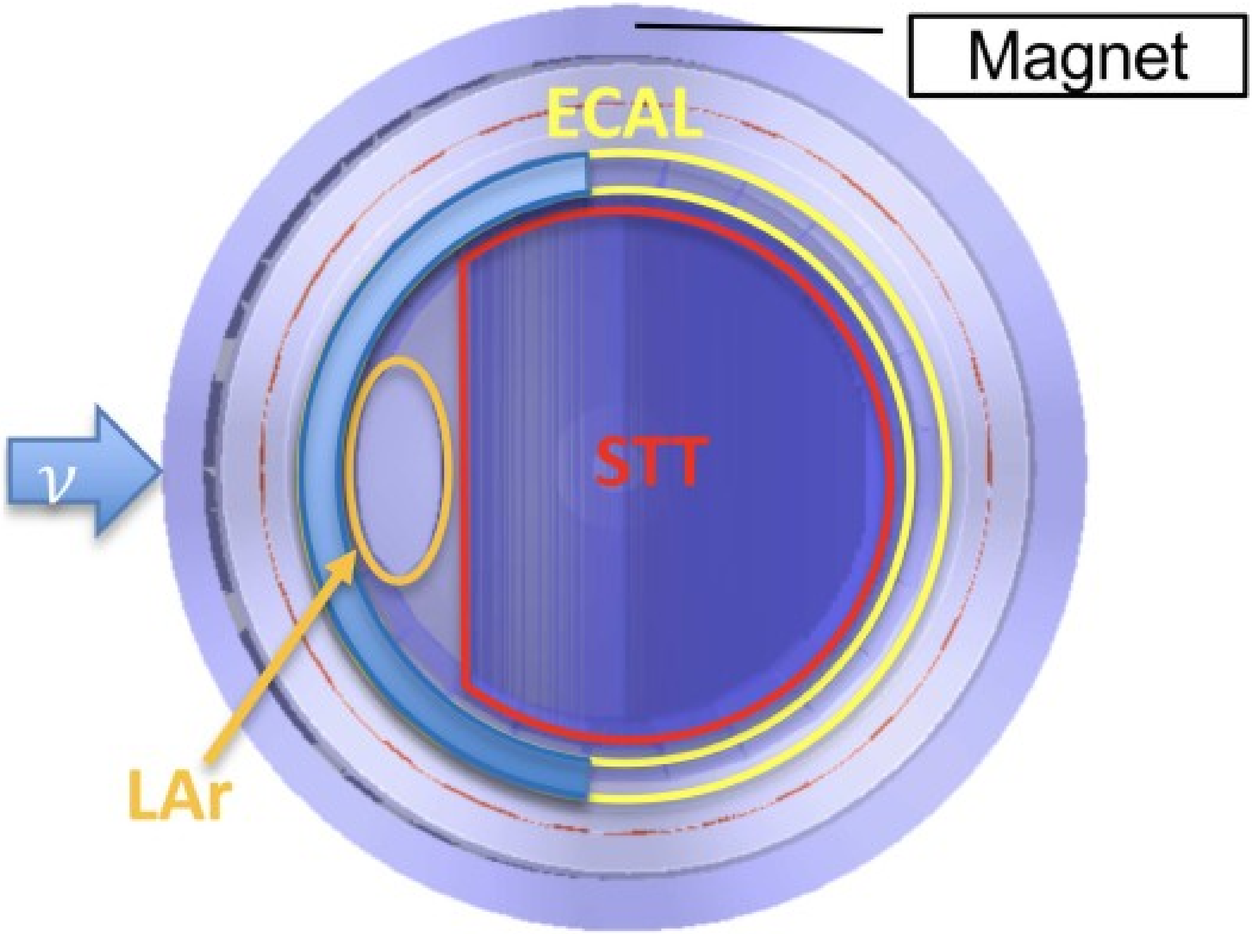


Introduction to SAND STT Tracker discussion

S. Di Falco and G. Sirri

CTS meeting, LNF

July 12, 2024

Outline

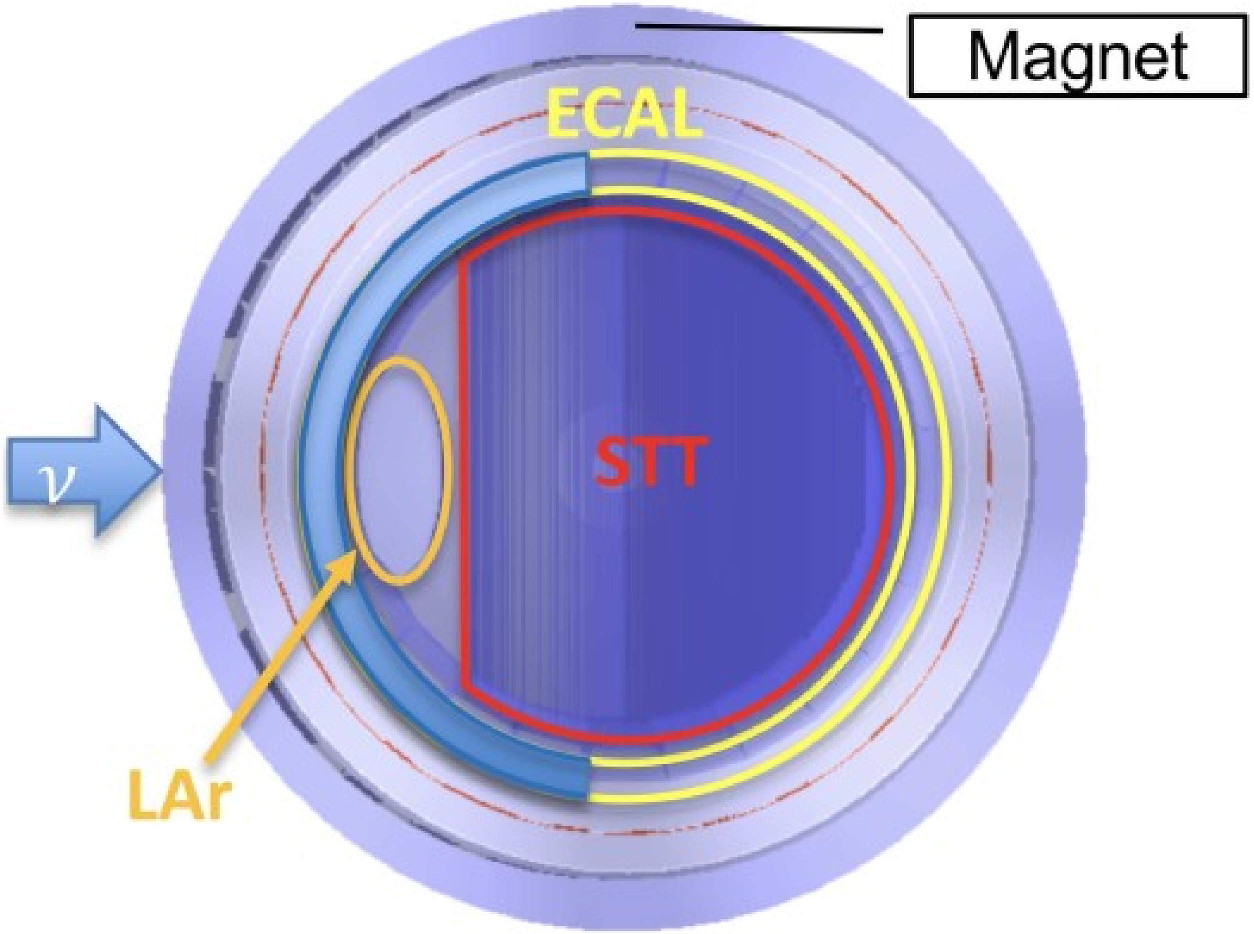
- SAND Inner Tracker requirements
- Straw Tube Tracker (STT) design
- STT prototypes
- Performance evaluation
- Readout electronics
- Gas System
- Cooling
- Schedule
- Costs

SAND requirements*

- Mass of ~5 tons to provide a precise measurement of ν_μ CC spectrum
- Muon momentum resolution 5% @ 1 GeV/c, < 10% at 5 GeV/c
- Localize neutrino interaction vertex in the target material (precision < 5 cm)
- Time resolution < 10 ns to distinguish particles from different buckets (18.83 ns)
- Low average density (~0.2g/cm^3) to minimize multiple scattering
- Charged particle point resolution < 1 mm to provide wanted momentum resolution
- < 1 X_0 and <1 λ_I from tracker center to ECAL
- Use C and H rich target to extract cross section on protons
- Combine H cross section with LAr cross section to correct systematic errors

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

The Straw Tube Tracker (STT)



The calorimeter inner volume can be filled* by a set of modules alternating C and CH_2 target planes and layers of very light straw tube layers.

The main parameters of the proposed STT are:

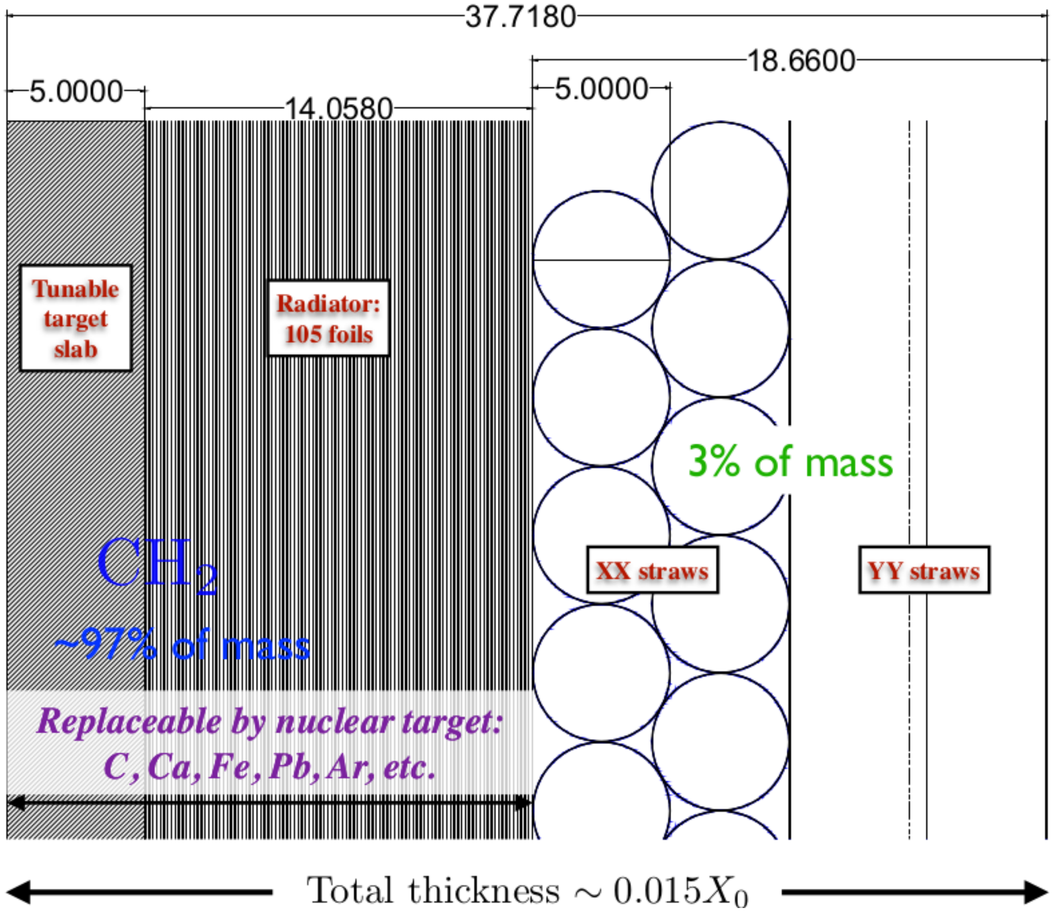
- magnetic field B = 0.6 T
- average density $\rho \sim 0.17$ g/cm^3
- radiation length $X_0 \sim 3.5$ m
- $\perp$ tracking sampling 0.15%X_0
- // tracking sampling 0.36%X_0

Total fiducial** mass 4.4 tons

Total thickness ~1 X_0

** The first part of the calorimeter volume is left free for the GRAIN LAr detector*
*** 20 cm from edges*

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

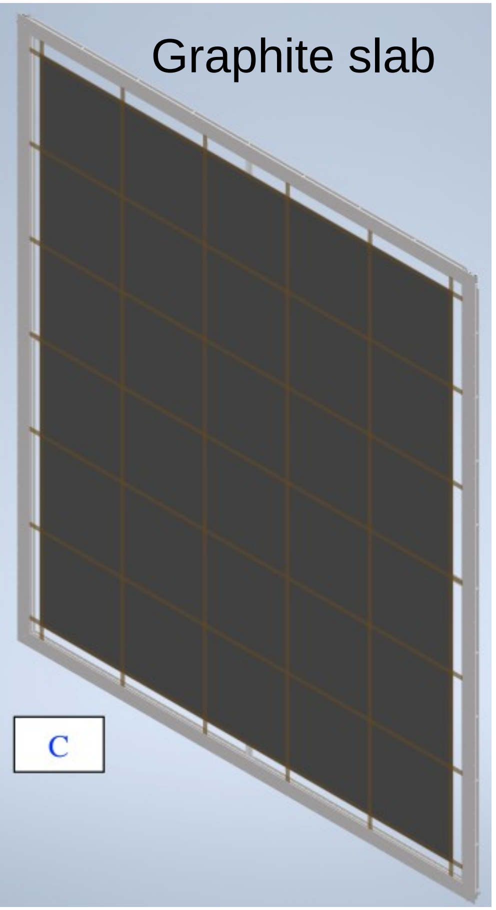
2+2 layers of 5 mm straws are disposed along the X and Y coordinates perpendicular to the beam

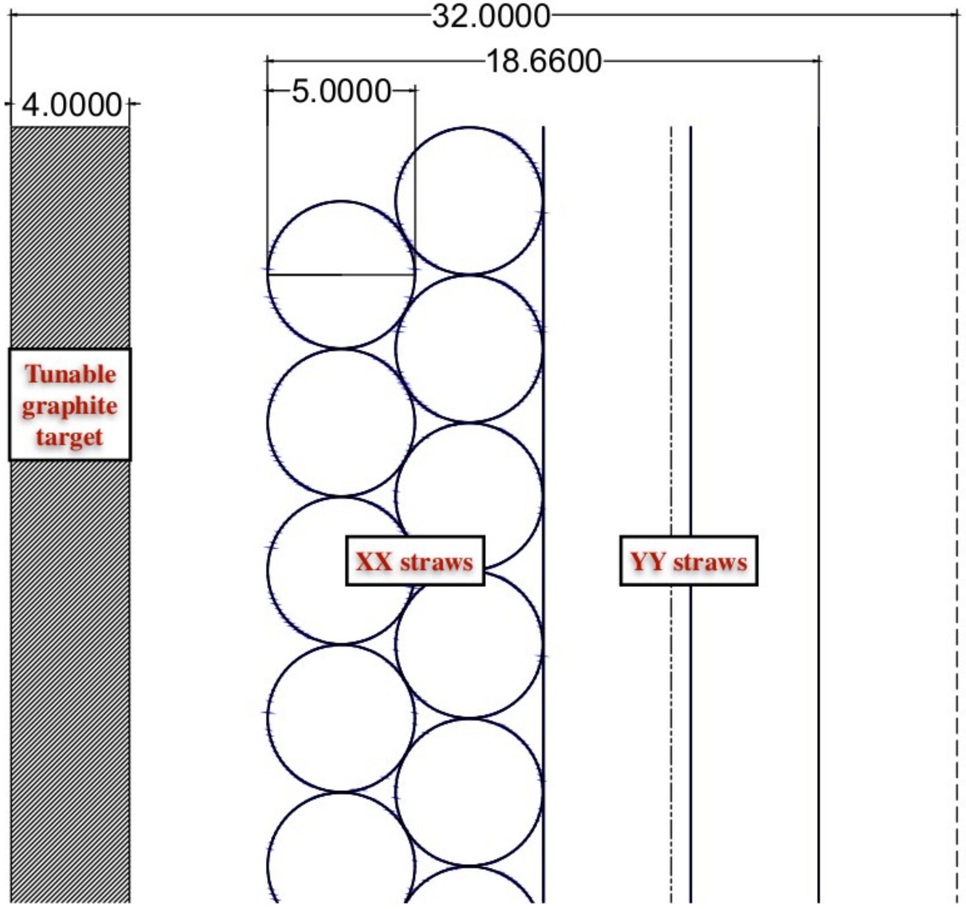
The default gas mixture is 70% Xe 30% $C0_2$

The overpressure is ~1 atm (2 atm absolute)

Straw length varies from 1 to 3.8 m

STT C modules



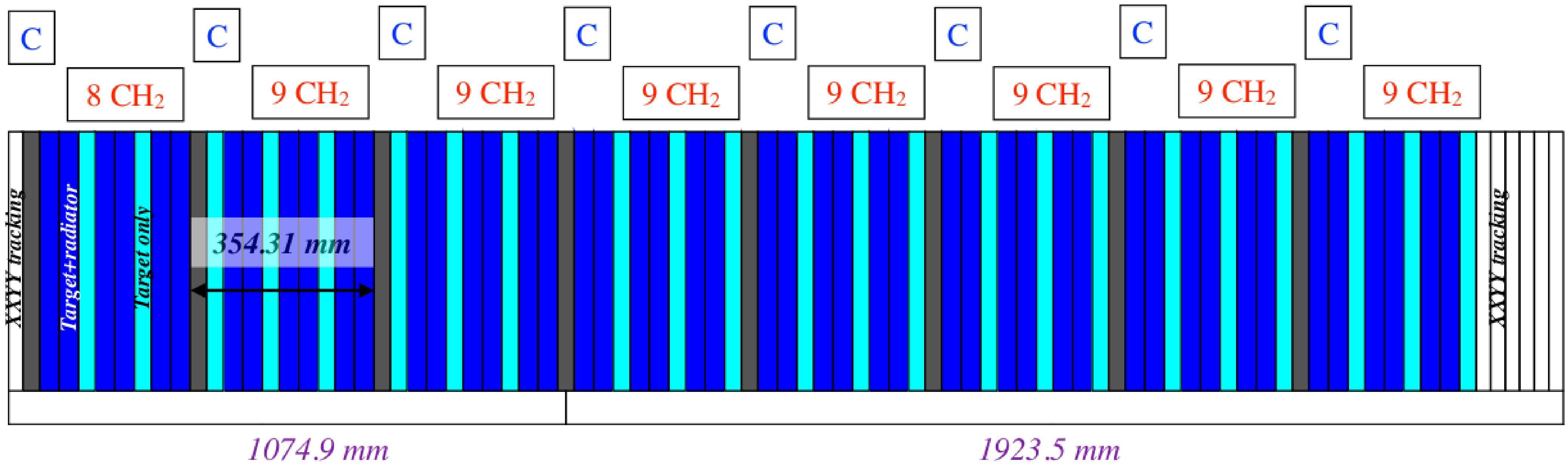


2+2 layers of 5 mm straws are disposed along the X and Y coordinates perpendicular to the beam

The default gas mixture is 70% Ar 30% $C0_2$

The overpressure is ~1 atm (2 atm absolute)

STT proposed structure



Default STT configuration with 925 mm upstream 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 module XXYY (28 mm)

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

STT straws

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

Max production rate for 5 m long straws: ~100/day

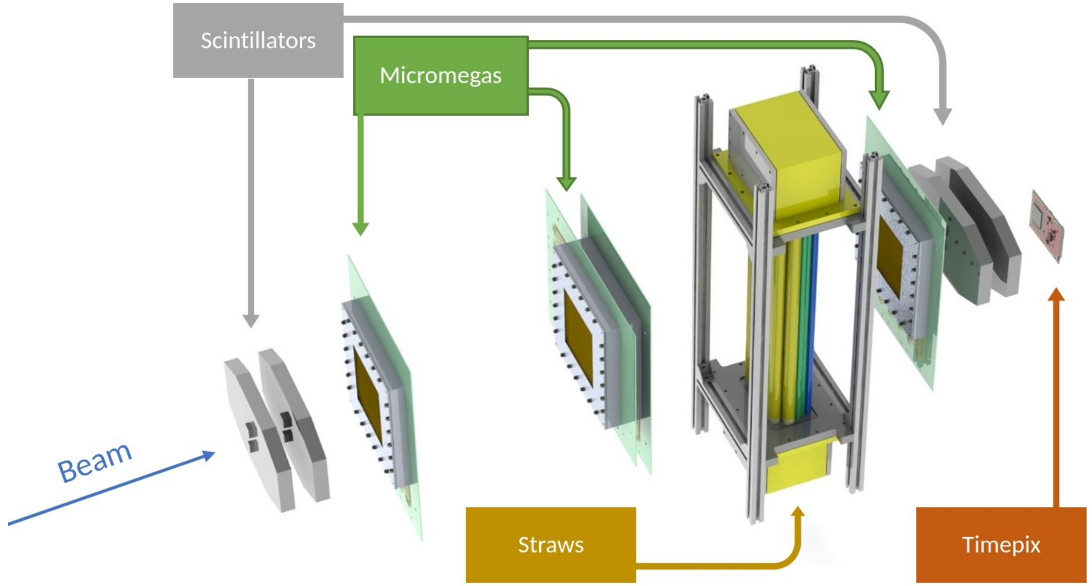
Straw production lines with ultrasonic welding currently operational:
1 JINR (5m) + 2 GTU (Tbilisi, 2×5m)+0.5 GTU (JINR, 2m)

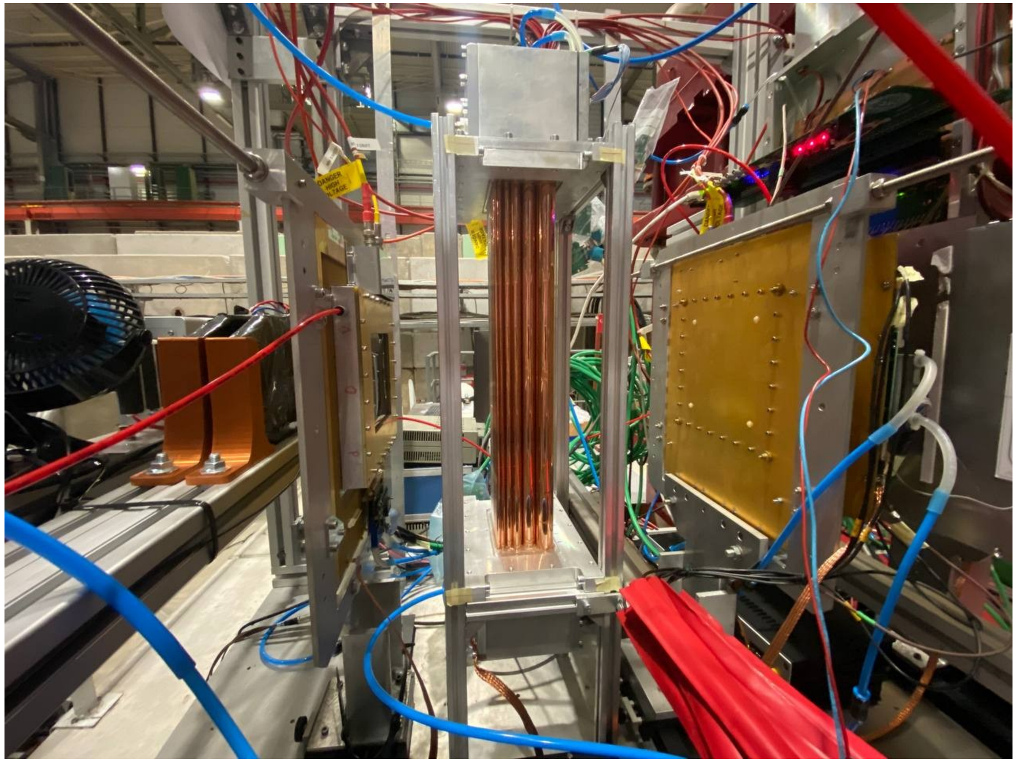
Expected total straw length produced in **3 years** (1 year=200 days):
50 straw/day × 600 day × 3.5 × 5 m = 525 km
with 16 people operating the 4 production lines + quality control

Existing straw production capacity not far from the wanted 700 km

In preparation at Almaty (Kazakhstan): 5m (2024?) + 12 m (2025?)

Prototyping activities: CERN test beams

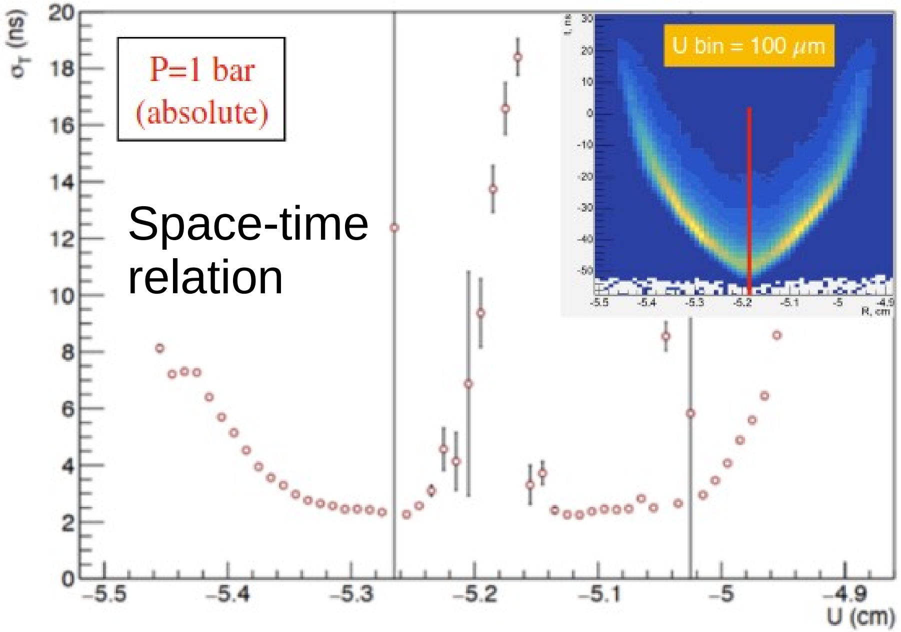




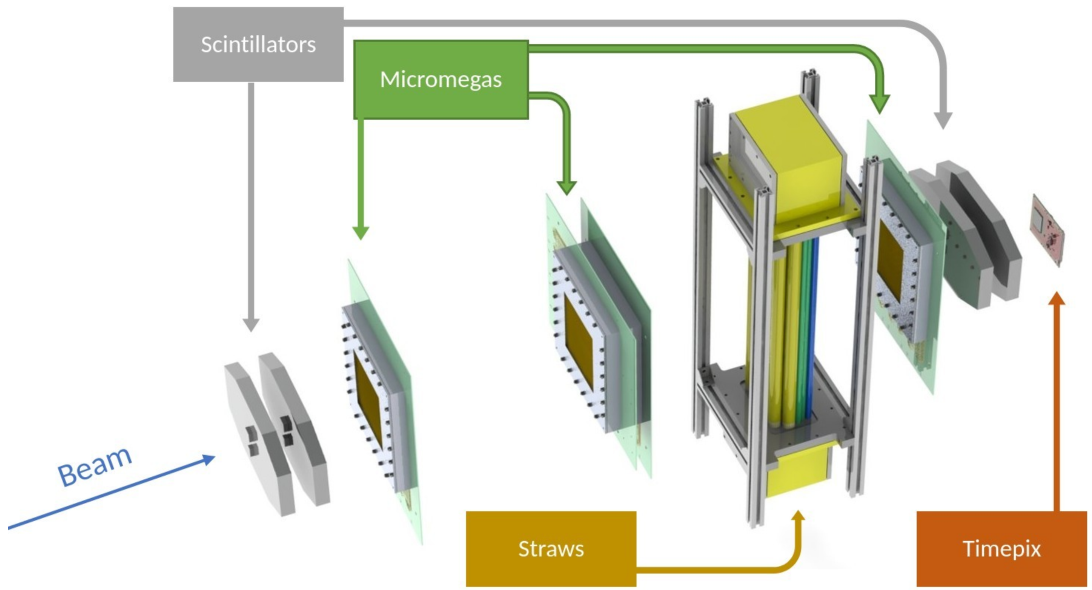
Long test beam activity started in 2021 at Cern H4

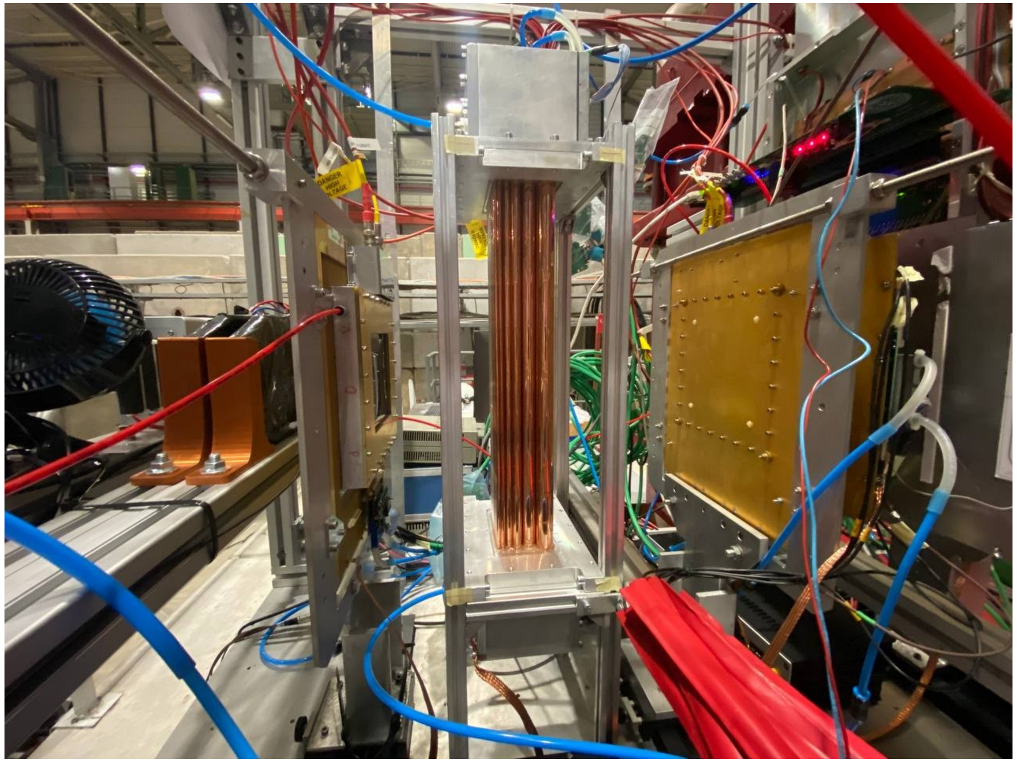
Mixed two layers of 5mm longitudinal straws has been tested at the H4 line at Cern

Further beam test time available at PS T9 starting from October 2024



Prototyping activities: CERN test beams





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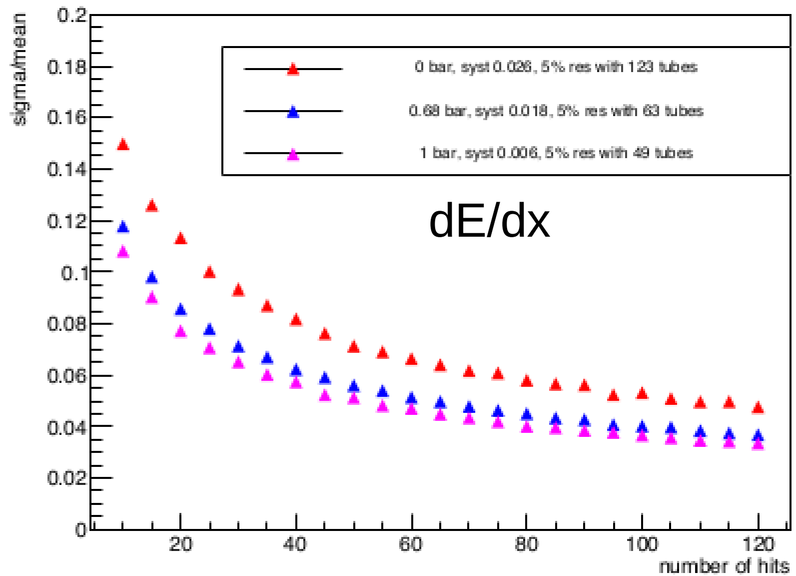
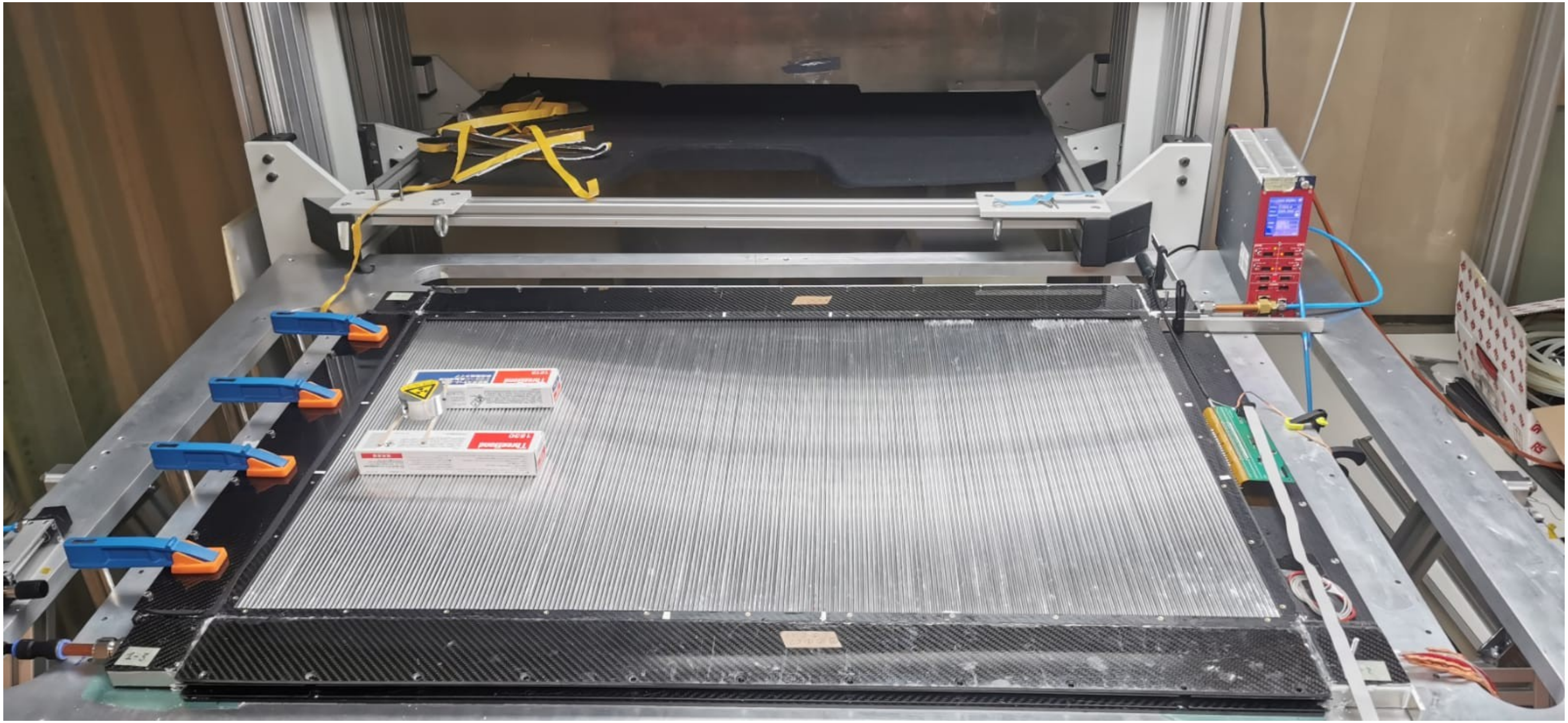
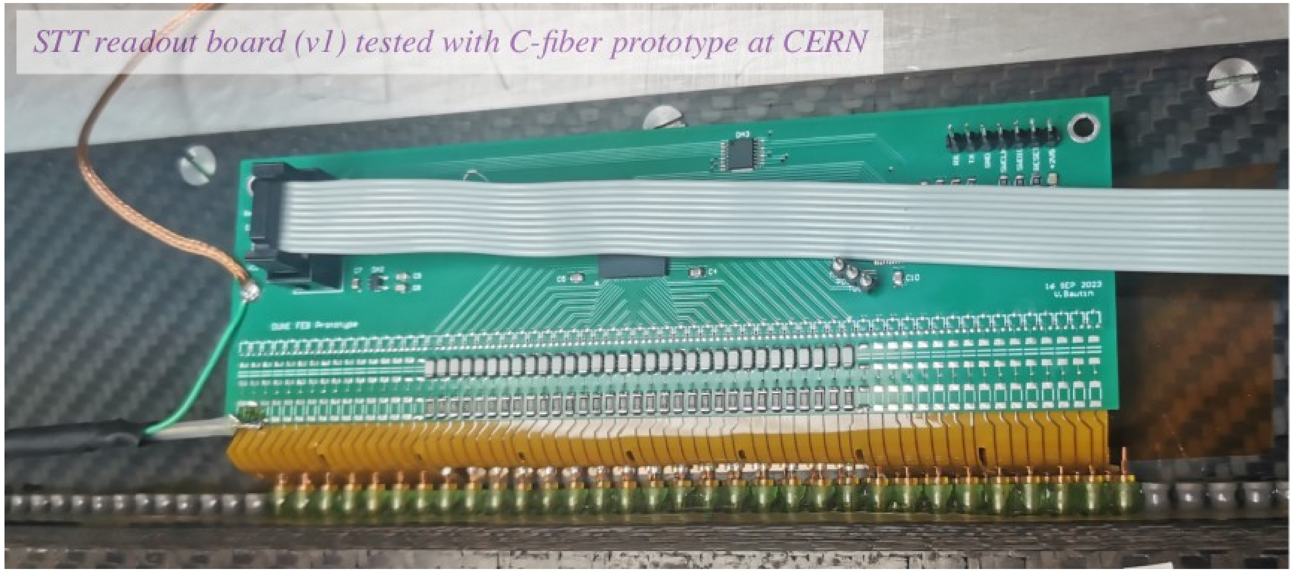


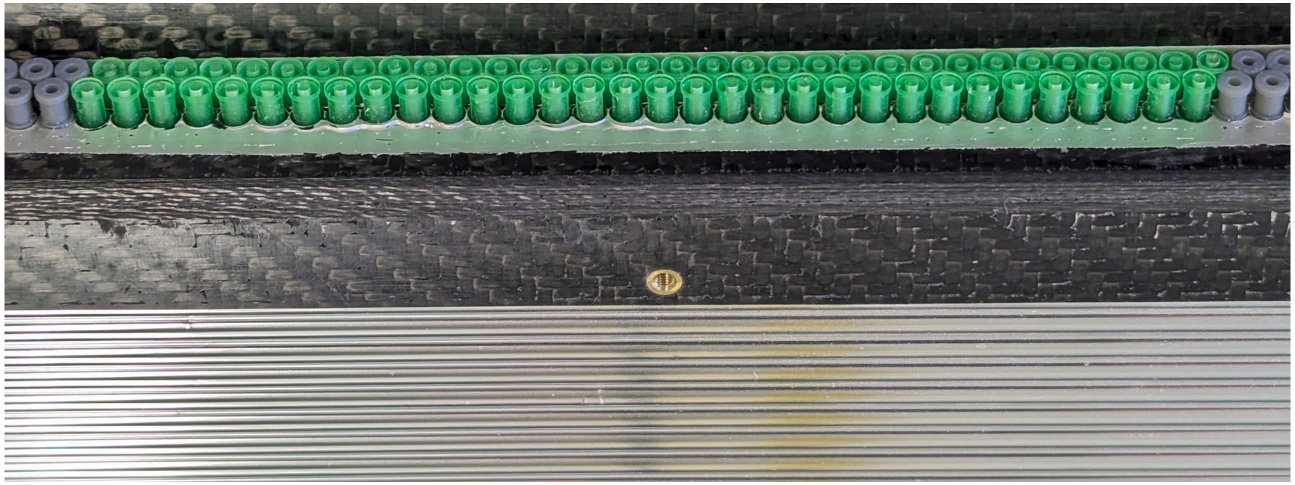
Prototyping activities: 80x120 cm prototype

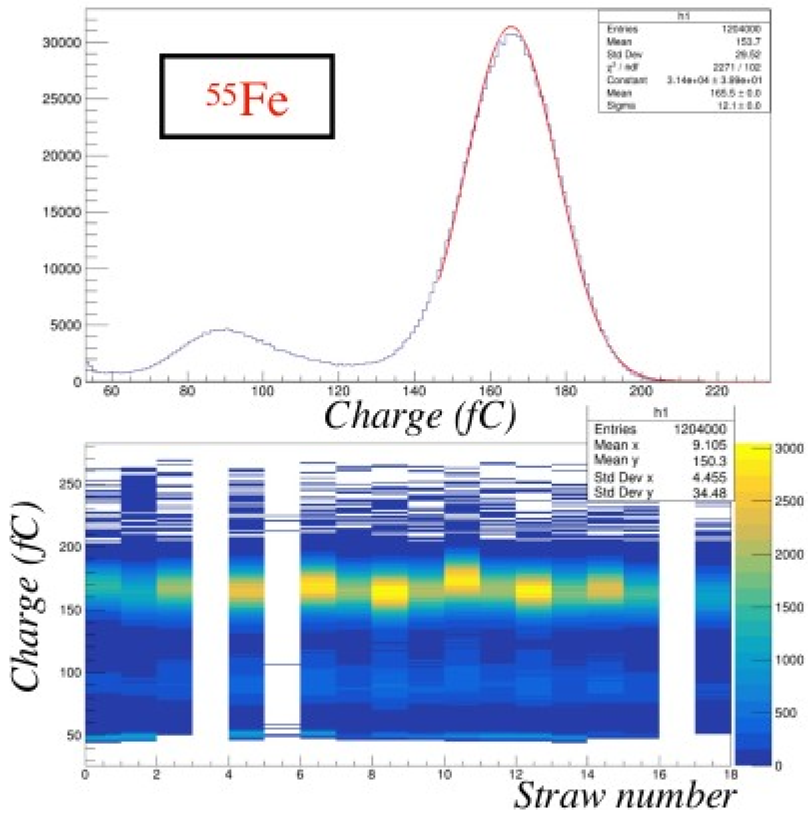


A 120x80 cm prototype has been built at Cern in November 2023:
- ~700 Straws (+spares) produced from GTU
- C-fiber frame (see F. Raffaelli's presentation)
- first version of integrated readout

Prototyping activities: 80x120 cm prototype

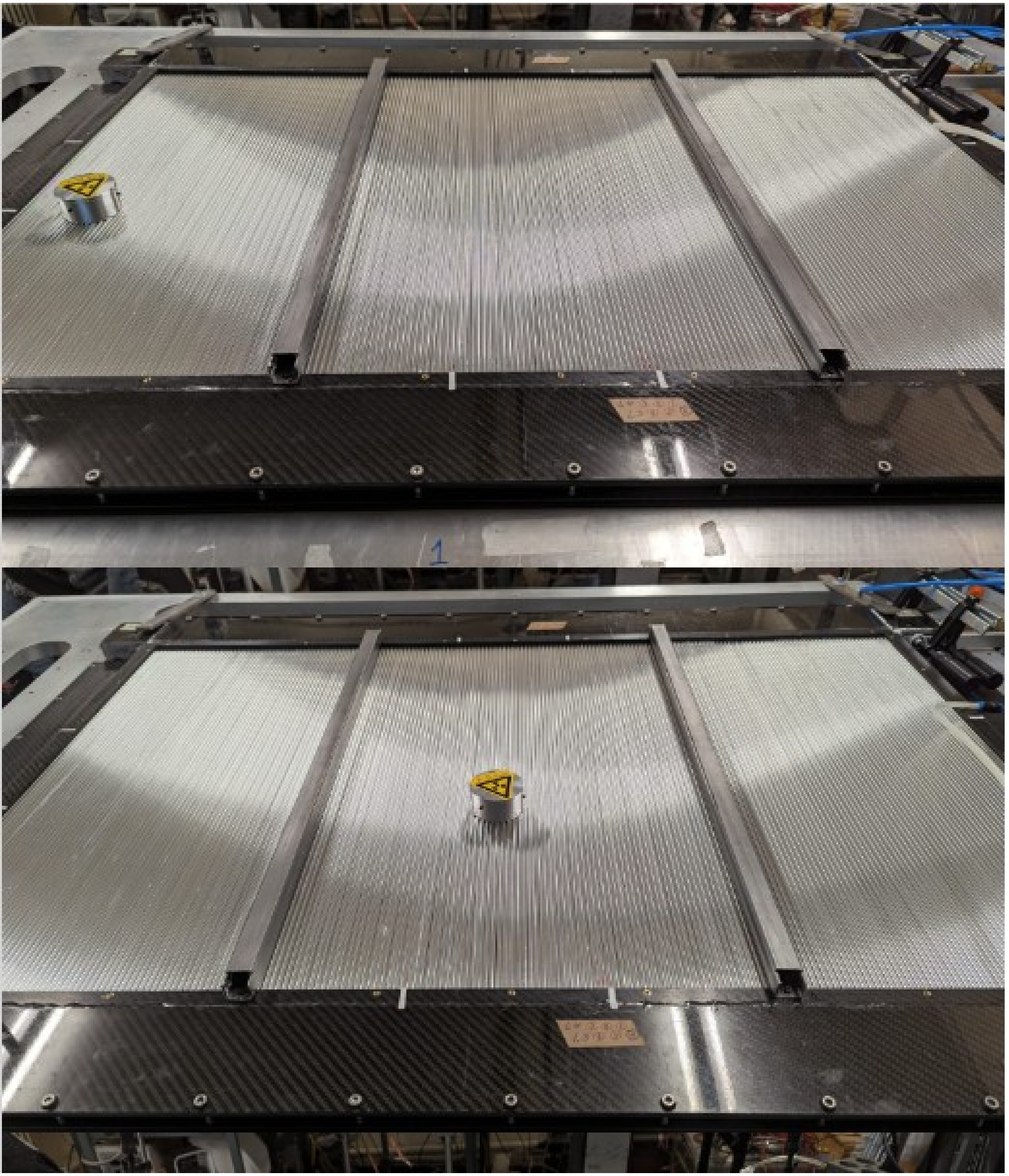


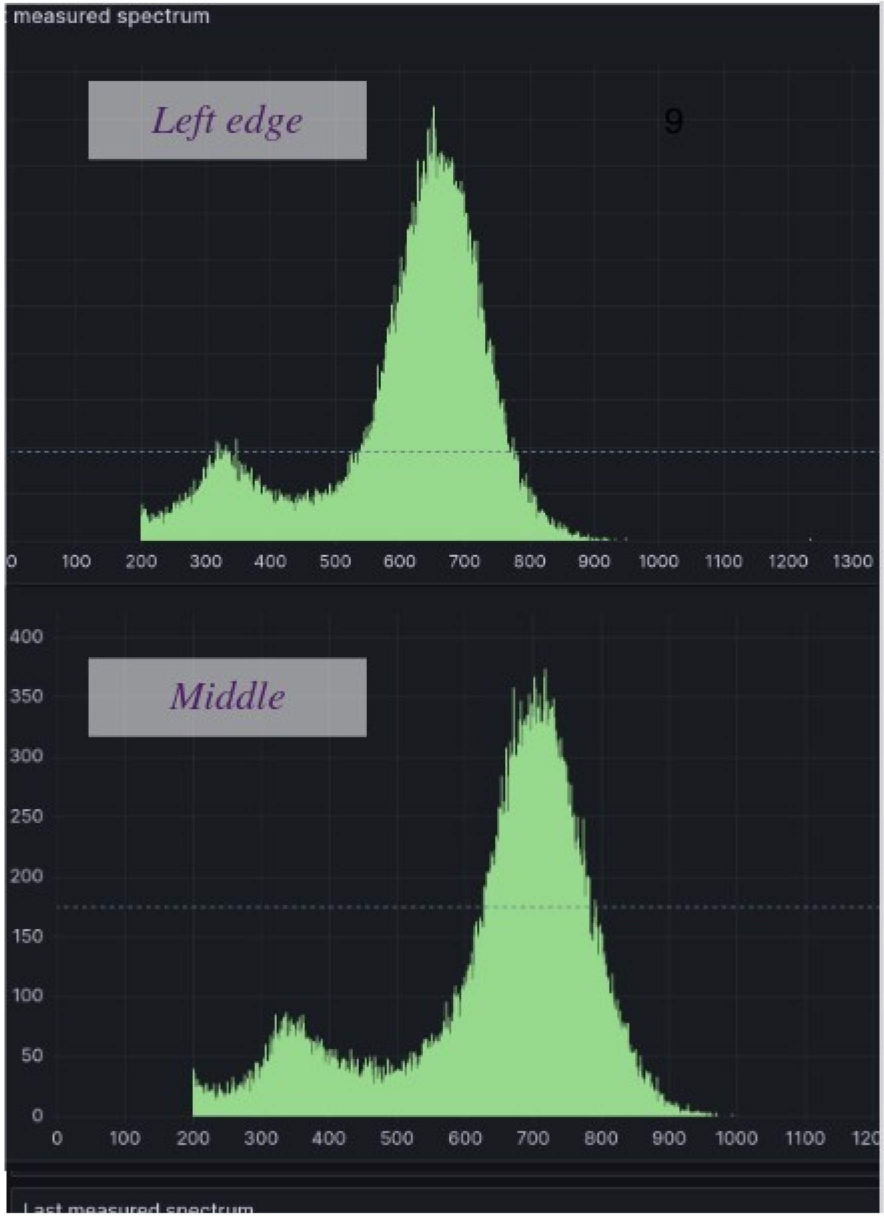




64 (XX)+64(YY) straws wired
Custom readout board using VMM3a ASIC chip

Prototyping activities: 80x120 cm prototype



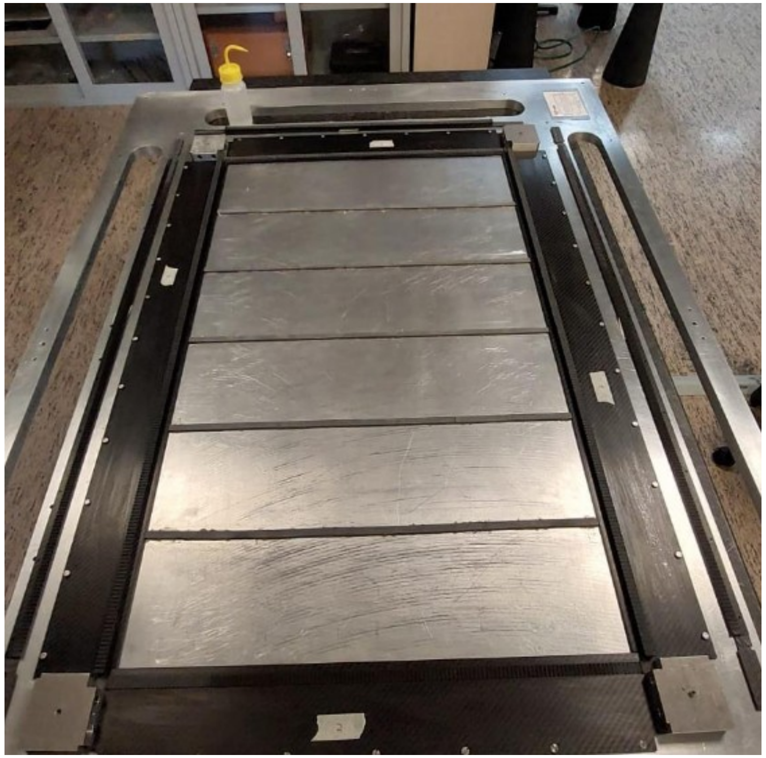


64 (XX)+64(YY) straws wired
Custom readout board using VMM3a ASIC chip

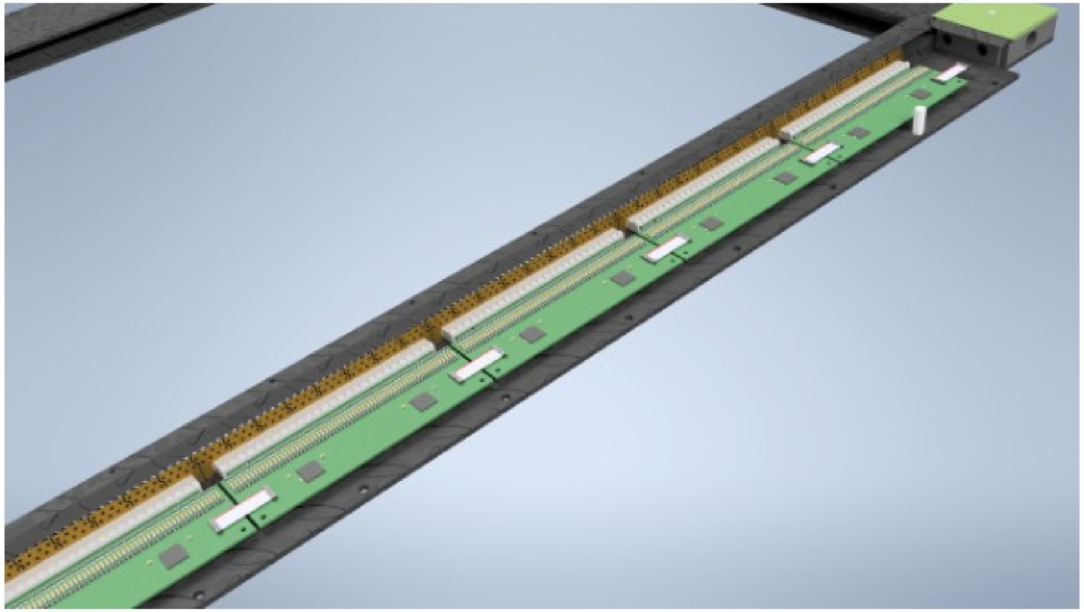
Prototyping activities: 80x120 cm prototypes

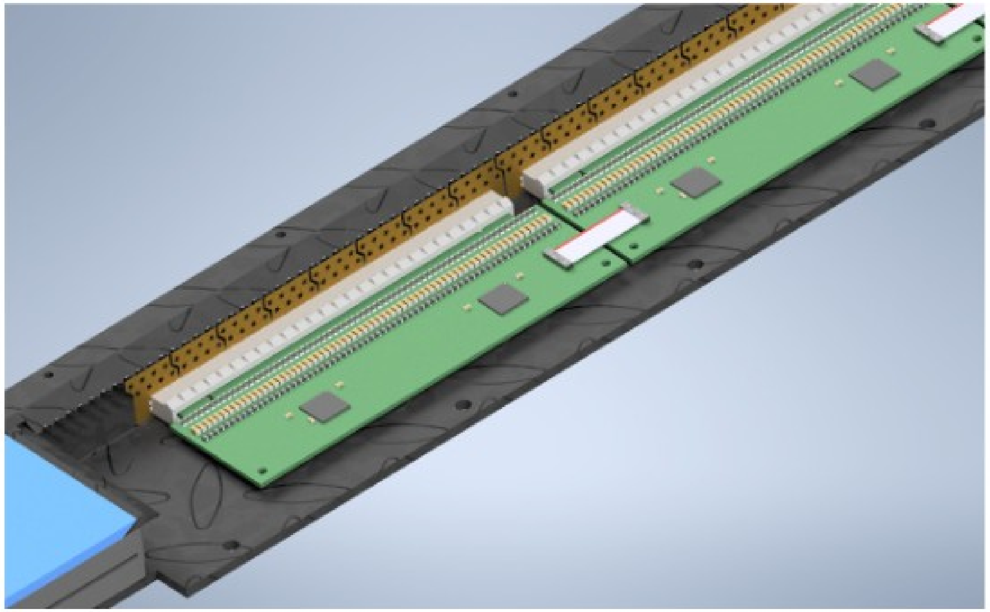
Further beam test time available at PS T9 starting from October 2024

New 120x80 cm prototype will be built in Pisa in September 2024 (see F. Raffaelli's talk)



Readout electronics: integrated boards





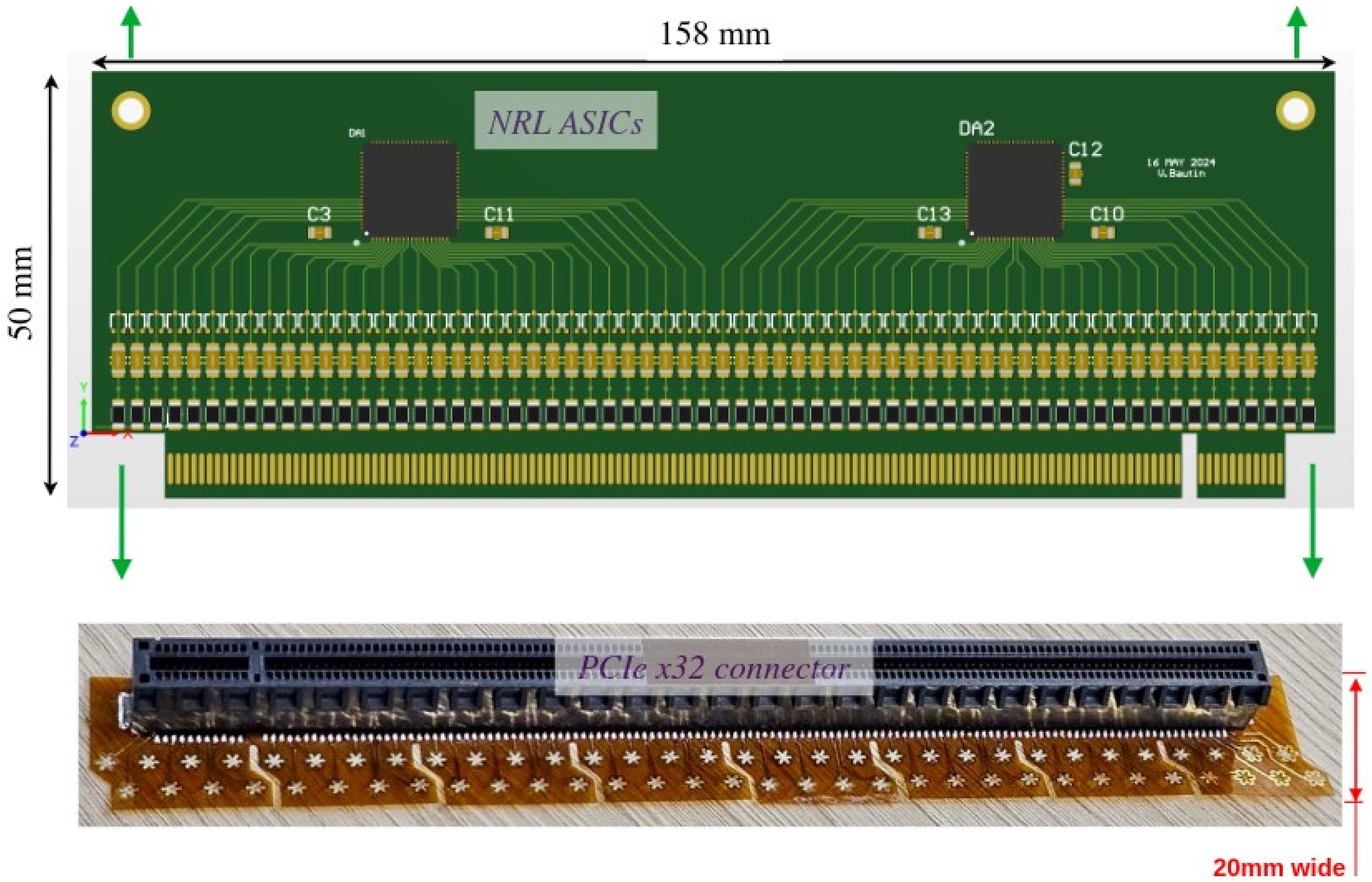
✦ *Integrated boards reading up to 64 straws each with ASIC + micro-controller (MCU):*

- *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*

$\Longrightarrow$ *First version (v1) successfully tested, prototypes of revised version (v2) in preparation*

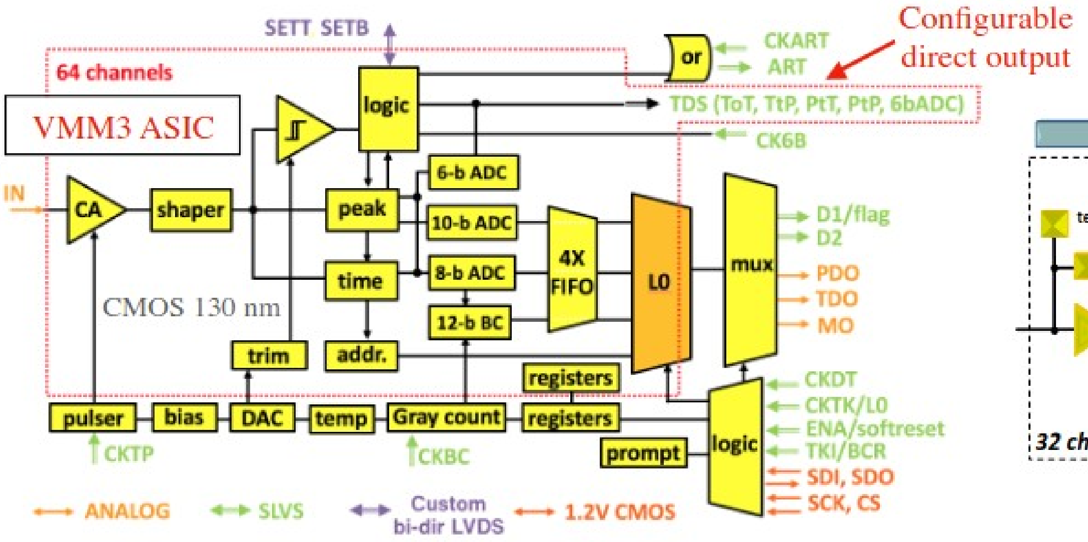
Readout electronics

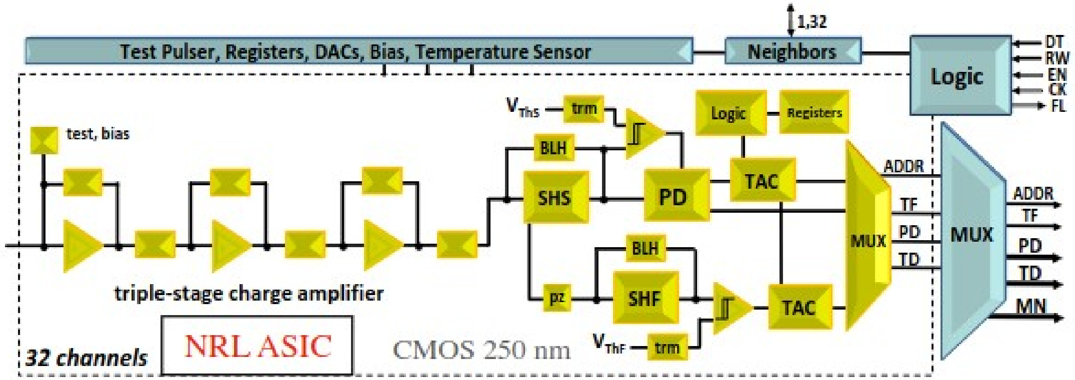


Revised design (v2) of the readout board and of the connecting flexible kapton board

Readout electronics: existing chips

VMM3A ASIC AND NRL ASIC





✦ *Design variant of STT readout board with existing VMM3a as backup solution:*

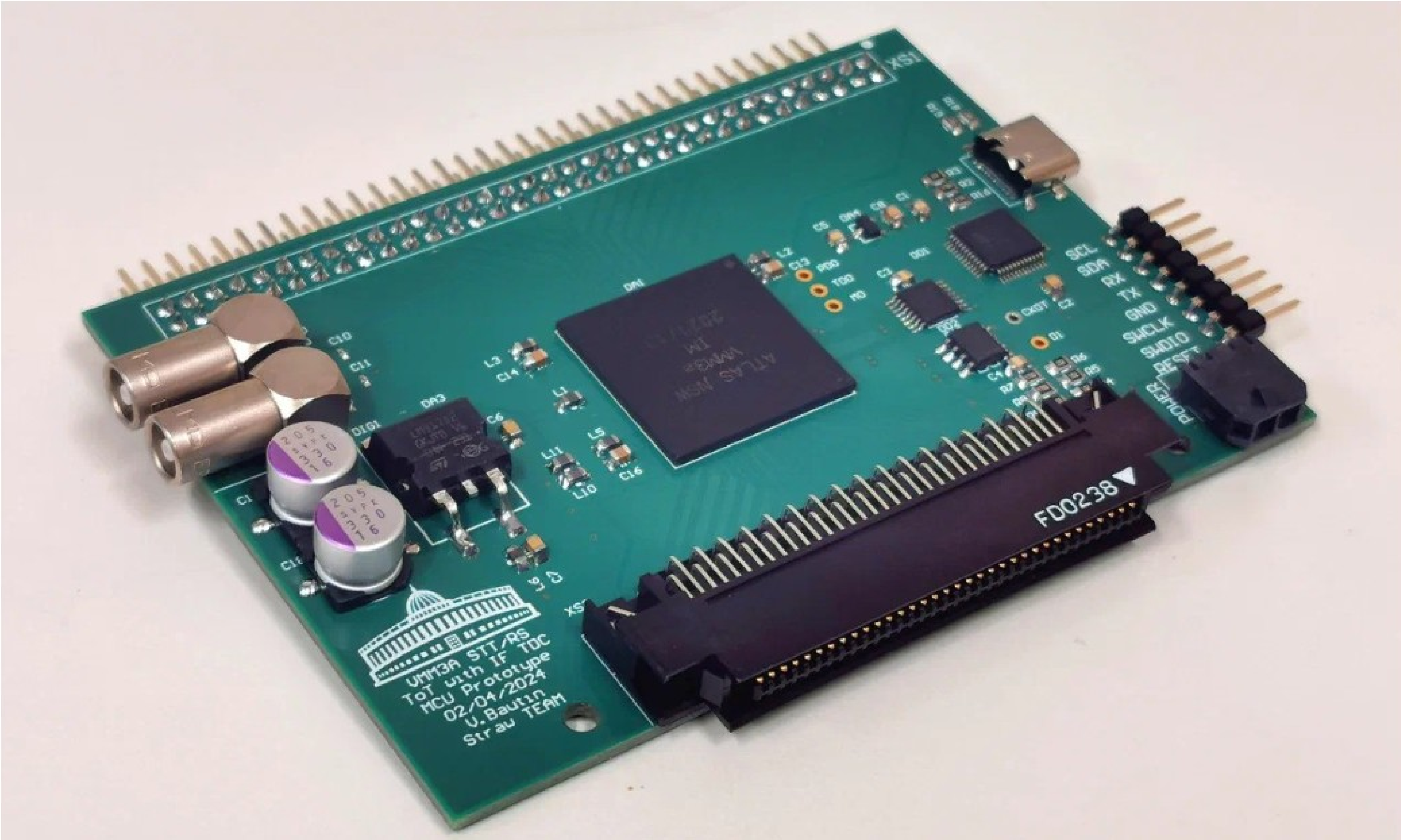
- *Use VMM3a direct output in "external" ADC mode with the MCU (bypassing internal ADCs);*
- *Readout variant readily available which could be used during construction and initial data taking;*
- *Default STT readout minimizing project risks while developing custom ASIC.*

✦ *Design variant with existing NRL ASIC to test base architecture for custom ASIC*

⟹ *Flexible design allows easy exchange/upgrade of individual STT readout boards*

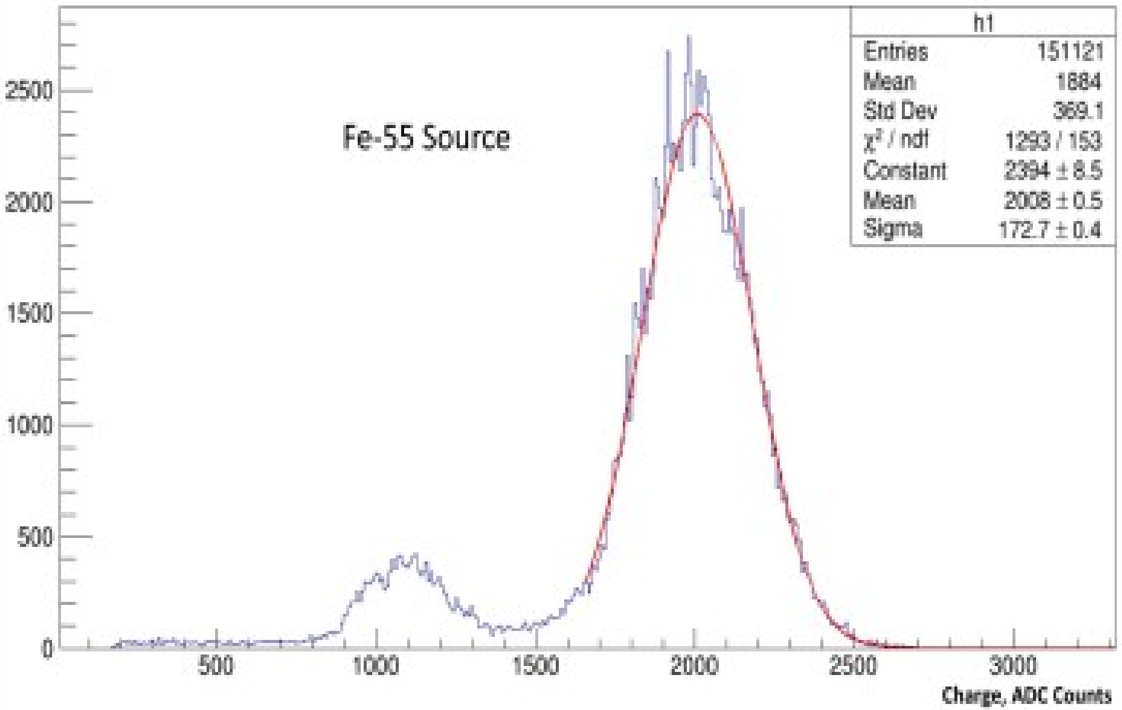
Readout electronics: backup solution

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.

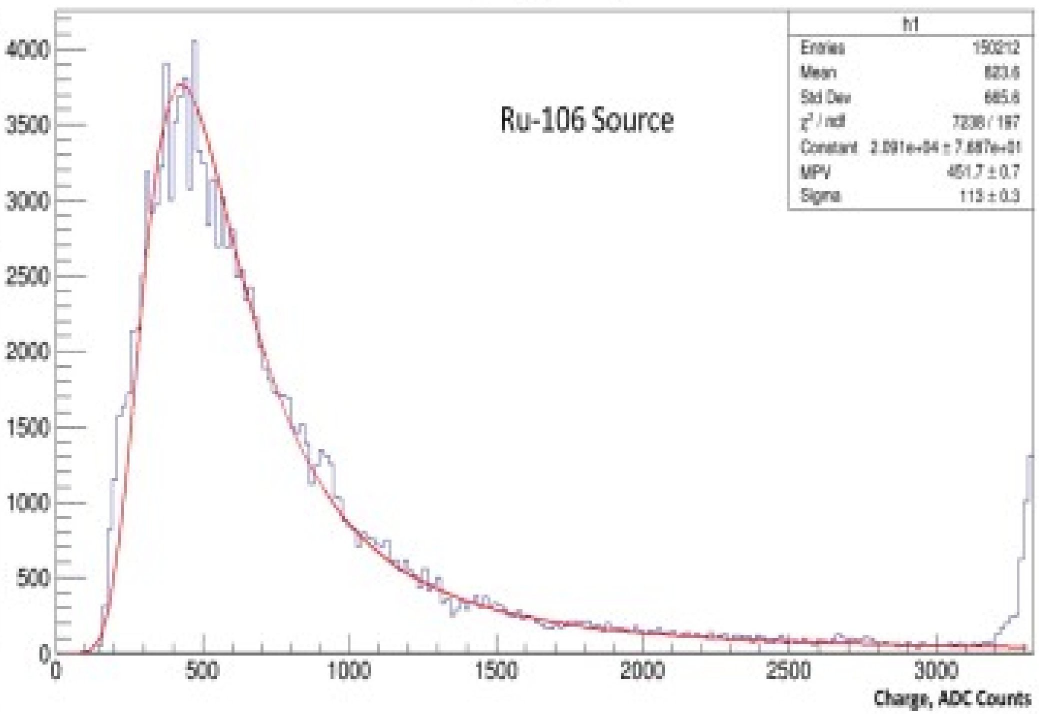


Readout electronics

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

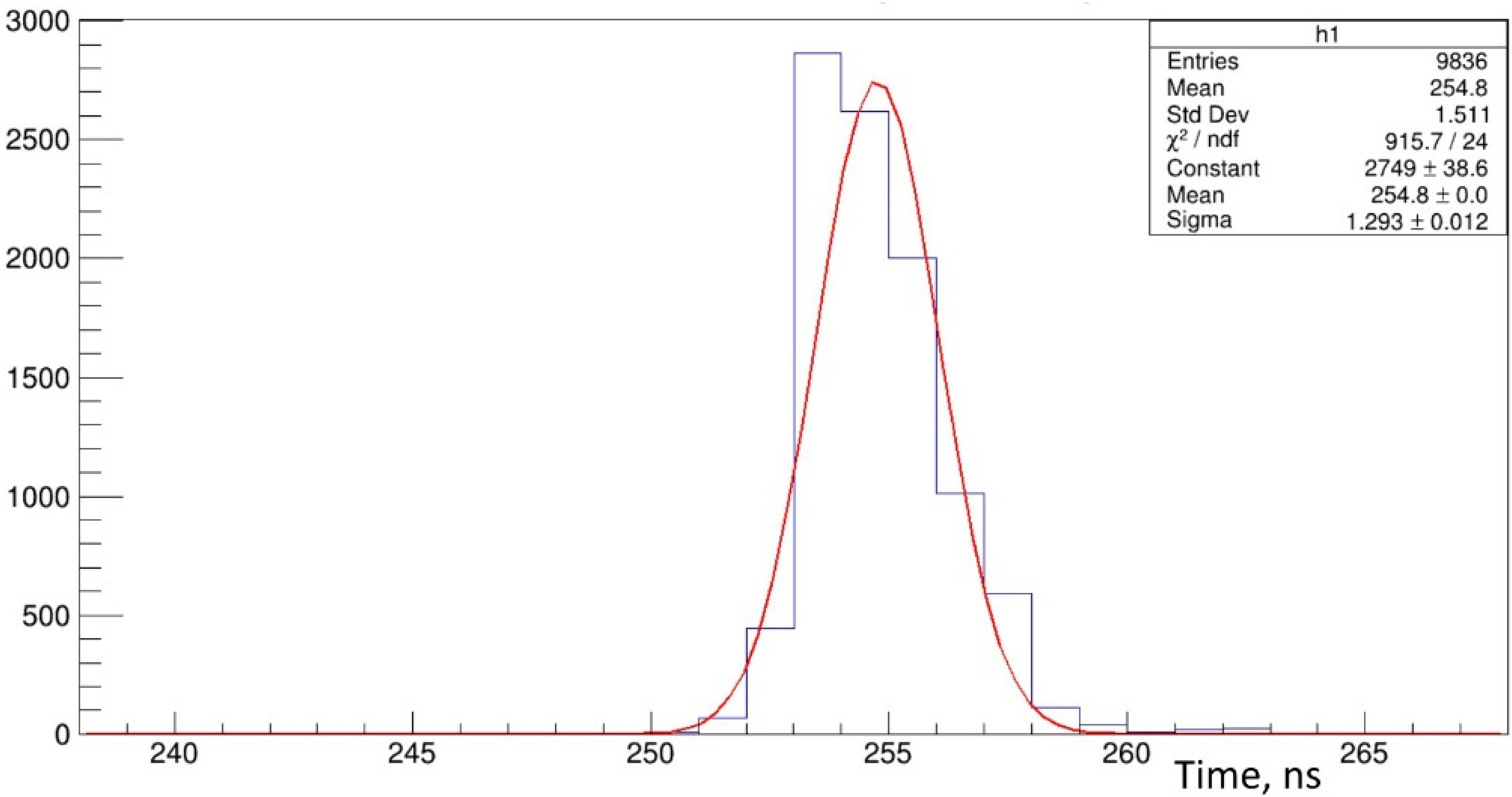


Fe55 Spectra, external ADC
Much better resolution



Ru106 Spectra, external ADC
Much better resolution

Readout electronics



Time measurements, external ADC
Much better resolution

Gas system

R. Guida (CERN)

- *Modular design based on several modules (building blocks):*
  mixer, pre-distribution, distribution, circulation pump, purifier, Xe recuperation, exhaust, gas analysis, etc.
- *Functional modules used same as gas systems of similar detectors at CERN like ATLAS-TRT & ALICE-TRD;*
- *Implementation: control rack and crates (flexible during installation phase and max modularity for large systems).*

Control rack

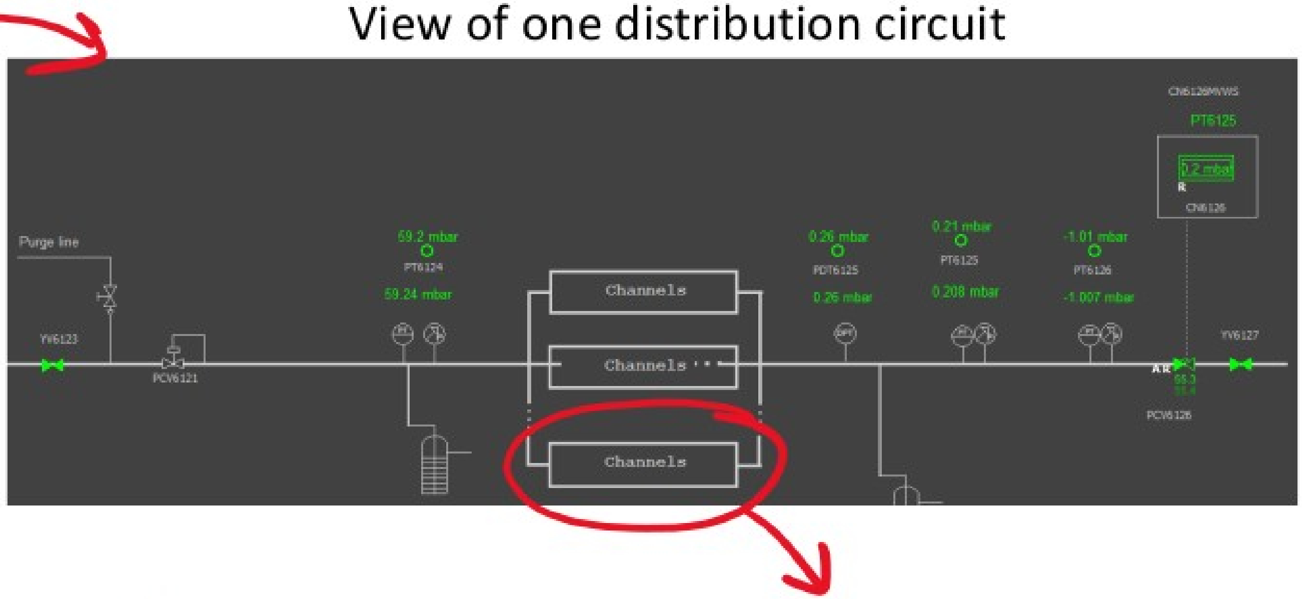
Control crate
(PLCs)

Modules crates
Profibus connection to
control crate

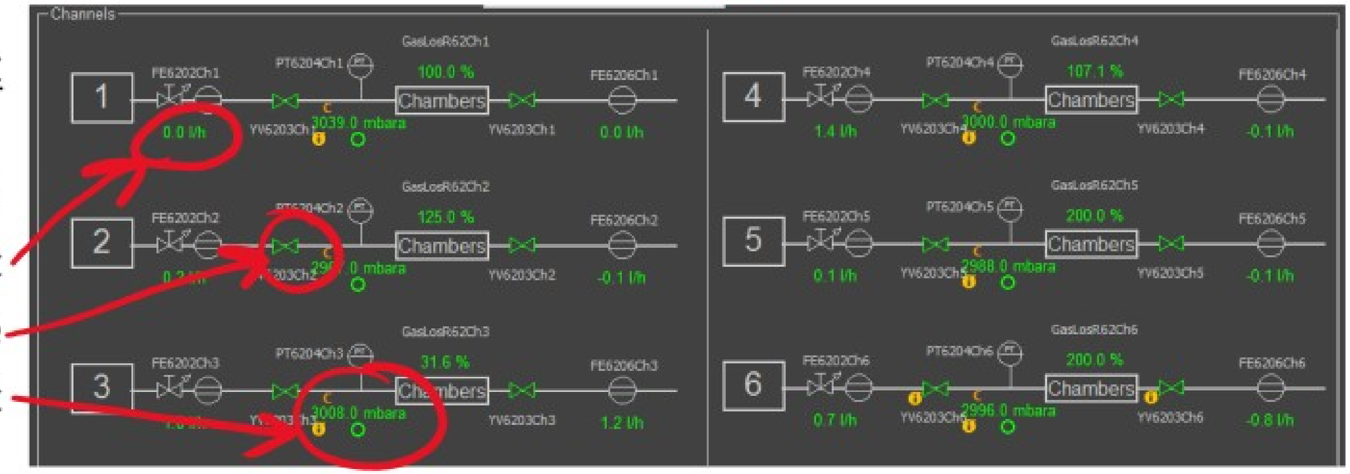
Gas system

STT distribution: 8 circuits Xe/CO_2, 7 circuits Ar/CO_2

View of one distribution circuit



6 STT modules per circuit



Example from LHC:

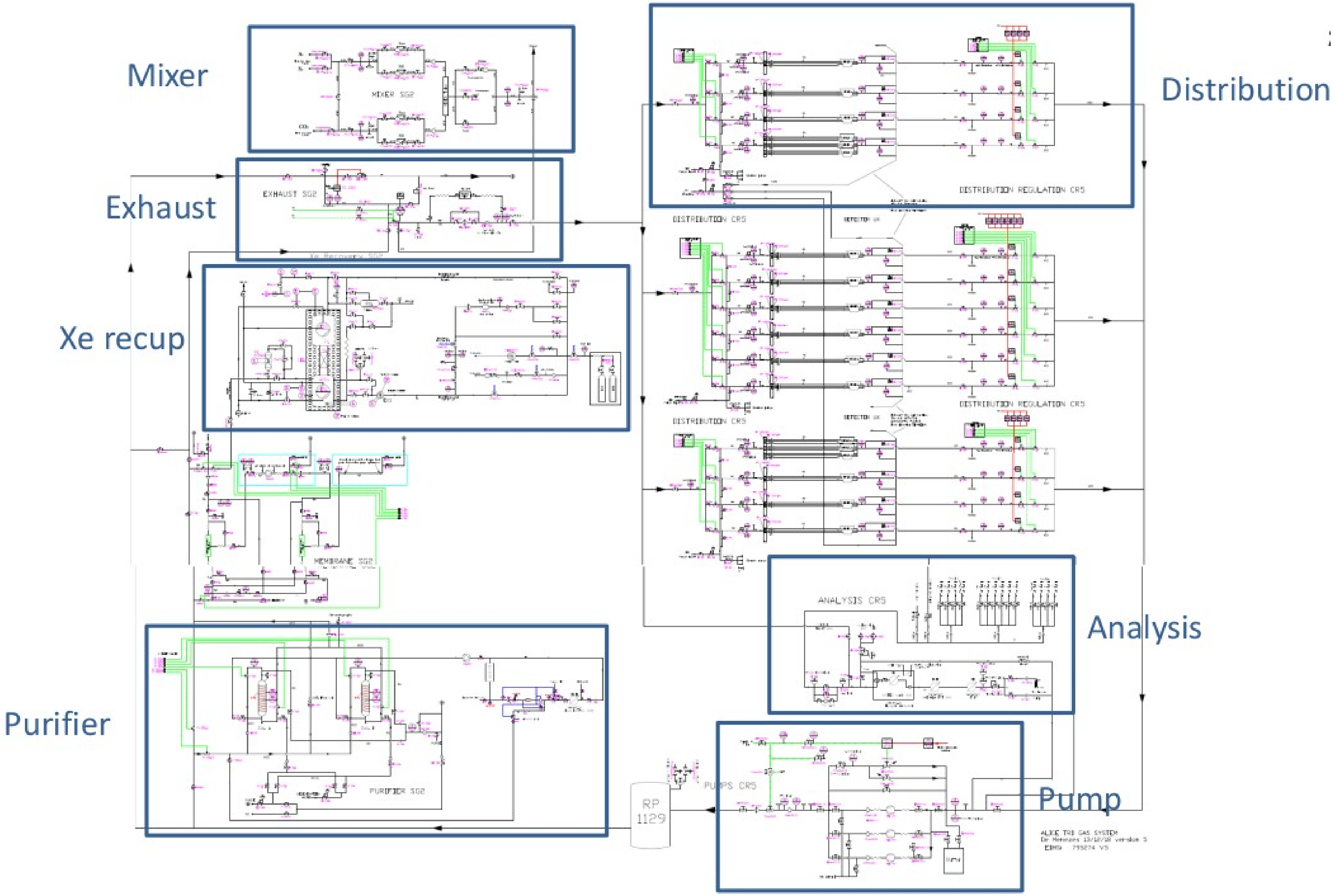
Flow readout

Individual valves per module

Absolute pressure for leak test

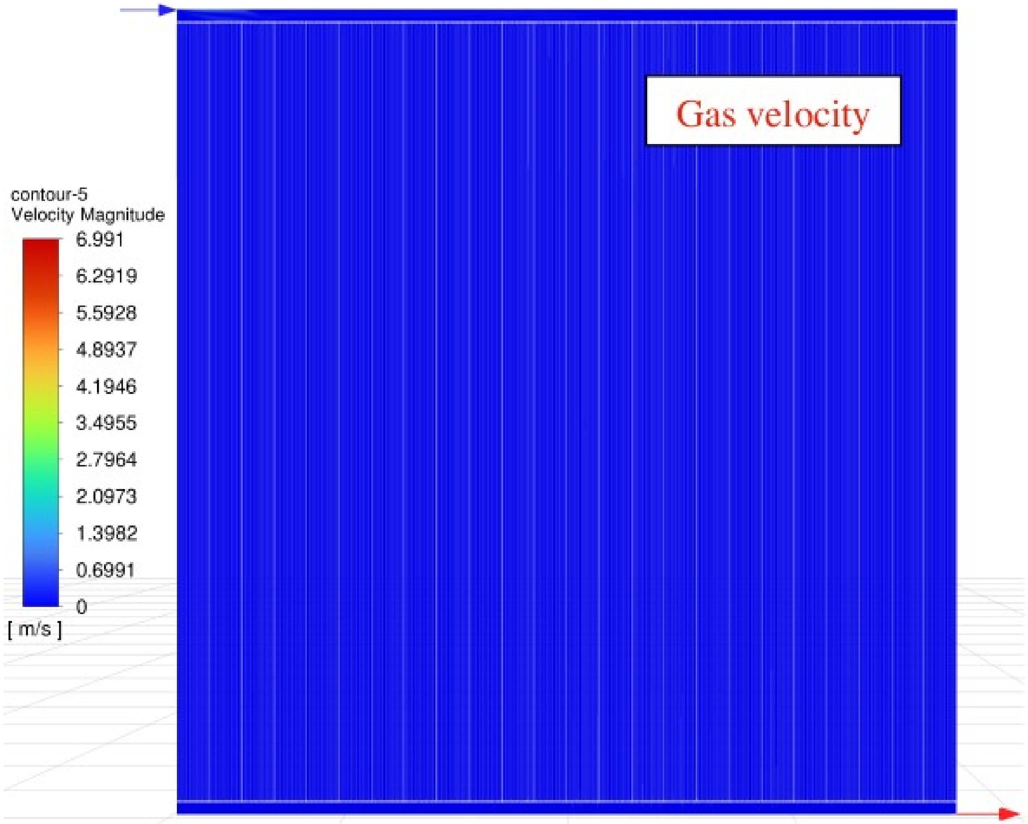
Gas distribution for the STT in SAND (with both Xe/CO_2 and Ar/CO_2)

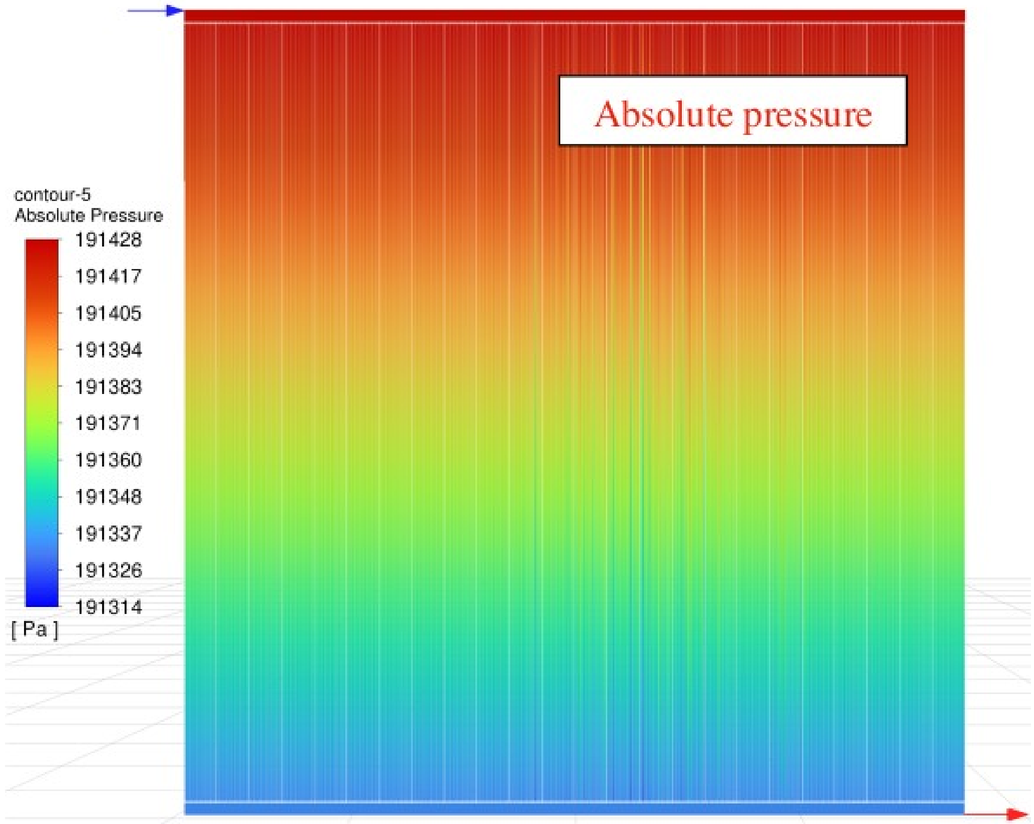
Gas system



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

Gas flow simulation

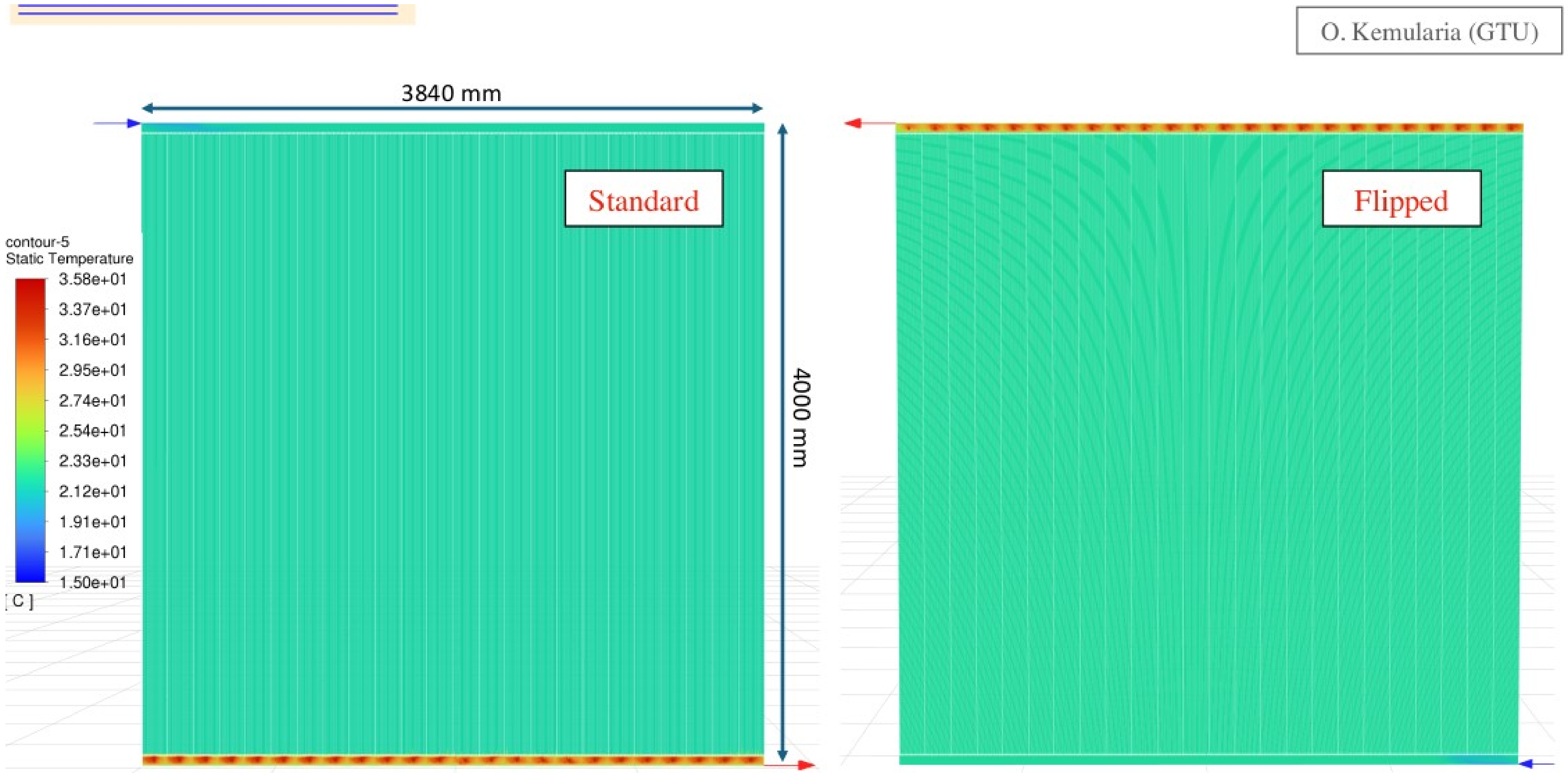




- *Study of gas flow within a 4m STT module to verify uniformity and inlet/outlet design;*
- *Check local gas velocity and pressure inside manifolds/straws for both standard and flipped modules*

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

Thermal simulation



- *Thermal analysis of full scale 4m STT module with 24 integrated readout boards;*
- *Self-cooling design with expected total power dissipation about 0.65 W per board (mostly ASIC)*

$\Longrightarrow$ *Maximal temperatures obtained well below 40⁰ C allow extended board lifetime*

Assembly sites

- *MA units currently operational:*
  - *Assembly site at JINR (operated by INP/JINR) ⟶ 1 MA unit*

  ⟹ *1 MA unit capable to produce 4m STT modules available in 2023*

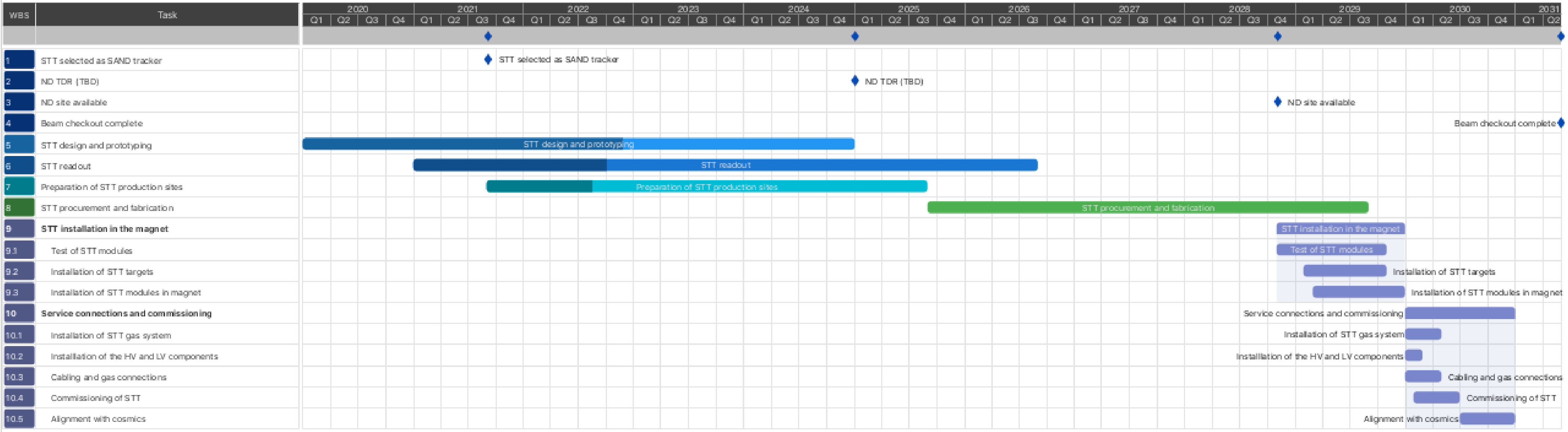
- *MA units under construction / in preparation:*
  - *Assembly site at INP (Kazakhstan) ⟶ 2+1 MA units;*
  - *Assembly site at GTU (Georgia) ⟶ 1 MA unit.*

  ⟹ *A total of 4 MA units expected to be operational by 2026*

- *MA units planned:*
  - *Assembly site at IIT Guwahati (India) ⟶ 1 MA unit;*
  - *Assembly site at Punjab University (India) ⟶ 1 MA unit;*
  - *Assembly site at NISER Bhubaneswar (India) ⟶ 1 MA unit;*
  - *Assembly site INFN (Italy) ⟶ 1 MA unit;*
  - *Assembly site in USA ⟶ 1 MA unit.*

  ⟹ *Additional 5 MA units planned for STT production*

Schedule (to be updated)



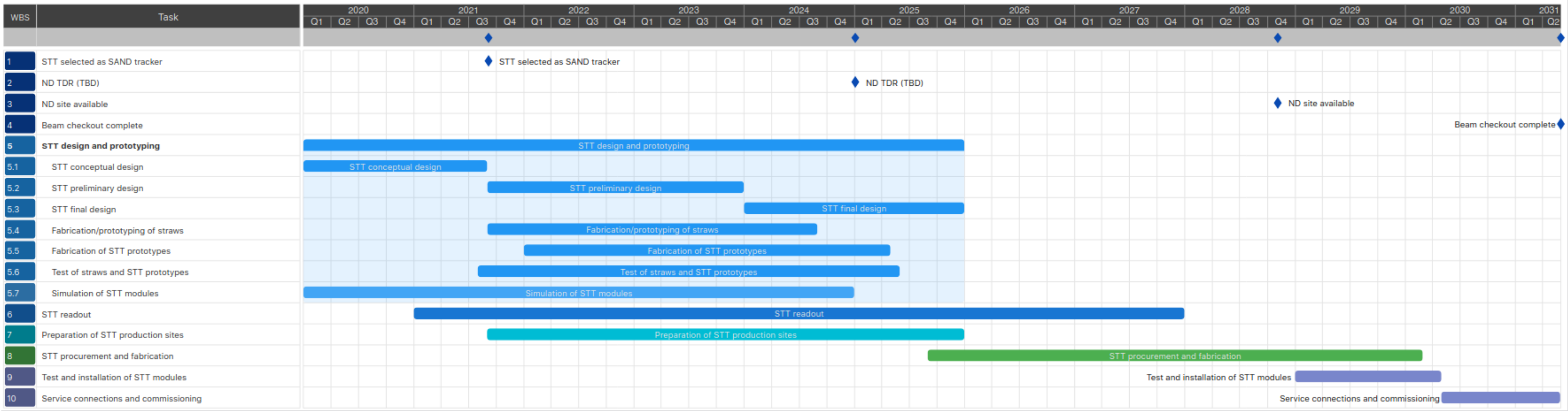
Test beam of 120x80 module end of 2024 – start of 2025 at Frascati BTF
Technical choice between STT and DCH expected by summer 2025

First STT full scale prototype in advanced procurement status planned to start end of 2024 in Almaty
First full scale module construction in Italy SJ to technical choice

Assembly sites in preparation in GTU, Kazakhstan and India
Italian production sites preparation waiting for technical choice

Custom ASIC chip order waiting for technical choice

Tentative Schedule



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*)

Oct 2030 – Jun 2031: detector commissioning

Jun 2031: First beam

** Assuming 2 months for each of the 86 modules and 4 assembly sites*

Cost estimate (obsolete from 2020)

Item	Cost (USD)	Comment
Procure straws	1,550,731	Quote from Lamina Tubular Tech., UK [7]
Procure end plugs	335,911	Quote from FBM, Italy
Procure wire spacers	335,911	Quote from FBM, Italy
Procure crimping pins	295,183	Quote from Medspeztrub, Russia
Procure anode wire	211,038	Quote from Luma metall AB, Sweden
Procure miscellaneous components	123,000	Cost from NA62, ATLAS TRT
Procure mechanics & C-fiber frames	990,000	Quote from Bercella, Italy
Procure STT tools (3 sites)	249,000	Cost from existing facilities
Procure equipment & consumables	100,000	Cost from other straw detectors
Procure gas system (Xe/CO_2 + Ar/CO_2 + cooling)	495,600	Quote from CERN gas group
Procure radiator foils	112,000	Quote from Bloomer Plastics, USA
Procure polypropylene targets	32,200	Quote from Boedeker Plastics, USA
Procure graphite targets (ET10)	49,400	Quote from Weaver Industries, USA
Procure front-end electronics (VMM3)	283,469	Quote from Fraunhofer/BNL
Procure back-end electronics (FELIX)	93,708	Cost from ProtoDUNE
Procure HV components	97,489	Quote from CAEN, Italy
Procure LV components	64,299	Quote from CAEN, Italy
Procure distribution boards	57,360	Cost from ATLAS NSW
Procure cables & connectors	62,310	Quote from CERN store
Total	5,538,609	

Table 43: Estimated core costs for the construction of the baseline STT design described in Sec. 3.3.3. We assume a standard 20% contingency to be added to the core costs.

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

Almost final estimate of core costs ~5M$ still to be presented to the working group (slightly lower than previous estimate) will be discussed and reviewed within the collaboration in the next months

BACKUP

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

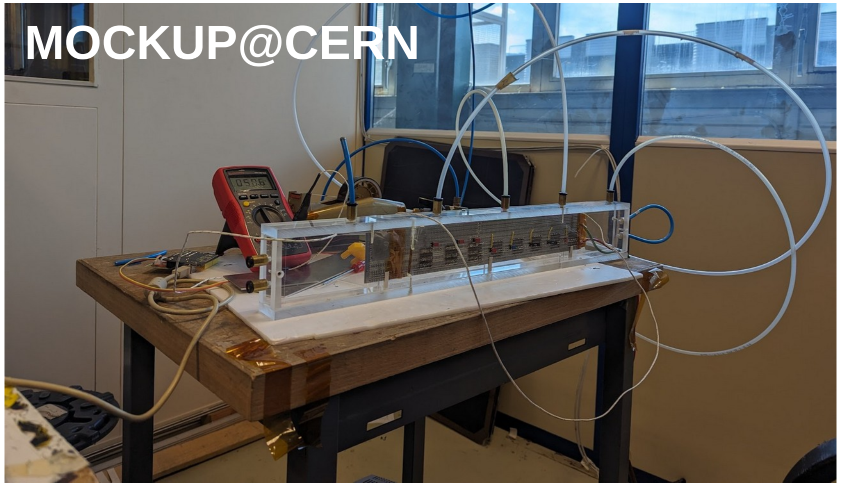
** from 'Physics requirements of the Phase I Near Detector', April 2024*

SAND inner tracker capabilities goals*

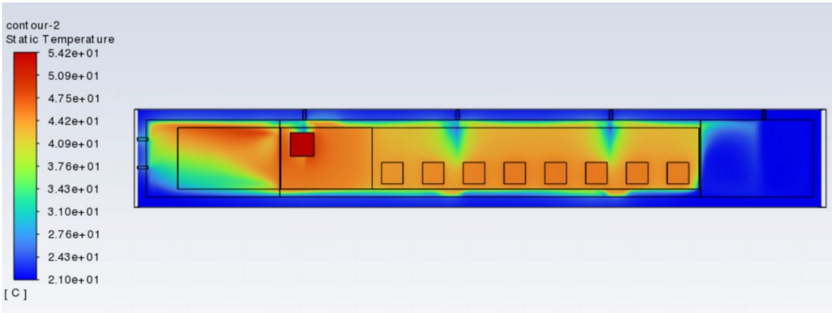
Label	Name	Requirement	Rationale	Ref. Req.
ND-C3.1	Tracker density	The SAND inner tracker should have average density $\rho < 0.22\text{g}/\text{cm}^3$	Low density is essential to minimize multiple scattering and allow precision magnetic spectrometry	ND-X1, ND-X8
ND-C3.2	Tracker momentum resolution	The SAND inner tracker should have charged particle momentum resolution $< 5\%$ up to $p \sim 5\text{GeV}/c$	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 $\nu - \text{Ar}$ interactions with $\nu - \text{H}$ measurements enabled in ND-C3/5.	ND-X6, ND-X7

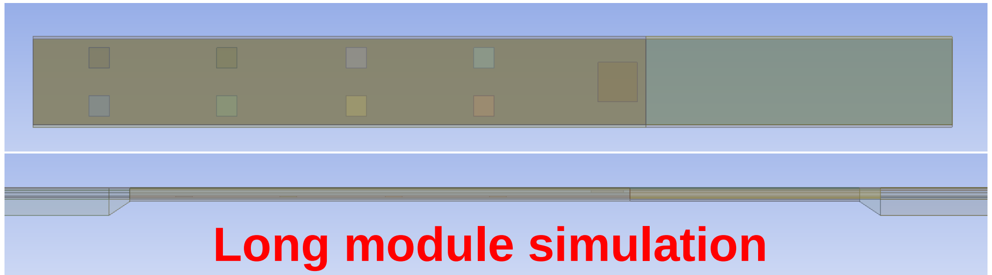
** from 'Physics requirements of the Phase I Near Detector', April 2024*

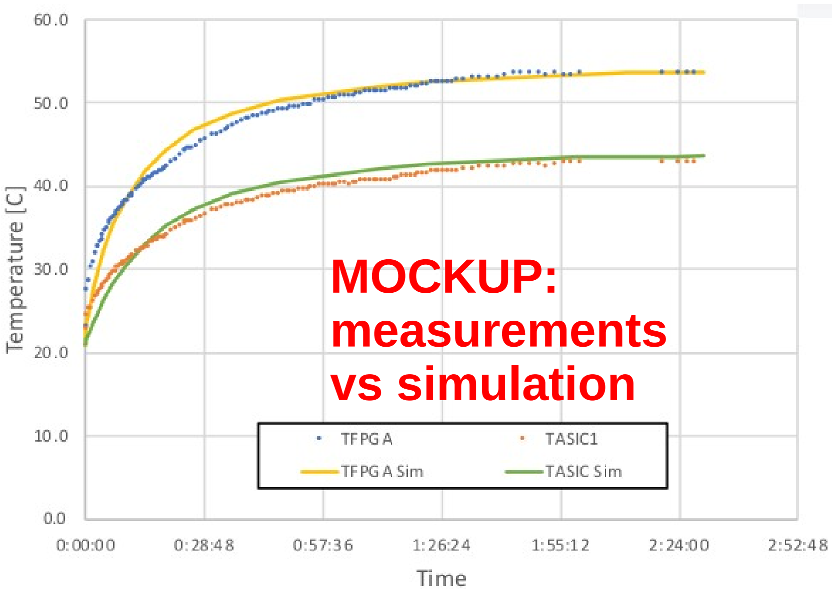
Validazione della simulazione termica con mockup

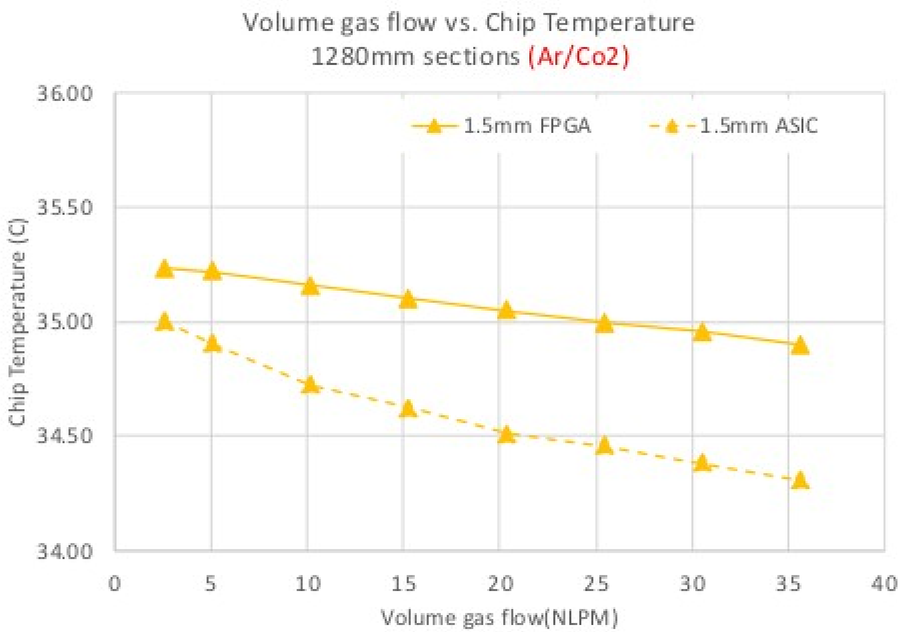


Un simulatore della dispersione termica prevista dall'elettronica posta all'interno dei moduli STT è stato usato per verificare i risultati della simulazione.
L'accordo è molto buono e convalida il risultato della simulazione di un intero modulo.

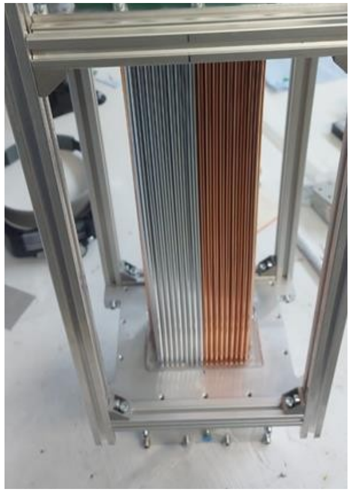


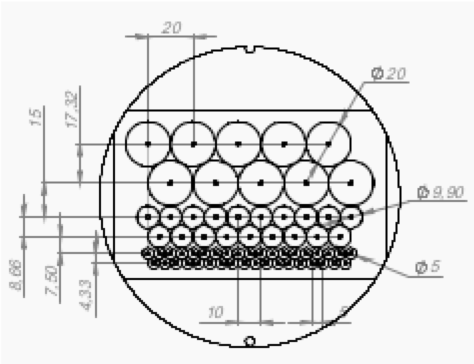




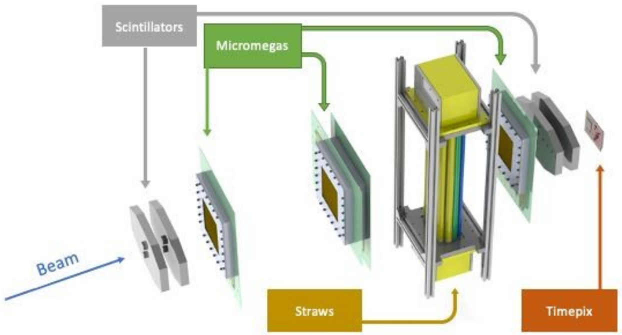


Ultimi risultati dai test su prototipi di straw al Cern



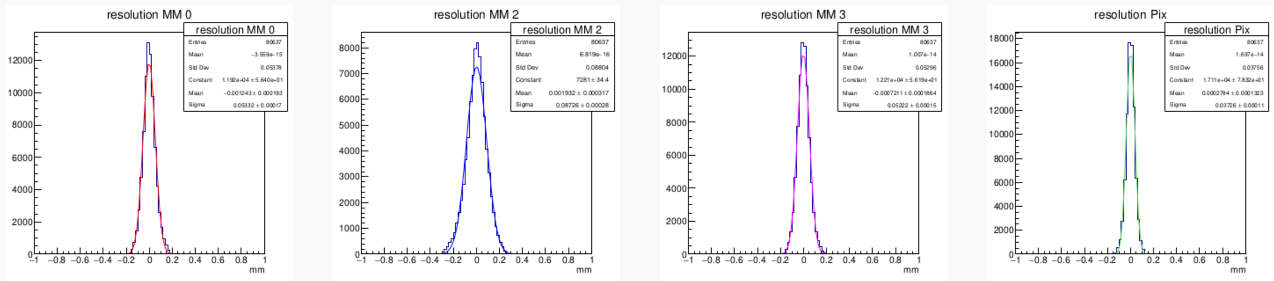


Il gruppo di Dubna sta continuando l'attività di test sui prototipi (collegata anche a altri esperimenti: SHIP, HIKE, NA62, SPD, COMET) presso la North Area del CERN (H4 beam line).

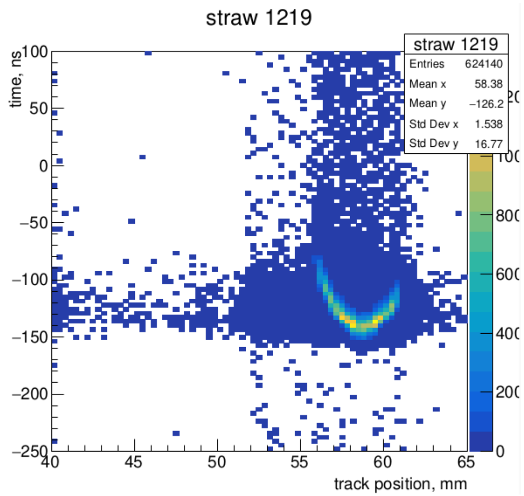


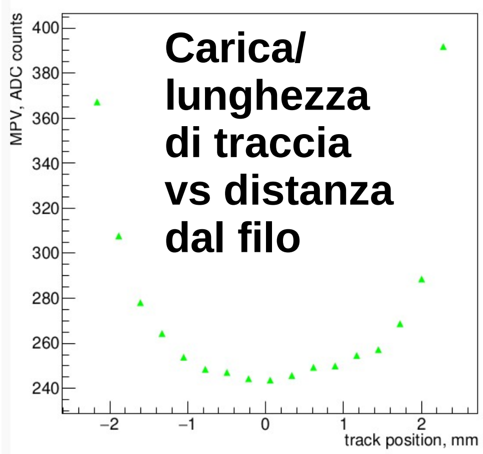
Sistema di tracciatura: 3 MicroMegas + 1 Pixel detector:

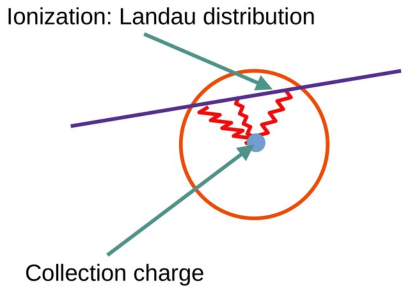
$\sigma = 0.053\ mm$ $\sigma = 0.087\ mm$ $\sigma = 0.052\ mm$ $\sigma = 0.037\ mm$



Relazione tempo-distanza di drift

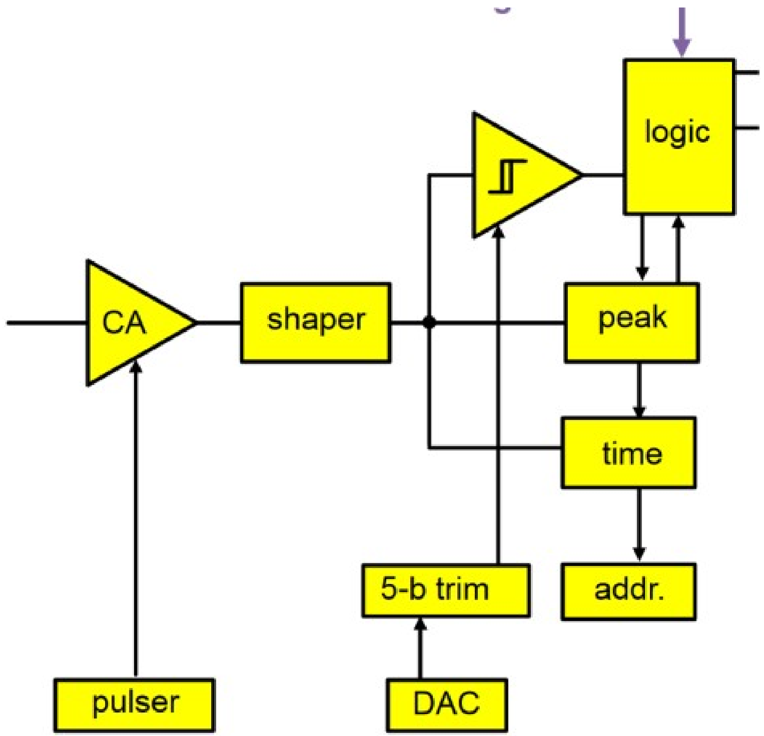




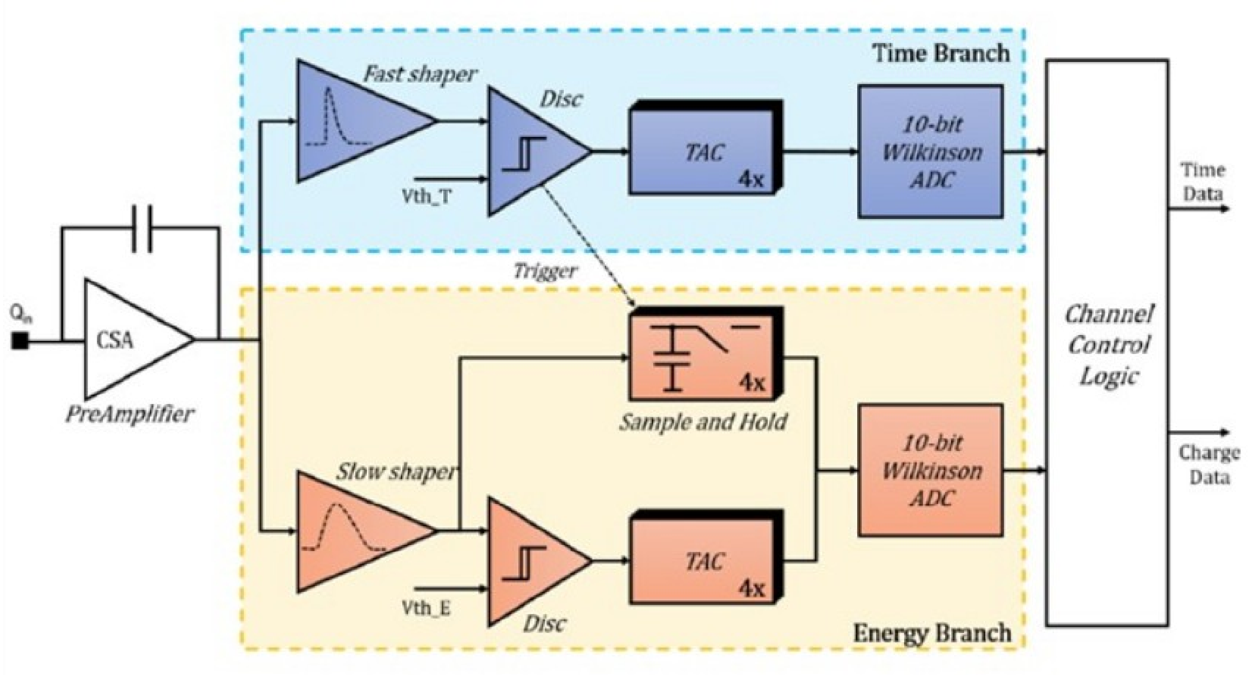


Chip usato per leggere gli straw: VMM3

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)