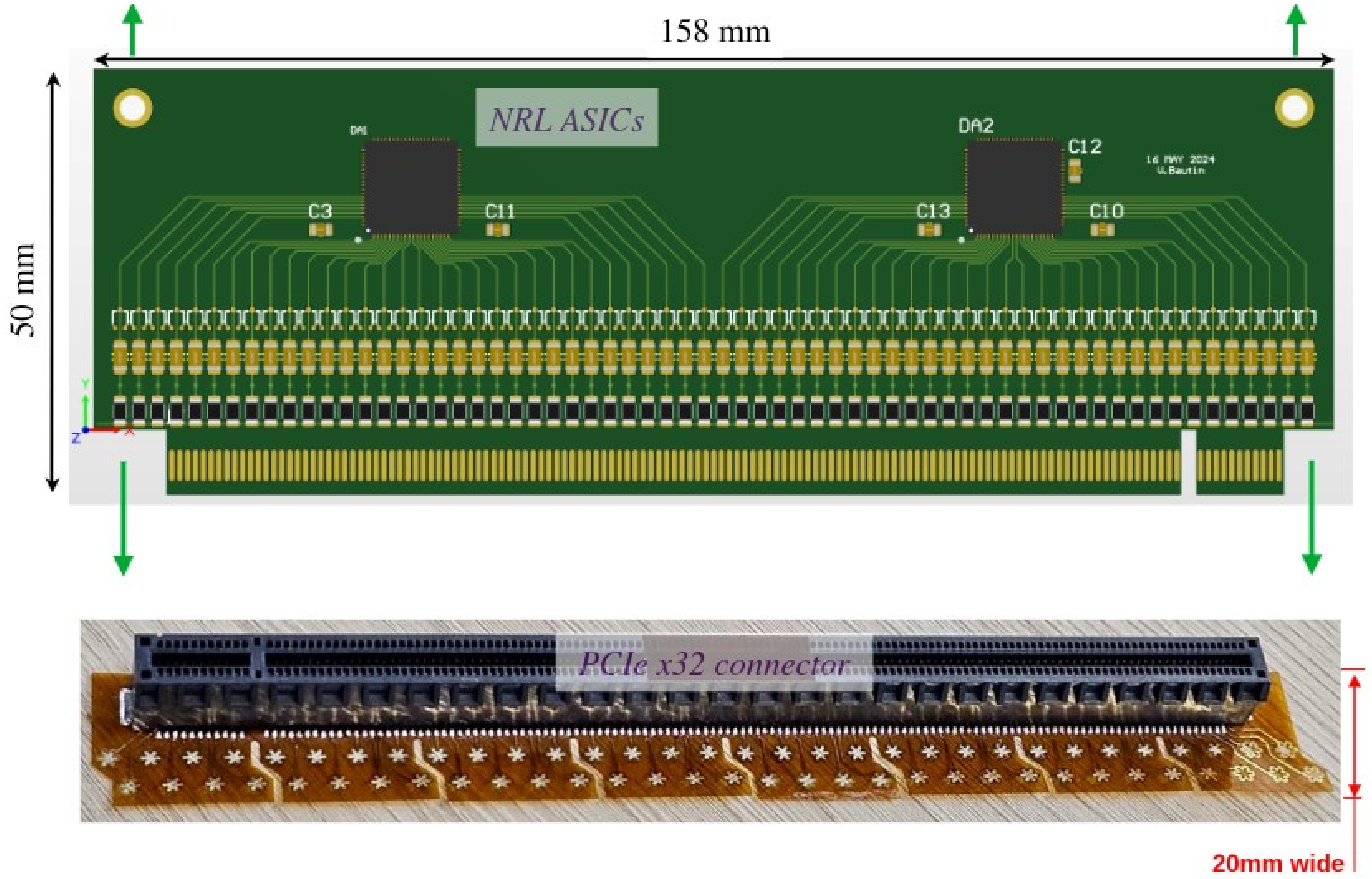
Readout electronics



σ_t~1.3 ns

Time measurements, external ADC
Much better resolution

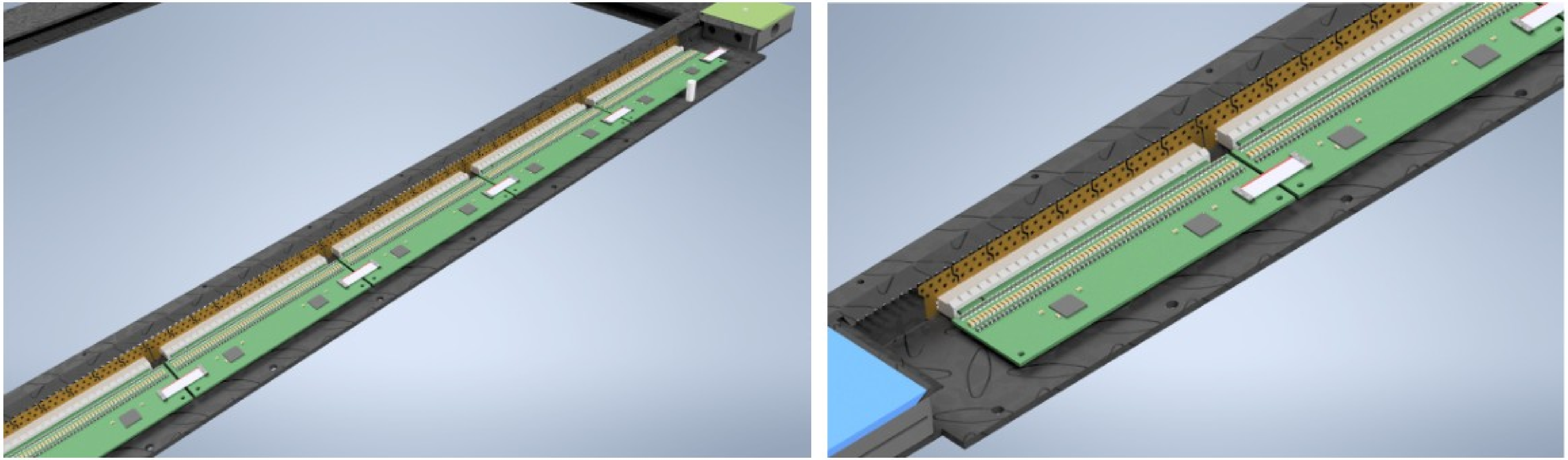
FEE boards and connectors

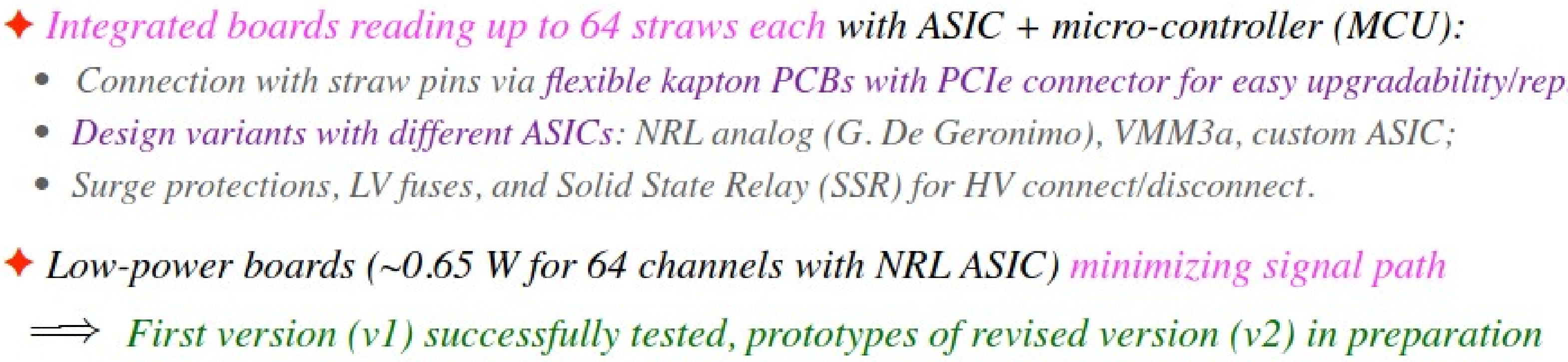


Revised design (v2) of the readout board and of the connecting flexible kapton board

Kapton boards design already finalized, some will be produced and installed in Pisa prototype

FEE boards inside the frame

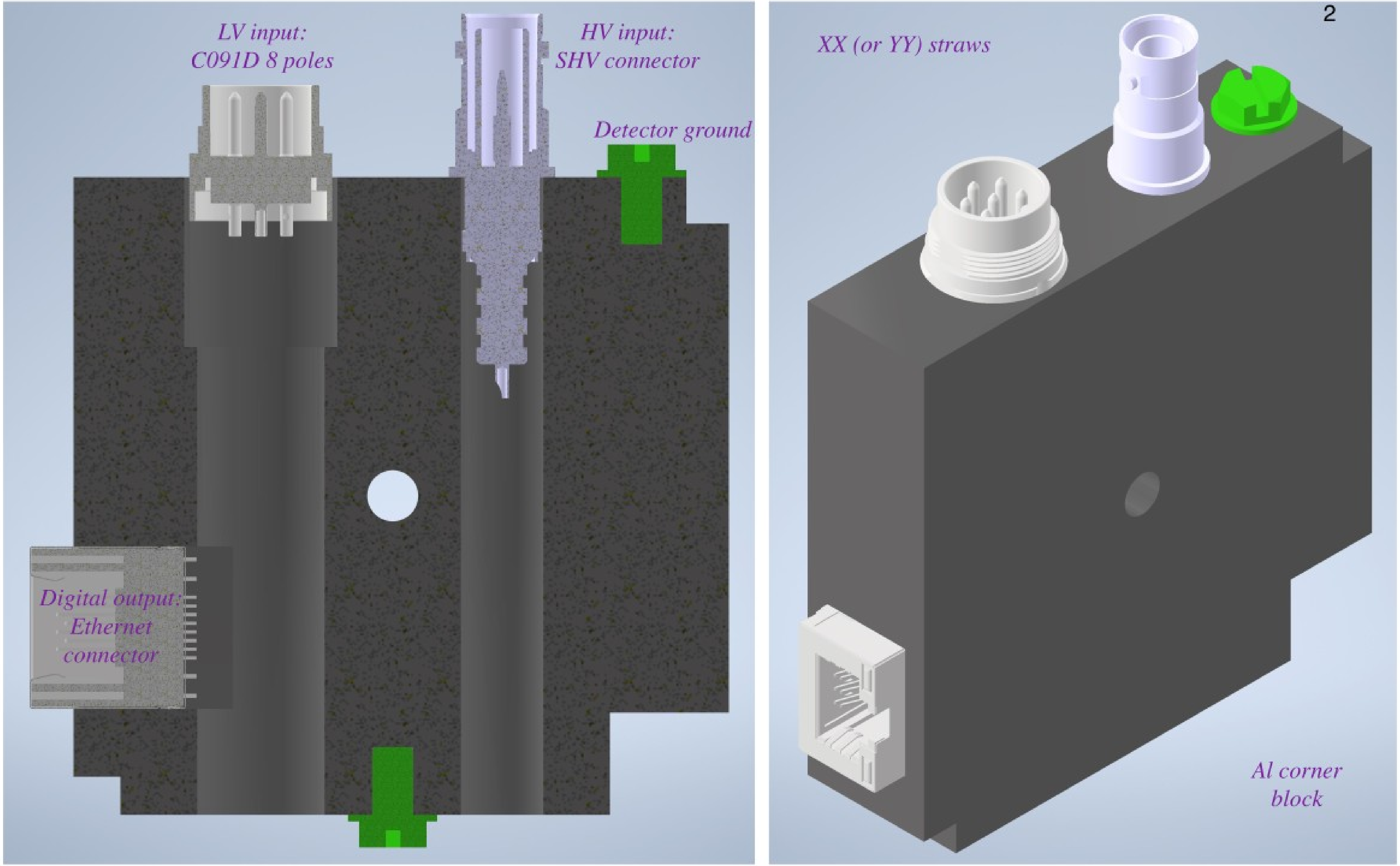




- ✦ Integrated boards reading up to 64 straws each with ASIC + micro-controller (MCU):
  - Connection with straw pins via flexible kapton PCBs with PCIe connector for easy upgradability/replacement;
  - Design variants with different ASICs: NRL analog (G. De Geronimo), VMM3a, custom ASIC;
  - Surge protections, LV fuses, and Solid State Relay (SSR) for HV connect/disconnect.
- ✦ Low-power boards (~0.65 W for 64 channels with NRL ASIC) minimizing signal path

⟹ First version (v1) successfully tested, prototypes of revised version (v2) in preparation

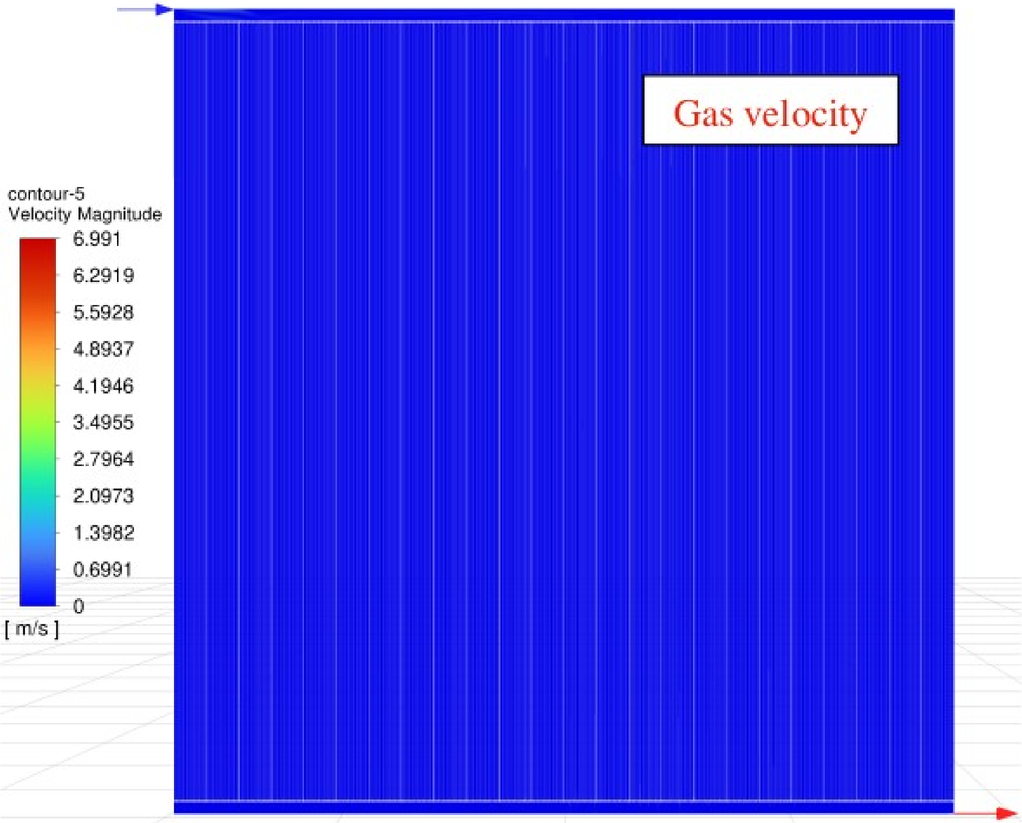
Corner blocks

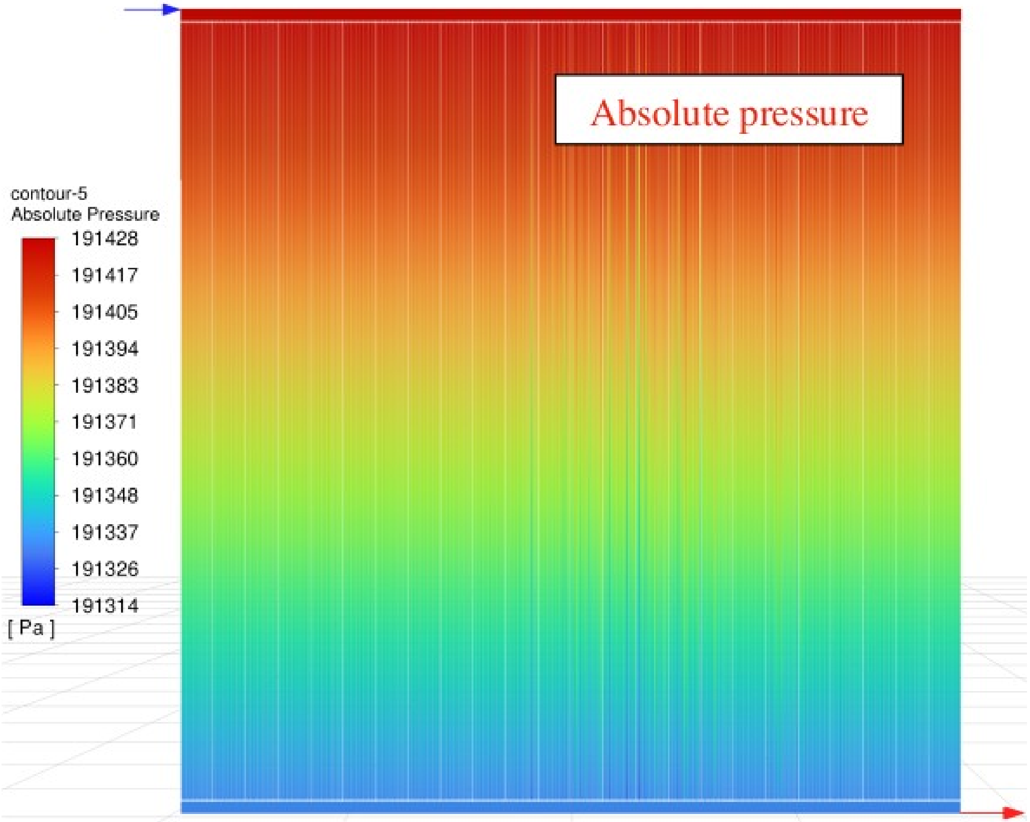


Details of the electrical input/output connections of STT modules (independent for XX and YY layers)

Gas flow and cooling

Gas flow simulation

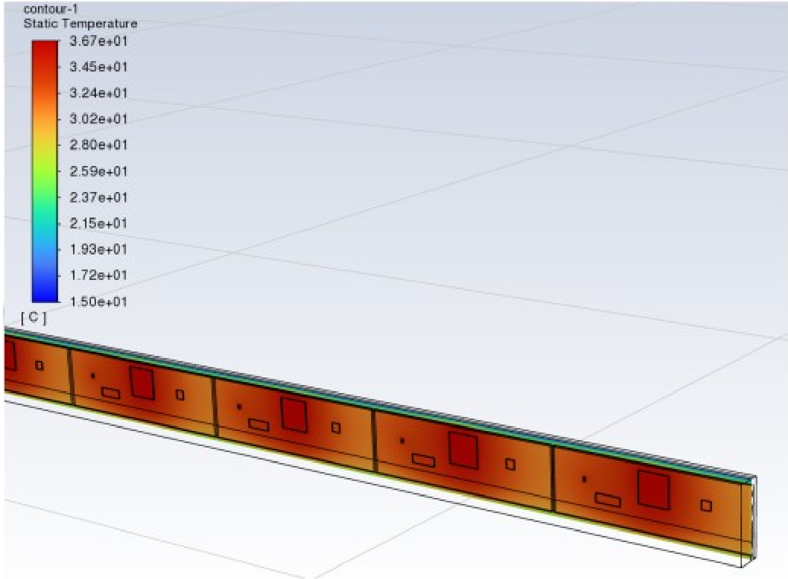


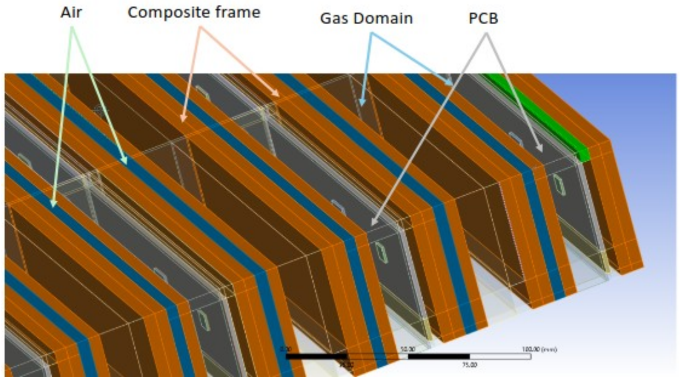


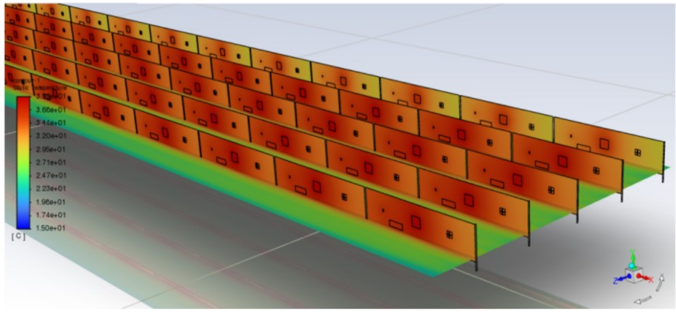
- *Study of gas flow within a 4m STT module to verify uniformity and inlet/outlet design;*
- *Check local gas velocity and pressure inside manifolds/straws for both standard and flipped modules*

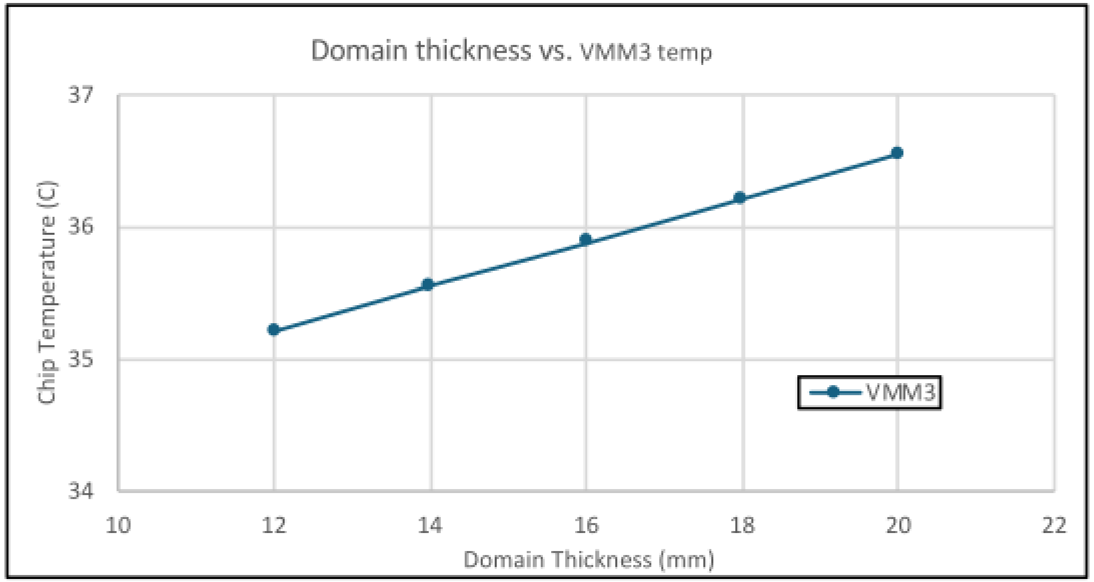
$\Longrightarrow$ *We can achieve steady state with uniform gas flow across the 4m STT module*

Thermal simulation









Max chip temperature well below limit: < 37^{o}

Supermodule simulation in progress

Validation with full scale prototype

Resource needs

Straws production

Number of straws	219,334
Total straw length (km)	700
Straw outer diameter (mm)	5
Average straw length (m)	3.19
Maximal straw length (m)	3.75
Total straw film area (m^2)	10,990
Total straw internal volume (m^3)	14
Total detector length (mm)	2,998

Production rate for **5 m** long straws: **~70/day**

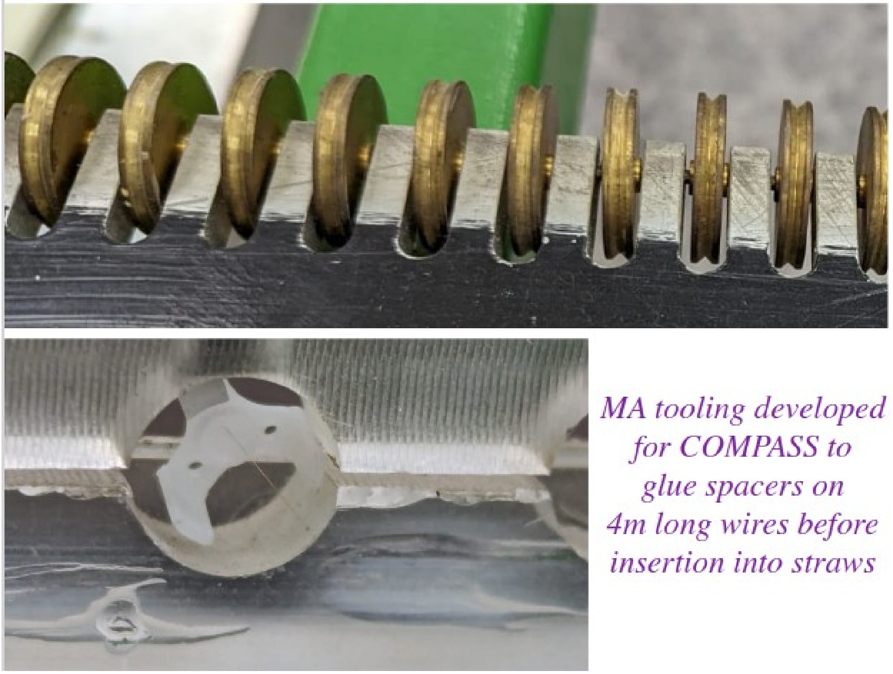
Length produced in 1 year (200 days) by a 5m Straw Production Site:
5 m/straw x 70 straws/day × 200 days = **70 km/year/PS**
(**4 people per single production line** + quality control)

Number of production sites to complete the production in 3 years:
700 km/70 km/3 years= **3.3 sites**

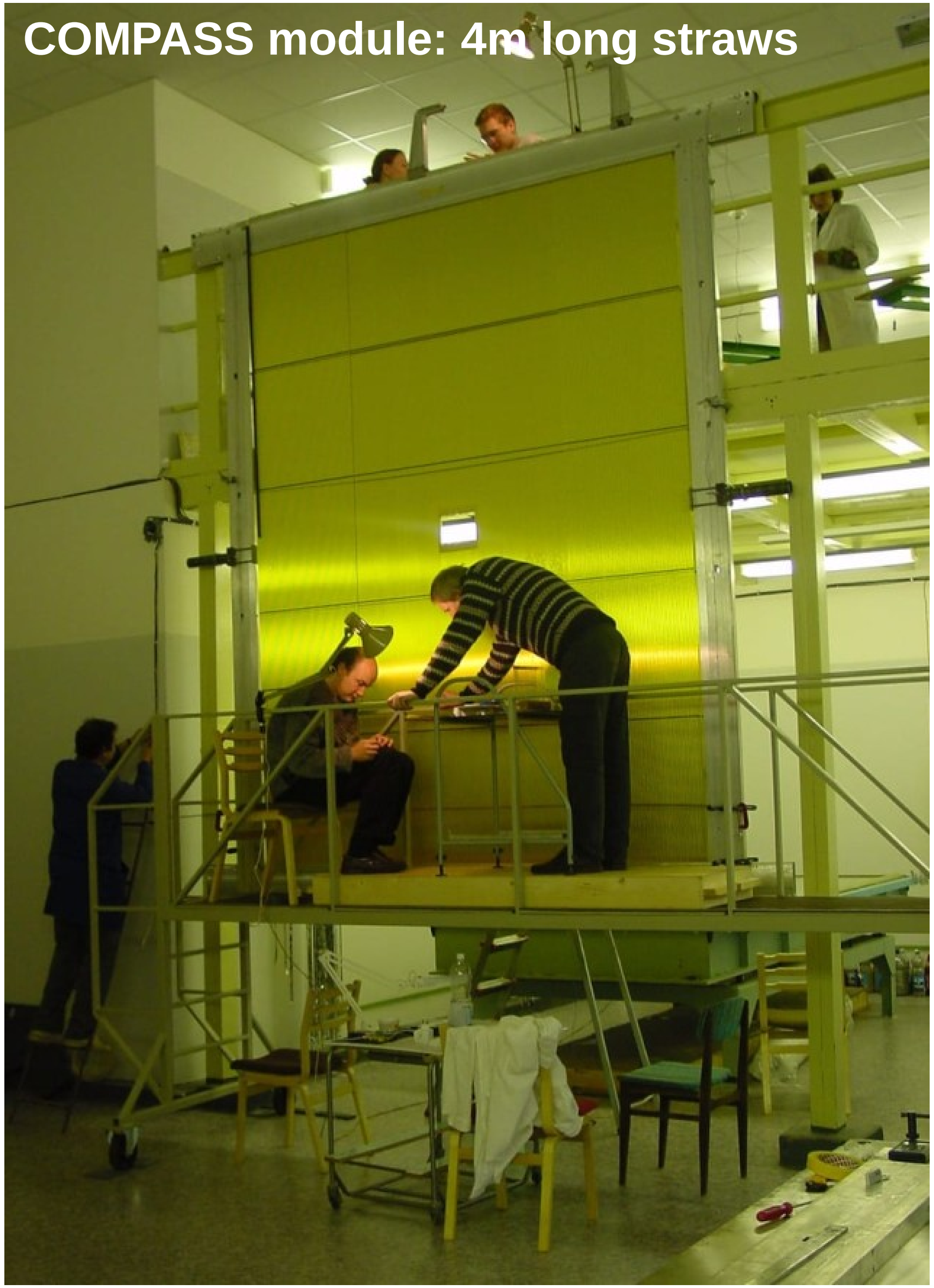
Available Production sites:
1 JINR (5m) (?) + 2 GTU (Tbilisi, 2×5m)+0.5 GTU (JINR, 2m)

In preparation at Almaty (Kazakhstan): 5m + 12 m (2025?)

Module Assembly



MA tooling developed for COMPASS to glue spacers on 4m long wires before insertion into straws



COMPASS module: 4m long straws

7 people per Module Assembly line (including QC tests)

Expected average production time: **3 months / module**

86 modules → 22 years x MA line

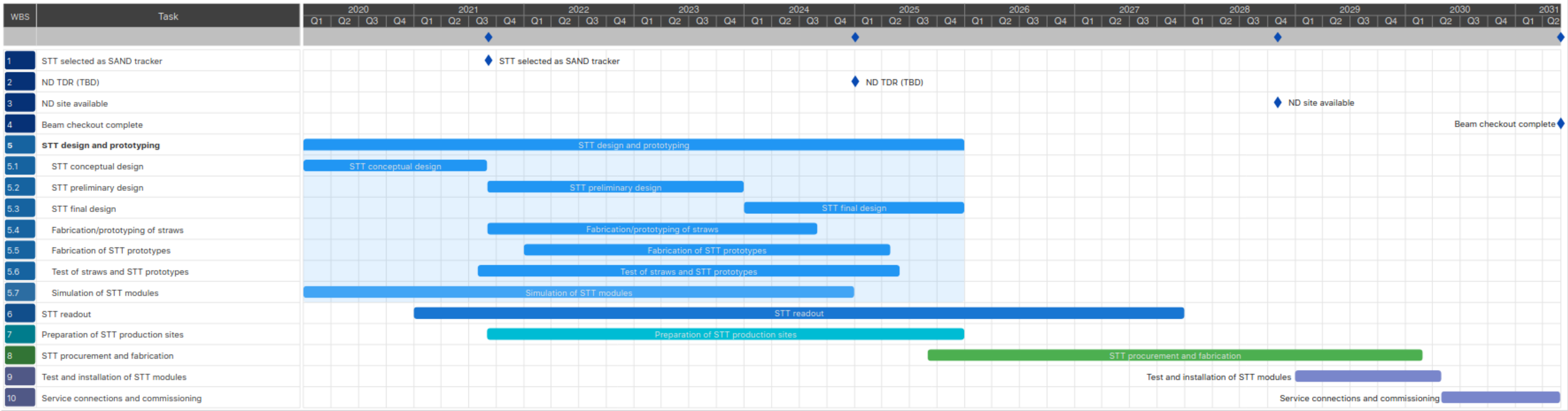
Need **6 MA lines** to have 86 modules in **3.5 years**
(starting in Jan 2026, ready by July 2029)

1 MA operational: JINR
4 MA under construction: 3 Kazakhstan, 1 Georgia
5 MA planned: 3 India, 1 USA*, 1 Italy

** Proposals submitted to NSF and DOE by South Carolina and Duke University. The answer is expected by summer 2025*

Current STT schedule

Tentative Schedule



WBS	Task
1	STT selected as SAND tracker
2	ND TDR (TBD)
3	ND site available
4	Beam checkout complete
5	**STT design and prototyping**
5.1	STT conceptual design
5.2	STT preliminary design
5.3	STT final design
5.4	Fabrication/prototyping of straws
5.5	Fabrication of STT prototypes
5.6	Test of straws and STT prototypes
5.7	Simulation of STT modules
6	STT readout
7	Preparation of STT production sites
8	STT procurement and fabrication
9	Test and installation of STT modules
10	Service connections and commissioning

Sep 2024 – Dec 2025 final design and tests of prototypes

Sep 2025 – Sep 2028 Straw tube production (3 years)

Sep 2025 – Sep 2027 Custom ASIC chip development and test (2 years)

Jan 2026 – Dec 2029 Module assembly (4 years*)

Mar 2029 – Jun 2030* Modules installation

Oct 2030 – Jun 2031: detector commissioning

Jun 2031: First beam

** From Claudio’s schedule*

Cost estimate

Cost estimate

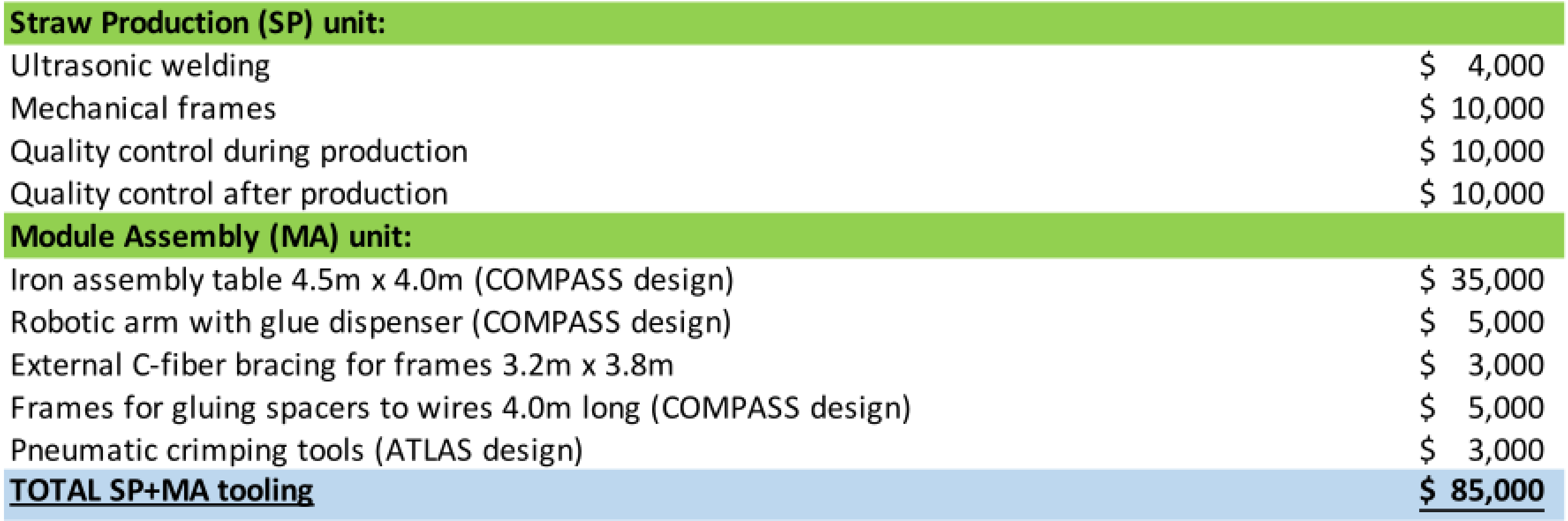
Many contacts with vendors

Components qualified during prototypes construction

Vendors identified

Realistic estimates for all the components available

Pre-production procurements already done



Straw Production (SP) unit:	
Ultrasonic welding	$ 4,000
Mechanical frames	$ 10,000
Quality control during production	$ 10,000
Quality control after production	$ 10,000
Module Assembly (MA) unit:	
Iron assembly table 4.5m x 4.0m (COMPASS design)	$ 35,000
Robotic arm with glue dispenser (COMPASS design)	$ 5,000
External C-fiber bracing for frames 3.2m x 3.8m	$ 3,000
Frames for gluing spacers to wires 4.0m long (COMPASS design)	$ 5,000
Pneumatic crimping tools (ATLAS design)	$ 3,000
TOTAL SP+MA tooling	**$ 85,000**

Cost estimate for STT standard configuration

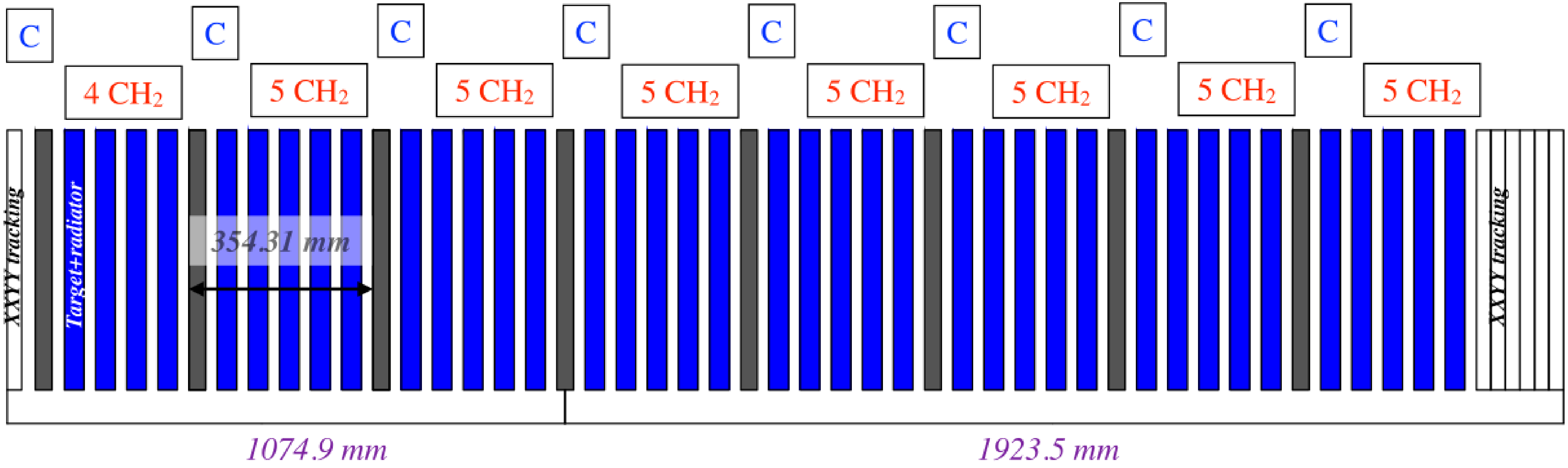
ITEM	COST	SUPPLIER/SOURCE	QUOTE	DELIVERY TIME	VALIDATED
Procure mylar film (19 µm, double 70 nm Al)	$ 239,610	Fraunhofer FEP, Germany	Mar-24	3 months	✓
Procure endplugs (PC transparent)	$ 11,651	CLM Co. LTD, China	Apr-24	45 days	✓
Procure wire spacers (PC black)	$ 32,748	GJT Co. LTD, China	Apr-24	45 days	✓
Procure crimping pins (1.2 mm gold plated)	$ 21,540	SZLE Co. LTD, China	Feb-24	4 weeks	✓
Procure anode wire (W/Re 20 µm)	$ 327,810	Luma metall AB, Sweden	Feb-24	14 weeks	✓
Procure C-fiber frames	$ 902,737	DSNM Co. LTD, China	Jul-24	5 months	
Procure Al corner blocks	$ 2,064	PIM Co. LTD, China	Jun-24	2 weeks	✓
Procure gas and electrical connectors	$ 8,499	CERN store, Switzerland	Jun-24	4 weeks	✓
Procure STT tools	$ 340,000	JINR/GTU facilities			
Procure miscellaneous items & consummables	$ 125,000	STT prototypes			
Procure gas system (Xe/CO_2 + Ar/CO_2 + cooling)	$ 525,000	CERN DT, Switzerland	Jul-24	6 months	✓
Procure BOPP radiator film (18 µm, 3.3 m)	$ 4,050	HMNM Co. LTD, China	May-24	8 weeks	✓
Procure CH_2 targets (HDPE tiles)	$ 18,791	HJM Co. LTD, China	Jun-24	8 weeks	
Procure graphite targets (isostatic IFS-H7 tiles)	$ 15,066	CFCC Co. LTD, China	Mar-24	8 weeks	✓
Procure C-fiber frames for targets/radiators (T700)	$ 70,136	HRC Co. LTD, China	Jun-24	1 month	✓
Procure rods+nuts for super-module assembly	$ 4,942	PIM Co. LTD, China	Jul-24	3 weeks	✓
Custom ASIC design (64 channels, 180 nm)	$ 600,000	DG Circuits, USA	May-24	12 months	✓
Procure ASIC prototypes (MPW+packaging)	$ 41,000	Muse semiconductor, USA	May-24	10 weeks	✓
Procure ASIC production mask	$ 105,000	Muse semiconductor, USA	May-24	4 weeks	✓
Procure ASIC chips (6 wafer pilot)	$ 9,000	Muse semiconductor, USA	May-24	6 weeks	✓
Procure ASIC packaging	$ 30,000	Muse semiconductor, USA	May-24	2 weeks	✓
Procure integrated readout boards (MCU, ADC, SSR)	$ 148,643	PCBWay, China	Jul-24	7 weeks	✓
Procure flexible Kapton PCBs (PCIe connector)	$ 32,314	PCBWay, China	Jun-24	36 days	✓
Procure HV components	$ 50,492	CAEN, Italy	Jun-24	3 months	✓
Procure LV components	$ 81,699	CAEN, Italy	Jun-24	4 months	✓
Procure cables & connectors	$ 36,985	CERN store, Switzerland	Jul-24	4 months	✓
Procure LV distribution boards	$ 18,000	ATLAS NSW			
Procure DAQ/DTS interface boards	$ 45,000	DUNE DAQ group			
TOTAL	**$ 3,847,779**				

Average cost per module: $44,742

(Without ASIC design and mask: $ 3,107,779)

Average cost per channel: $18 ($14)

Backup STT configuration



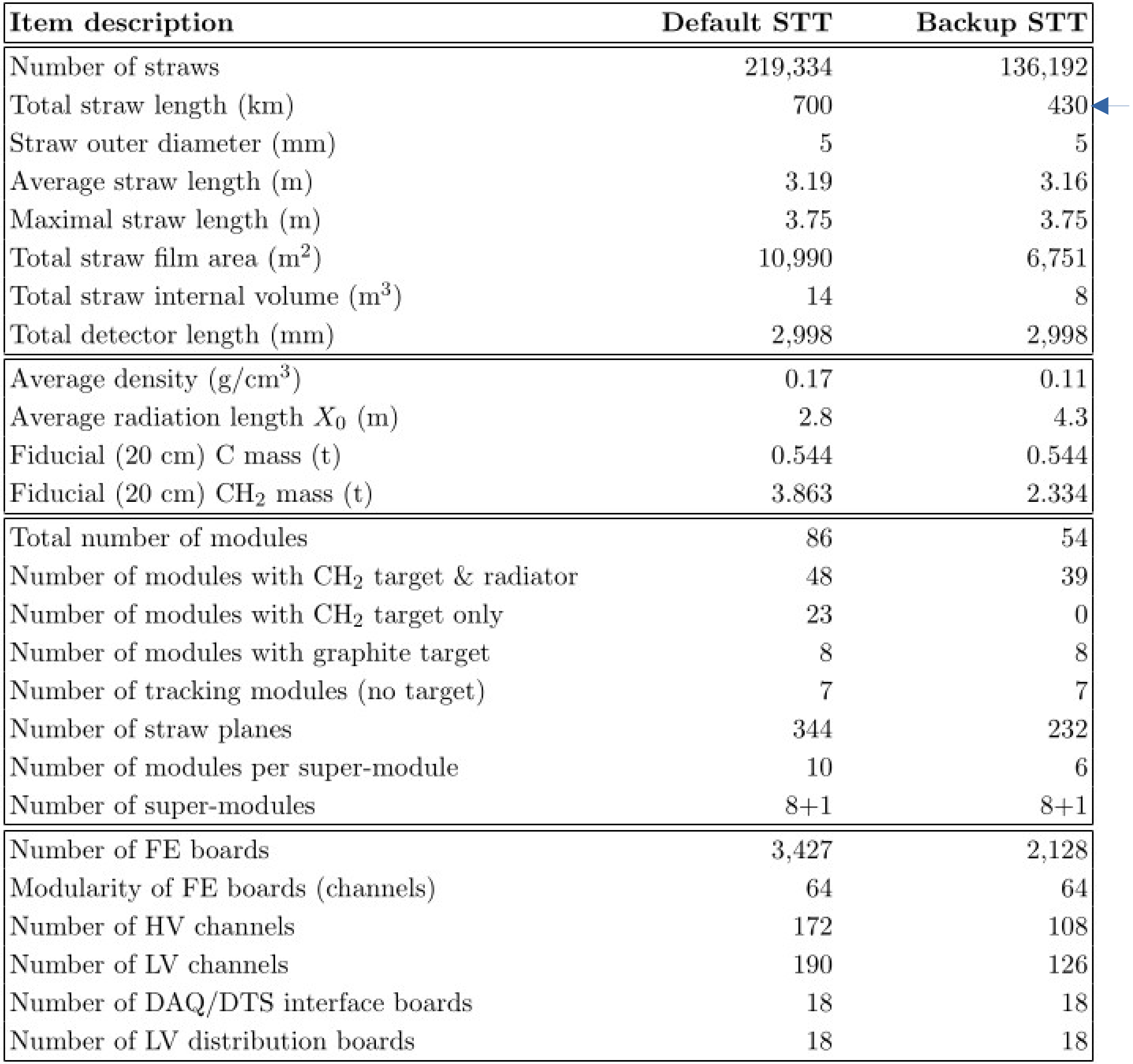
- 925 mm upstream space for GRAIN
- ~~48~~ 39 CH_2 (polypropylene) modules with target+radiator (37.718 mm)
- ~~23 CH_2 modules with target only (32 mm)~~
- 8 C (graphite) modules (32 mm)
- 7 tracking only module XXYY (28 mm)

Total: 54 modules
(7(1) super-modules of 6(5) modules,
1 tracker only supermodule with 6 modules)

$<\rho>\sim$ ~~0.17~~ 0.11 g/cm^3
$X_0\sim$ ~~3.5~~ 4.3 m
$\perp$ sampling 0.15%X_0
// sampling 0.36%X_0

FV mass ~~4.4~~ 2.9 ton
Thickness ~~~1~~ 0.8 X_0

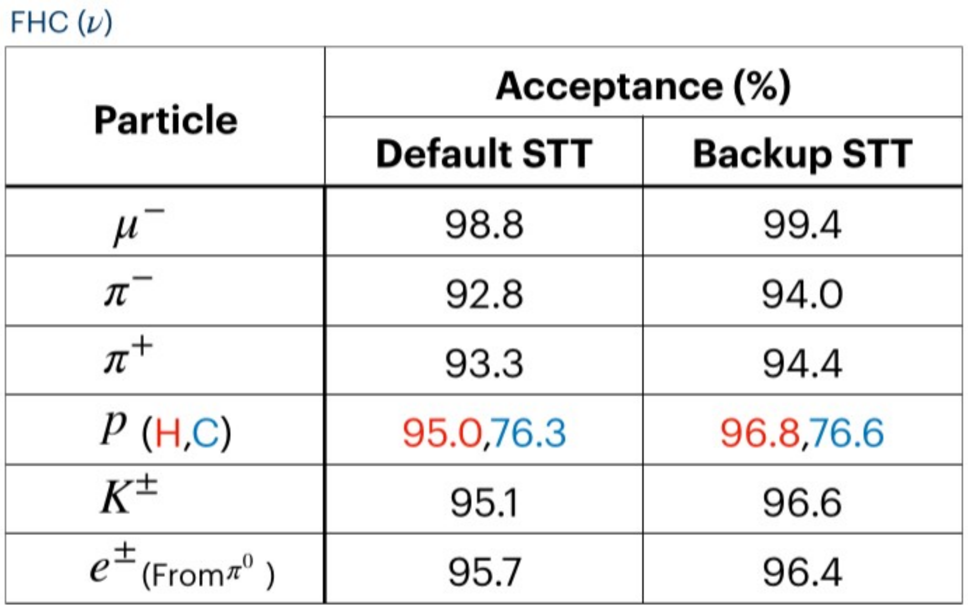
Backup vs Default STT configuration



Item description	Default STT	Backup STT
Number of straws	219,334	136,192
Total straw length (km)	700	430
Straw outer diameter (mm)	5	5
Average straw length (m)	3.19	3.16
Maximal straw length (m)	3.75	3.75
Total straw film area (m^2)	10,990	6,751
Total straw internal volume (m^3)	14	8
Total detector length (mm)	2,998	2,998
Average density (g/cm^3)	0.17	0.11
Average radiation length X_0 (m)	2.8	4.3
Fiducial (20 cm) C mass (t)	0.544	0.544
Fiducial (20 cm) CH_2 mass (t)	3.863	2.334
Total number of modules	86	54
Number of modules with CH_2 target & radiator	48	39
Number of modules with CH_2 target only	23	0
Number of modules with graphite target	8	8
Number of tracking modules (no target)	7	7
Number of straw planes	344	232
Number of modules per super-module	10	6
Number of super-modules	8+1	8+1
Number of FE boards	3,427	2,128
Modularity of FE boards (channels)	64	64
Number of HV channels	172	108
Number of LV channels	190	126
Number of DAQ/DTS interface boards	18	18
Number of LV distribution boards	18	18

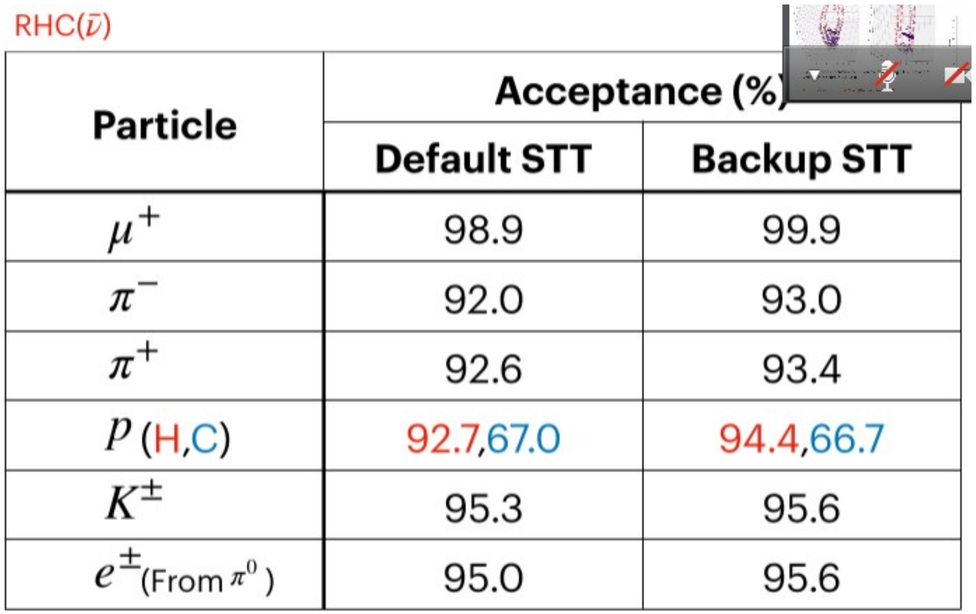
Total straw tube length
reduced by **~40%**

Backup vs Default STT configuration



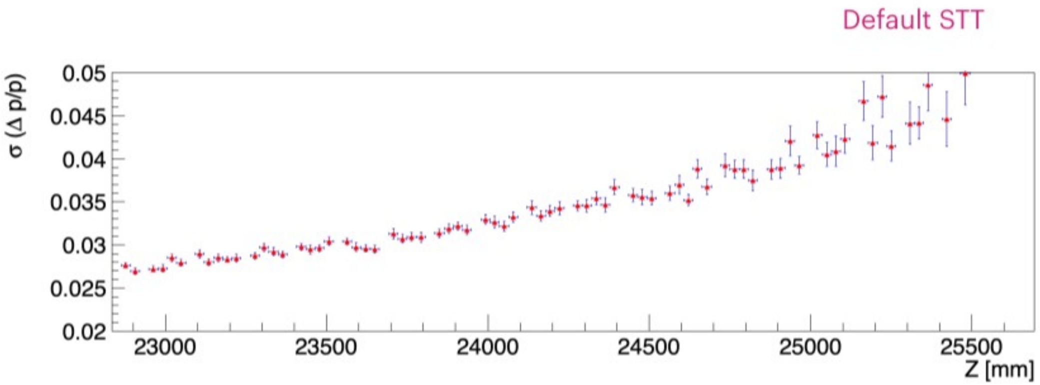
FHC (ν)

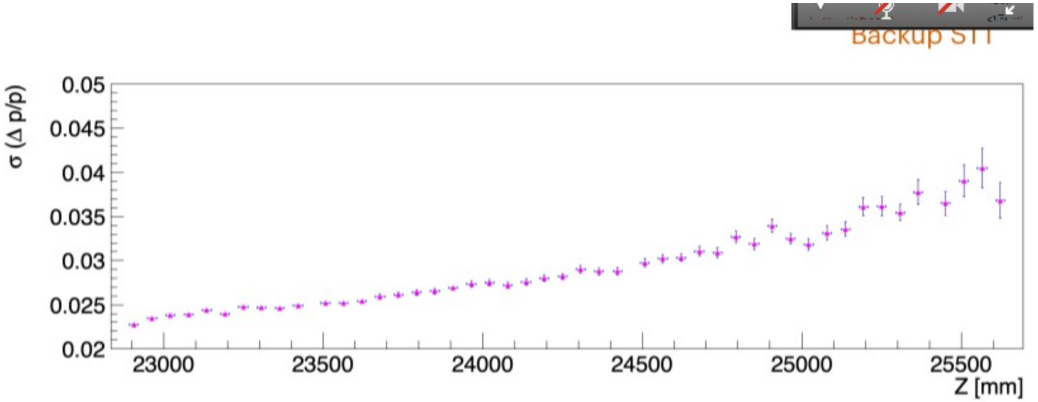
Particle	Acceptance (%)	
	Default STT	Backup STT
μ^-	98.8	99.4
π^-	92.8	94.0
π^+	93.3	94.4
p (H,C)	95.0,76.3	96.8,76.6
$K^\pm$	95.1	96.6
$e^\pm$(Fromπ^0)	95.7	96.4



RHC($\bar{\nu}$)

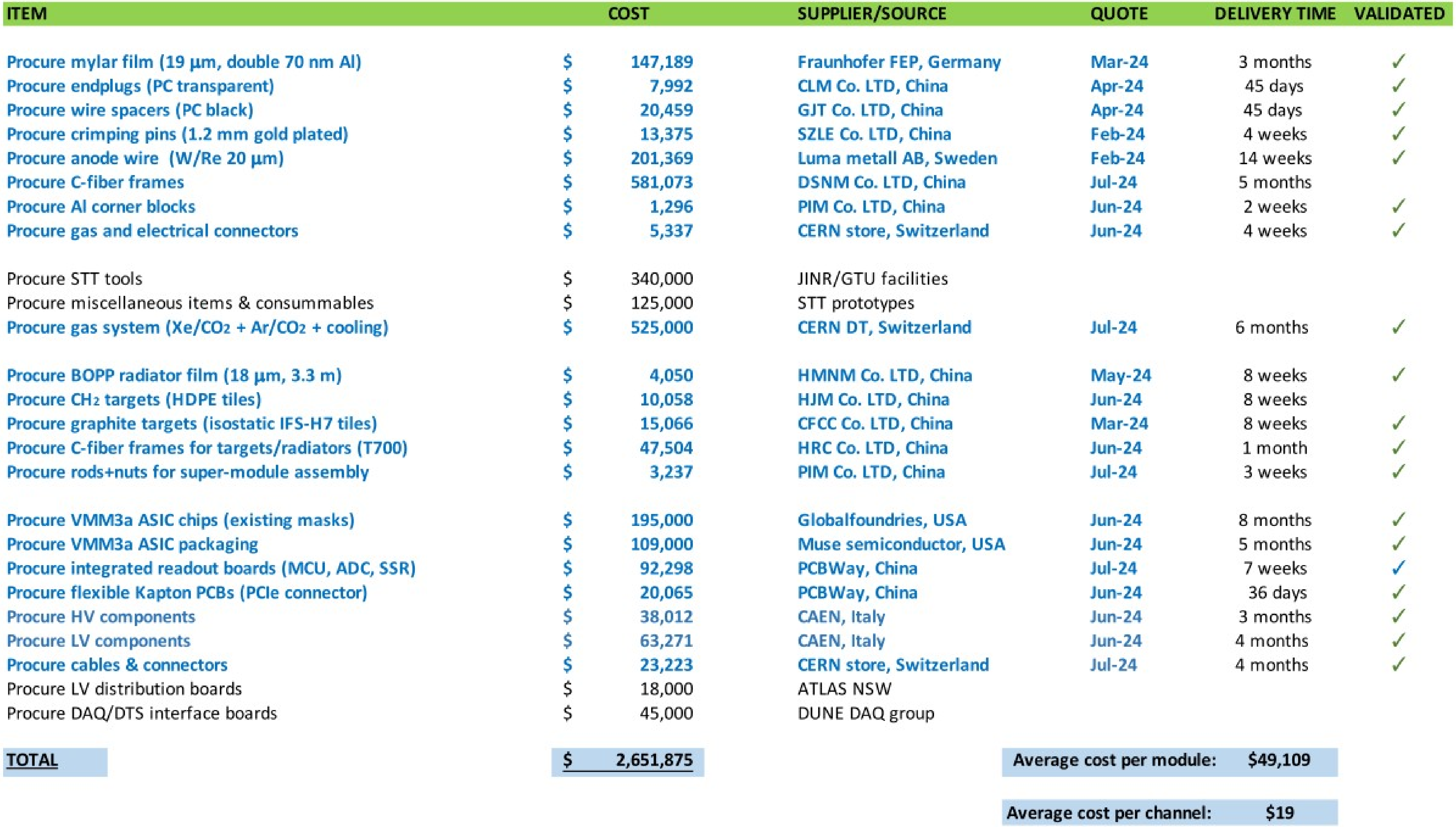
Particle	Acceptance (%)	
	Default STT	Backup STT
μ^+	98.9	99.9
π^-	92.0	93.0
π^+	92.6	93.4
p (H,C)	92.7,67.0	94.4,66.7
$K^\pm$	95.3	95.6
$e^\pm$(From π^0)	95.0	95.6





Acceptance is very similar
Momentum resolution improves because of lower material effects
Angular resolution studies in progress

Cost estimate for STT backup configuration

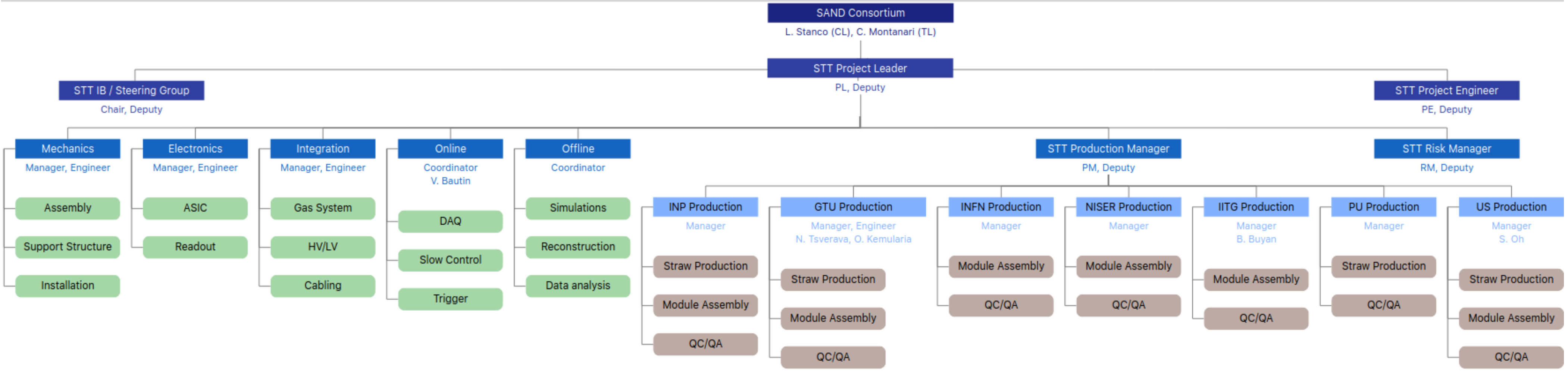


ITEM	COST	SUPPLIER/SOURCE	QUOTE	DELIVERY TIME	VALIDATED
Procure mylar film (19 µm, double 70 nm Al)	$ 147,189	Fraunhofer FEP, Germany	Mar-24	3 months	✓
Procure endplugs (PC transparent)	$ 7,992	CLM Co. LTD, China	Apr-24	45 days	✓
Procure wire spacers (PC black)	$ 20,459	GJT Co. LTD, China	Apr-24	45 days	✓
Procure crimping pins (1.2 mm gold plated)	$ 13,375	SZLE Co. LTD, China	Feb-24	4 weeks	✓
Procure anode wire (W/Re 20 µm)	$ 201,369	Luma metall AB, Sweden	Feb-24	14 weeks	✓
Procure C-fiber frames	$ 581,073	DSNM Co. LTD, China	Jul-24	5 months	
Procure Al corner blocks	$ 1,296	PIM Co. LTD, China	Jun-24	2 weeks	✓
Procure gas and electrical connectors	$ 5,337	CERN store, Switzerland	Jun-24	4 weeks	✓
Procure STT tools	$ 340,000	JINR/GTU facilities			
Procure miscellaneous items & consummables	$ 125,000	STT prototypes			
Procure gas system (Xe/CO_2 + Ar/CO_2 + cooling)	$ 525,000	CERN DT, Switzerland	Jul-24	6 months	✓
Procure BOPP radiator film (18 µm, 3.3 m)	$ 4,050	HMNM Co. LTD, China	May-24	8 weeks	✓
Procure CH_2 targets (HDPE tiles)	$ 10,058	HJM Co. LTD, China	Jun-24	8 weeks	
Procure graphite targets (isostatic IFS-H7 tiles)	$ 15,066	CFCC Co. LTD, China	Mar-24	8 weeks	✓
Procure C-fiber frames for targets/radiators (T700)	$ 47,504	HRC Co. LTD, China	Jun-24	1 month	✓
Procure rods+nuts for super-module assembly	$ 3,237	PIM Co. LTD, China	Jul-24	3 weeks	✓
Procure VMM3a ASIC chips (existing masks)	$ 195,000	Globalfoundries, USA	Jun-24	8 months	✓
Procure VMM3a ASIC packaging	$ 109,000	Muse semiconductor, USA	Jun-24	5 months	✓
Procure integrated readout boards (MCU, ADC, SSR)	$ 92,298	PCBWay, China	Jul-24	7 weeks	✓
Procure flexible Kapton PCBs (PCIe connector)	$ 20,065	PCBWay, China	Jun-24	36 days	✓
Procure HV components	$ 38,012	CAEN, Italy	Jun-24	3 months	✓
Procure LV components	$ 63,271	CAEN, Italy	Jun-24	4 months	✓
Procure cables & connectors	$ 23,223	CERN store, Switzerland	Jul-24	4 months	✓
Procure LV distribution boards	$ 18,000	ATLAS NSW			
Procure DAQ/DTS interface boards	$ 45,000	DUNE DAQ group			
TOTAL	**$ 2,651,875**		**Average cost per module:**	**$49,109**	
			Average cost per channel:	**$19**	

Total cost reduced by 15% (wrt default with no new chip design)

Who makes what?

A tentative organization chart for STT



This just an exercise not yet discussed with SAND Consortium…
but need a consolidated organization chart to answer to the question:

Who makes what?

Unblessed list of contributions (and responsibilities)

Country	STT Institutions	Contributions	Planned Contributions
Italy	INFN Pisa, Bologna	Management Design and engineering Procurement of film, prototype frames, assembly tooling Testbeam exposures Construction of prototypes Simulations and reconstruction Analysis and physics studies	Setup at least 1 MA unit Assembly of STT modules ASIC and readout
Georgia	GTU	Design and engineering Tests of straw properties Construction of 2.5 SP units Product of straws for prototypes Construction of prototypes	Setup 1 MA unit Production of straws Assembly of STT modules
India	IIT Guwahati IIT Kanpur NISER Panjab	Procurement of components Tests of straw properties Readout and testbeam exposures Simulation and reconstruction Analysis and physics studies	Construction of 1 SP unit Setup 2 MA units Production of straws Assembly of STT modules Readout electronics
Kazakhstan	INP, Almaty (+ JINR)	Design and engineering Readout and testbeam exposures Tests of straw properties Construction of 1 (+ 3) SP units Construction of prototypes Simulations and analysis	Construction of 3 SP units Setup 2 MA units Production of straws Assembly of STT modules Readout electronics
USA	Duke University USC	Management Design and engineering Procurement of straw components, targets/radiator, VMM3a, readout Readout and testbeam exposures Tests of straw properties Simulations and reconstruction Analysis and physics studies	Construction of 1 SP unit Setup 1 MA unit Readout electronics

Risk analysis

STT Risk Analysis presented at the CM (1/2)

Risk ID (tentative)	Risk title	Risk area (RBS)	Prob.	Impact	Rank	Mitigations and Responses
RT-131-ND.05-501	Delay in custom ASIC development for STT	Management Risk / Planning	10%	Low	Low	Complete backup readout based on existing VMM3a available, which satisfies the main STT requirements. The ASIC development is not on critical path, since the backup readout can be used for STT construction/testing and for initial data taking. The modular design of the readout boards with PCIe connector allows easy replacements/upgrades.
RT-131-ND.05-502	Delay of the full-scale STT prototype	Management Risk / Planning	35%	Moderate	Medium	Schedule contingency allowed up to the end of 2025, with final engineering proceeding partially in parallel with the preparation of the production sites. Early procurement and test of main components required for full-scale prototypes already started in 2024.
RT-131-ND.05-503	Delay in module assembly during the STT construction	Management Risk / Planning	20%	Moderate	Medium	The STT design makes each individual module functionally independent, allowing the operation of the detector with less modules. A backup STT configuration with 54 modules instead of 86 is foreseen, which fulfills the main physics scopes and can be used at the beginning of the data taking while staging the remaining modules.
RT-131-ND.05-504	Inconsistent quality across the STT production sites	Technical Risk / Quality	20%	Low	Low	Strict QA/QC procedures and acceptance criteria will be required across all production sites. A production manager will coordinate the production and QA/QC at sites, including verifications by inspections. Common purchases of the detector components required for assembly and a joint training of the assembly personnel are foreseen. In addition, the backup STT configuration can be produced at a single assembly site equipped with 2-3 assembly tables.
RT-131-ND.05-505	Difficulties in procurement of C-fiber frames for STT	External Risk / Vendors	35%	Low	Low	Verification of quality of prototype C-fiber frames. Qualification of different vendors during prototyping activities and selection of backup vendors.
RT-131-ND.05-506	Difficulties in the procurement of W/Re wire for STT	External Risk / Vendors	20%	Low	Low	Qualification of different vendors during prototyping activities and selection of backup vendors. Quality tests of wire samples from all selected vendors at CERN.
RT-131-ND.05-507	Problems encountered during tests of custom ASIC prototypes	External Risk / Industry	20%	Low	Low	Development of custom ASIC for STT based upon sub-circuits and functions largely inherited from the well-established NRL and VMM3a chips, which have been extensively tested with STT prototypes. Direct involvement of the designer of NRL and VMM3a chips in the development of the custom ASIC for STT.
RT-131-ND.05-508	Problems with the tooling for the assembly of STT modules	External Risk / Facilities	20%	Moderate	Medium	Construction and test of STT full-scale prototype (“module 0”) will be used to validate the tooling and identify potential issues. Initial tooling from the existing ones developed for the COMPASS straw tracker with modules of similar size and geometry as in STT.
RO-131-ND.05-509	Use of boats and standard drums for the film production	External Risk / Vendors	20%	Low	Low	The selected vendor proposed a feasibility study to evaluate if the PET film with double side coating of 70 nm Al can be produced with boat evaporation and a standard cooling drum without film damages or wrinkles.
RO-131-ND.05-510	Reuse of some components from the gas system of the ATLAS TRT for	External Risk / Vendors	35%	Low	Low	The CERN gas group provided a list of components from ATLAS TRT which could be reused for STT after inspection of the TRT gas system in operation. The reuse of the components for STT has been already agreed with the management of the ATLAS TRT. The refurbishing of the relevant ATLAS TRT components is being studied.
RU-131-ND.05-511	Price variations from market changes	External Risk / Market	20%	Low	Low	For most items obtained quotes from multiple vendors and monitor costs over time. The contracts for the purchase of the main components are expected to be signed by 2026.

STT Risk Analysis presented at the CM (2/2)

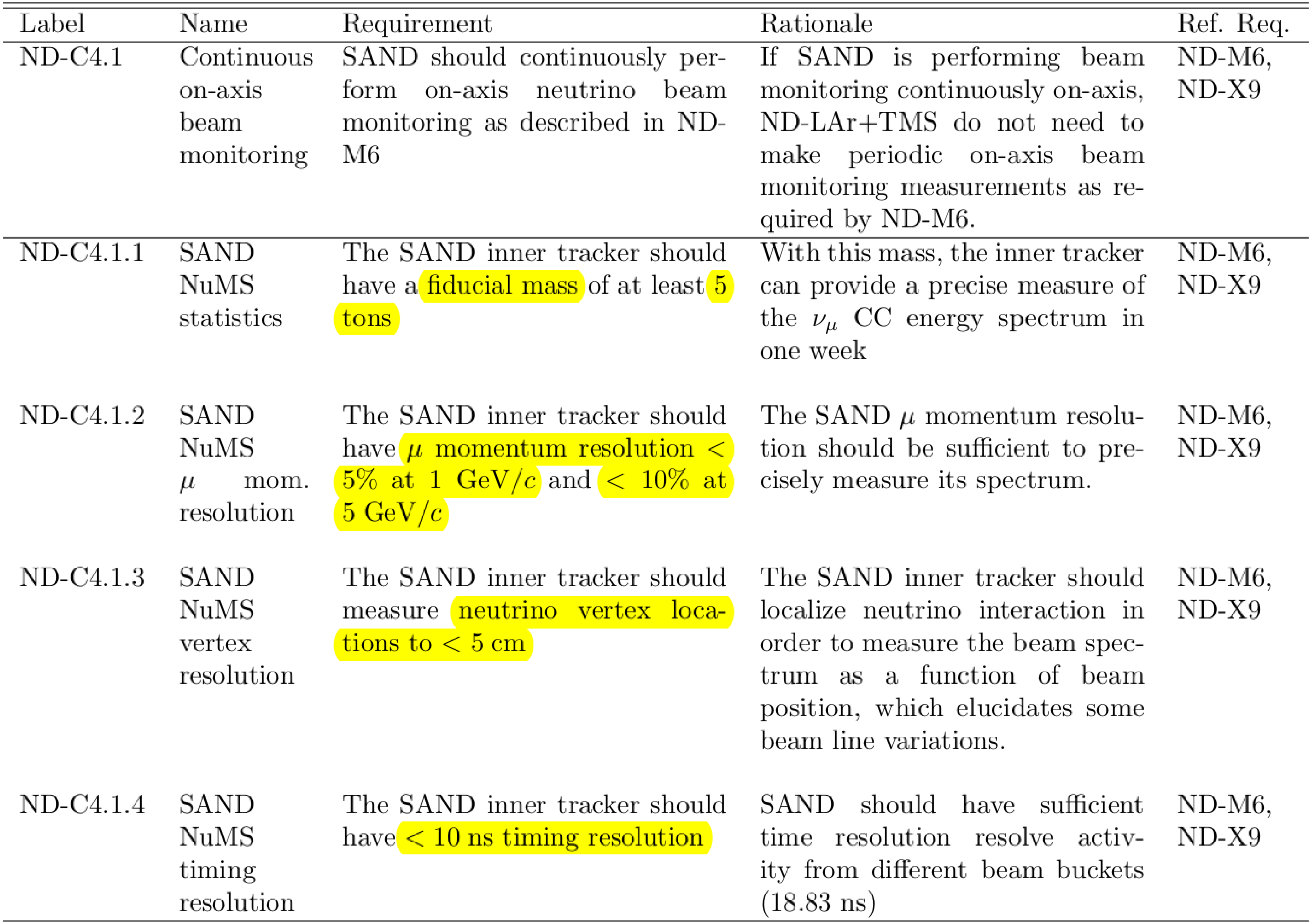
Risk ID (tentative)	Risk title	Risk area (RBS)	Prob.	Impact	Rank	Mitigations and Responses
RU-131-ND.05-512	Foreign exchange rate fluctuations	External Risk / Market	20%	Low	Low	STT core costs based on quotes from a mixture of currencies from selected vendors in different countries. The procurement of most components should occur by 2026, thus reducing long-term uncertainty in exchange rate fluctuations.
RT-131-ND.05-513	Delay in the availability/ approval of STT funding and	Management Risk / Funding and Resources	35%	Moderate	Medium	Multiple funding proposals for STT submitted to funding agencies by participating institutions. A firm support by the DUNE management is required.
RT-131-ND.05-514	Damage of STT modules during shipping to Fermilab	Management Risk / Logistics	5%	Low	Low	The STT modules will be shipped as super-module units via water/ground transportation. We will take advantage of the shipping experience of similar COMPASS modules from JINR to CERN. We will engage an engineering/shipping firm from an early stage of the production process.
RT-40ND-ND.05-515	Gas leakage in a STT module	Technical Risk / Reliability and Performance	1%	Low	Low	Each STT half-module (XX or YY straw double layer) is fed by independent parallel gas input/output lines, with an individual valve and pressure sensor for each module. Depending on the type of leak detected the affected half-module can be either moved from the Xe/CO_2 to the Ar/CO_2 distribution, or disconnected altogether from the gas distribution, without stopping the STT data taking. The STT design allows to fix leakages during one of the beam-off periods.
RT-40ND-ND.05-516	Failure of STT gas system including pump	Technical Risk / Reliability and Performance	1%	Low	Low	A second backup pump is included into the STT gas system allowing a quick switch without major losses of data taking while the faulty pump is being repaired.
RT-40ND-ND.05-517	Leakage/breakage of STT straws	Technical Risk / Reliability and Performance	<0.01%	Low	Low	Strict QA/QC protocols and acceptance criteria will be used during the straw production, similar to the ones implemented for the NA62 straw tracker, in which no straw breakage was observed over many years of operation. The quality of the straw welding has been validated with dedicated tests at CERN.
RT-40ND-ND.05-518	Failure of a STT integrated readout board	Technical Risk / Reliability and Performance	1%	Low	Low	The STT readout boards are connected in parallel with a robust BUS interface so that the failure of a readout board does not affect the remaining ones. The failure of a readout board implies the temporary loss of only 64 straws, corresponding to 0.03% of the detector, and does not require to stop the data taking. The affected board can be safely replaced during one of the beam-off periods.
RT-40ND-ND.05-519	High voltage short circuit/failure	Technical Risk / Reliability and Performance	1%	Low	Low	Each STT readout board is equipped with a Solid State Relay (SSR) allowing to remotely disconnect HV in case an overcurrent is detected. The effect of a HV short circuit/failure is a temporary loss of 64 straws, corresponding to 0.03% of the detector, and does not require to stop the data taking.
RT-40ND-ND.05-520	Low voltage short circuit/failure	Technical Risk / Reliability and Performance	1%	Low	Low	Each STT readout board is equipped with surge protections and LV fuses confining the effect of a LV short circuit within the individual board. The effect of a LV short circuit/failure is a temporary loss of 64 straws, corresponding to 0.03% of the detector, and does not require to stop the data taking.
RT-40ND-ND.05-521	Broken wire in a STT straw	Technical Risk / Reliability and Performance	<0.1%	Low	Low	The breakage of a wire in a STT straw requires to temporarily disconnect the corresponding readout board via the SSR, taking offline 64 straws. The broken wire is self-contained within the straw and will not be removed, the affected channel will be permanently disconnected by removing the HV resistor on the board during one of the beam-off periods.
RT-40ND-ND.05-522	Aging of STT straws	Technical Risk / Reliability and Performance	<0.5%/ year	Moderate	Low	The use of ultrasonic welding with double Al metallization protects the straws. The main aging effect expected is a relaxation of the tension on the straw walls over time, given that STT operates at room temperature with negligible irradiation. We will store all straws for 100 days at a pressure of 3 bar to allow a stabilization of the film before module assembly. The residual relaxation expected is 11% during 20 years, which does not have significant effects on the detector performance. Impact of humidity on the straws is reversible and can be corrected by monitoring temp. and humidity.

Risk analysis just started. Risk of no funding from institutions other than INFN not included!
(this is an outcome nobody wants...)

BACKUP

Thank you!

SAND capabilities*



Label	Name	Requirement	Rationale	Ref. Req.
ND-C4.1	Continuous on-axis beam monitoring	SAND should continuously perform on-axis neutrino beam monitoring as described in ND-M6	If SAND is performing beam monitoring continuously on-axis, ND-LAr+TMS do not need to make periodic on-axis beam monitoring measurements as required by ND-M6.	ND-M6, ND-X9
ND-C4.1.1	SAND NuMS statistics	The SAND inner tracker should have a fiducial mass of at least 5 tons	With this mass, the inner tracker can provide a precise measure of the ν_μ CC energy spectrum in one week	ND-M6, ND-X9
ND-C4.1.2	SAND NuMS μ mom. resolution	The SAND inner tracker should have μ momentum resolution $<$ 5% at 1 GeV/c and $<$ 10% at 5 GeV/c	The SAND μ momentum resolution should be sufficient to precisely measure its spectrum.	ND-M6, ND-X9
ND-C4.1.3	SAND NuMS vertex resolution	The SAND inner tracker should measure neutrino vertex locations to $<$ 5 cm	The SAND inner tracker should localize neutrino interaction in order to measure the beam spectrum as a function of beam position, which elucidates some beam line variations.	ND-M6, ND-X9
ND-C4.1.4	SAND NuMS timing resolution	The SAND inner tracker should have $<$ 10 ns timing resolution	SAND should have sufficient time resolution resolve activity from different beam buckets (18.83 ns)	ND-M6, ND-X9

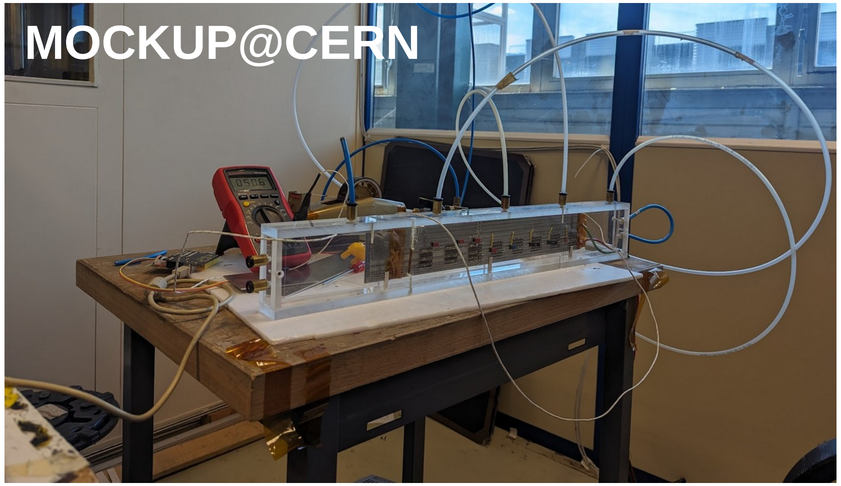
** from ‘Physics requirements of the Phase I Near Detector’, April 2024*

SAND inner tracker capabilities goals*

Label	Name	Requirement	Rationale	Ref. Req.
ND-C3.1	Tracker density	The SAND inner tracker should have average density $\rho < 0.22\mathrm{g/cm}^3$	Low density is essential to minimize multiple scattering and allow precision magnetic spectrometry	ND-X1, ND-X8
ND-C3.2	Tracker momentum resolution	The SAND inner tracker should have charged particle momentum resolution $< 5\%$ up to $p \sim 5\mathrm{GeV}/c$	Precise momentum measurements via curvature is needed to perform kinematic reconstruction.	ND-X1, ND-X3, ND-X8
ND-C3.3	Tracker radiation length	The SAND inner tracker should have < 1 radiation length from its center to the ECAL	Minimizing radiation lengths allows precise curvature measurements particularly for $e^{\pm}$	ND-X8
ND-C3.4	Tracker interaction length	The SAND inner tracker should have < 1 interaction length from its center to the ECAL	Minimizing interaction lengths minimizes secondary hadronic interactions in the tracker.	ND-X8
ND-C3.5	Tracker (hydro)carbon target	The SAND inner tracker should have both (hydrogen-rich) hydrocarbon and pure carbon target planes	Deploying a combination of pure carbon and hydrocarbon targets allows the isolation of interactions on free protons via subtraction.	ND-X5, ND-X6, ND-X7
ND-C3.6	Tracker nuclear targets	The SAND inner tracker should be configurable with other nuclear target planes	Deploying other nuclear target planes allows *A*-dependence of cross section properties to be studied	NC-X7
ND-C3.7	Tracker argon target	The SAND inner tracker volume should have an argon target	Deploying argon targets allows a direct comparison of $\nu - \mathrm{Ar}$ interactions with $\nu - \mathrm{H}$ measurements enabled in ND-C3/5.	ND-X6, ND-X7

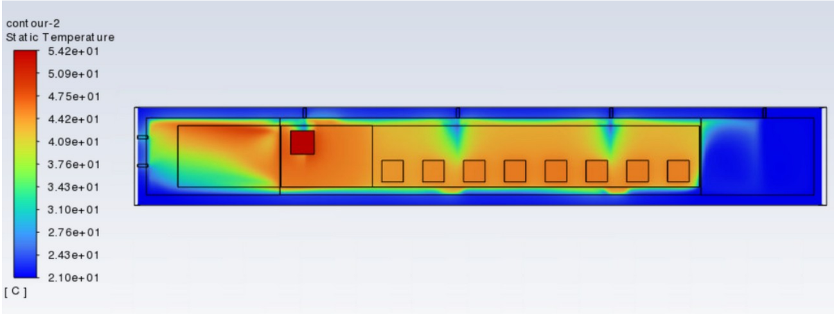
** from ‘Physics requirements of the Phase I Near Detector’, April 2024*

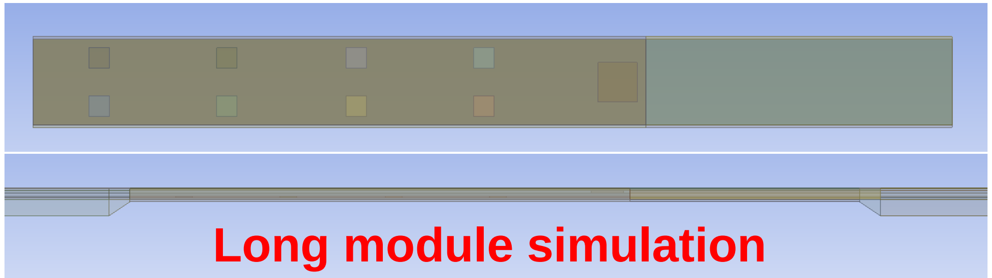
Validazione della simulazione termica con mockup

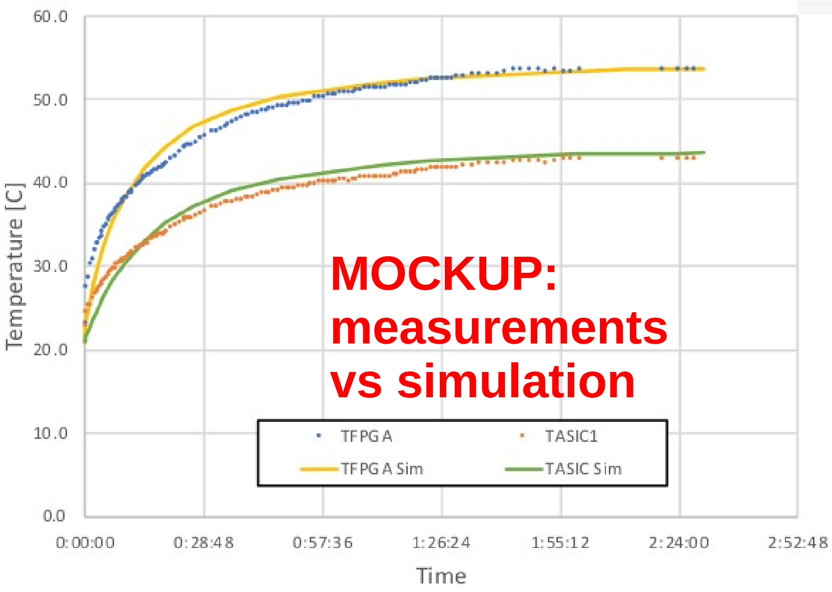

MOCKUP@CERN

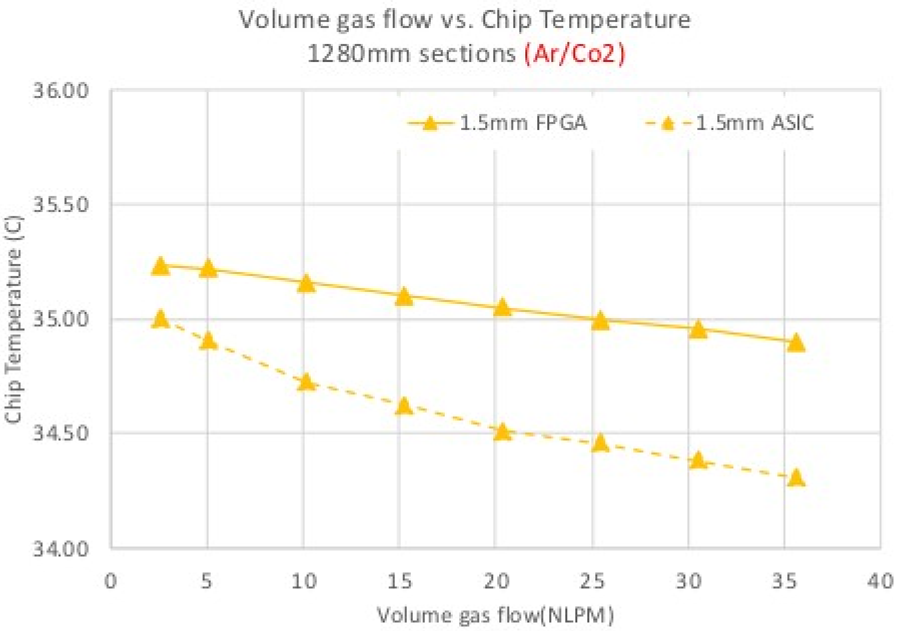
Un simulatore della dispersione termica prevista dall’elettronica posta all’interno dei moduli STT è stato usato per verificare i risultati della simulazione.

L’accordo è molto buono e convalida il risultato della simulazione di un intero modulo.

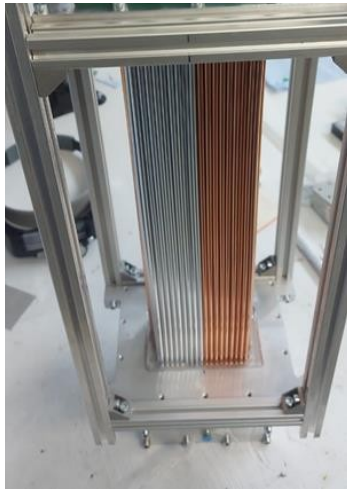


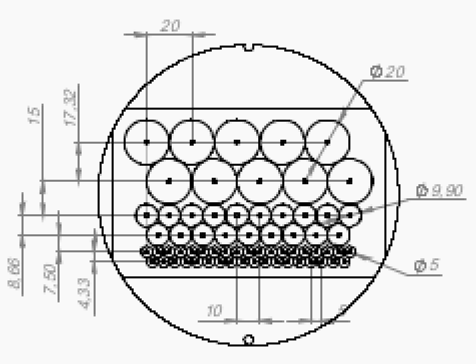

Long module simulation


MOCKUP: measurements vs simulation

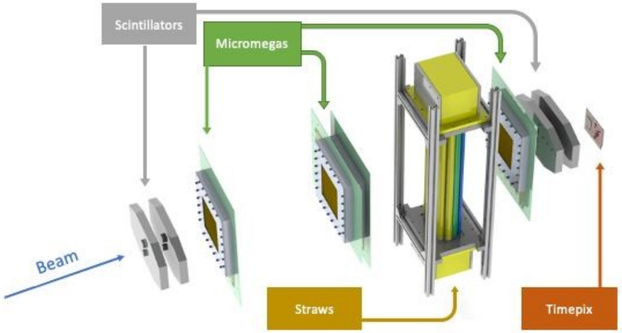


Ultimi risultati dai test su prototipi di straw al Cern



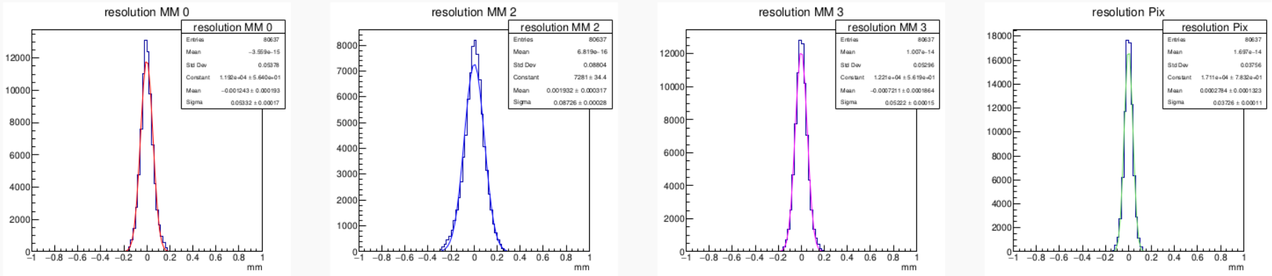


Il gruppo di Dubna sta continuando l'attività di test sui prototipi (collegata anche a altri esperimenti: SHIP, HIKE, NA62, SPD, COMET) presso la North Area del CERN (H4 beam line).

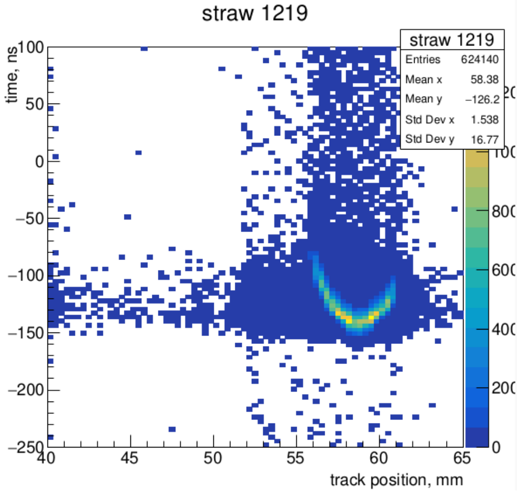


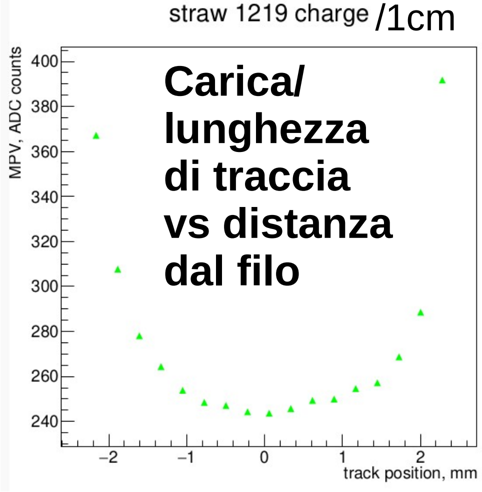
Sistema di tracciatura: 3 MicroMegas + 1 Pixel detector:

$\sigma = 0.053\ mm$ $\sigma = 0.087\ mm$ $\sigma = 0.052\ mm$ $\sigma = 0.037\ mm$



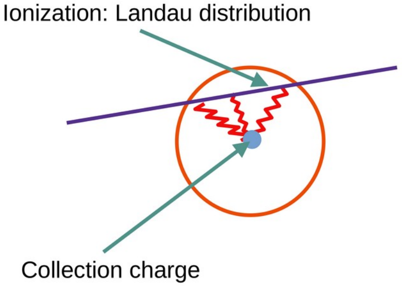
Relazione tempo-distanza di drift





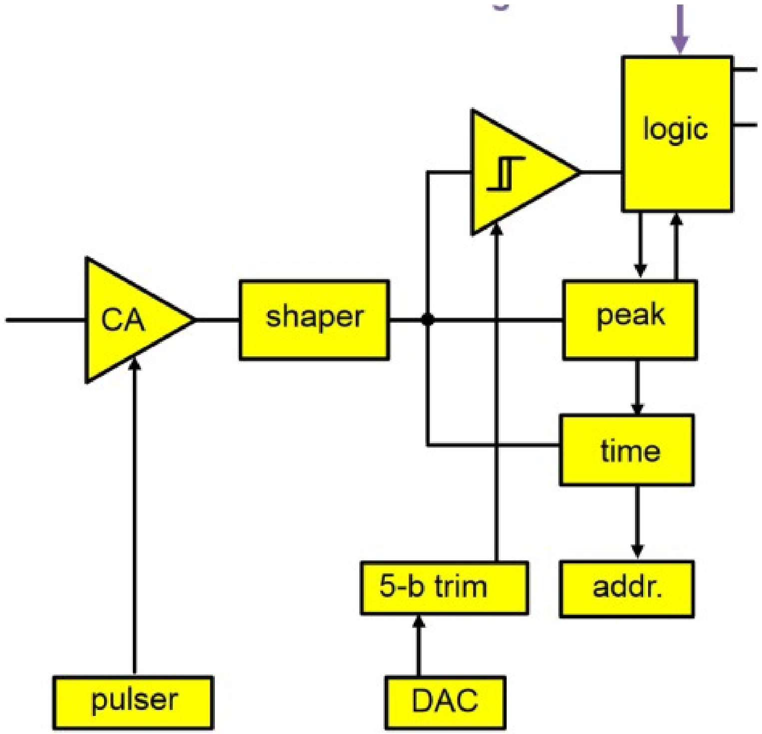
/1cm

Carica/ lunghezza di traccia vs distanza dal filo

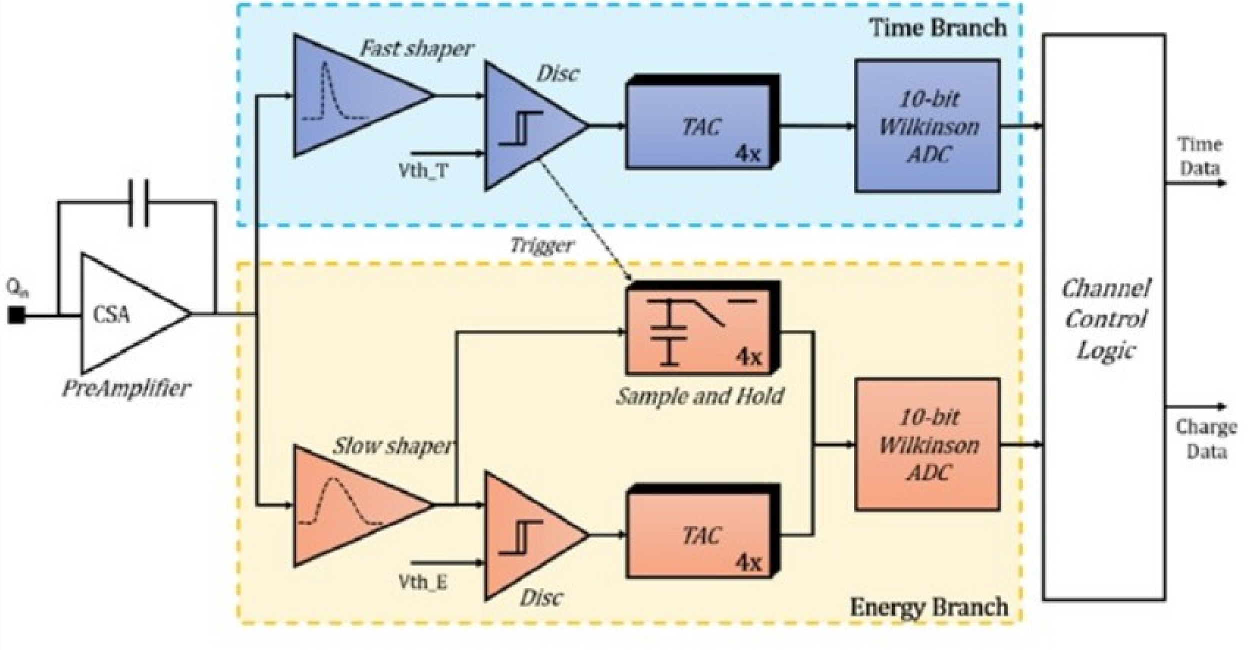


Chip usato per leggere gli straw: VMM3

ASIC selection: VMM3 vs TIGER



VMM3 Architecture



TIGER Architecture

BOTH ASICS NEED TO BE REVISED:

VMM3 has a bug on Energy measurement for low signals.
(VMM3a has fixed the energy bug but has a bug on time measurement).

TIGER has two different shapers for Time and Energy measurements. Two threshold levels are also possible. Dynamic range needs to be adapted.

ASIC requirements

- *Modularity*: *64 channels*
- *Input capacitance*: *10-40 pF (optimize for 40 pF)*
- *Flat cable length*: *10-60 cm (capacitance 1-5 pF)*
- *Architecture*: *dual sub-channel with independent gain and shaper and integrated digital path*
  - *(i) fast shaper & high gain for time measurement*
  - *(ii) slow shaper & low gain for energy measurement*
- *Minimum charge*: *4 fC (time measurement), 20-40 fC (energy measurement)*
- *Maximal charge*: *10-20 pC (energy measurement)*
- *Dynamic range*: *1,000 (energy measurement)*
- *Timing resolution*: *< 1 ns*
- *Gain settings*: *(i) 6, 9, 12 mV/fC for time measurement*
  - *(ii) 0.1-0.5 mV/fC for energy measurement*
- *Peaking times*: *(i) 6, 10, 25 ns fast shaper*
  - *(ii) 50, 100, 200 ns slow shaper*
- *Power consumption*: *<10 mW/channel*
- *Expected rates*: *≪1 kHz*

These requirements have been discussed with:
- Gianluigi De Geronimo (VMM3)
- Alberto Bortone (TIGER)