Straw Tube Tracker (STT)
Introduzione e attività in corso

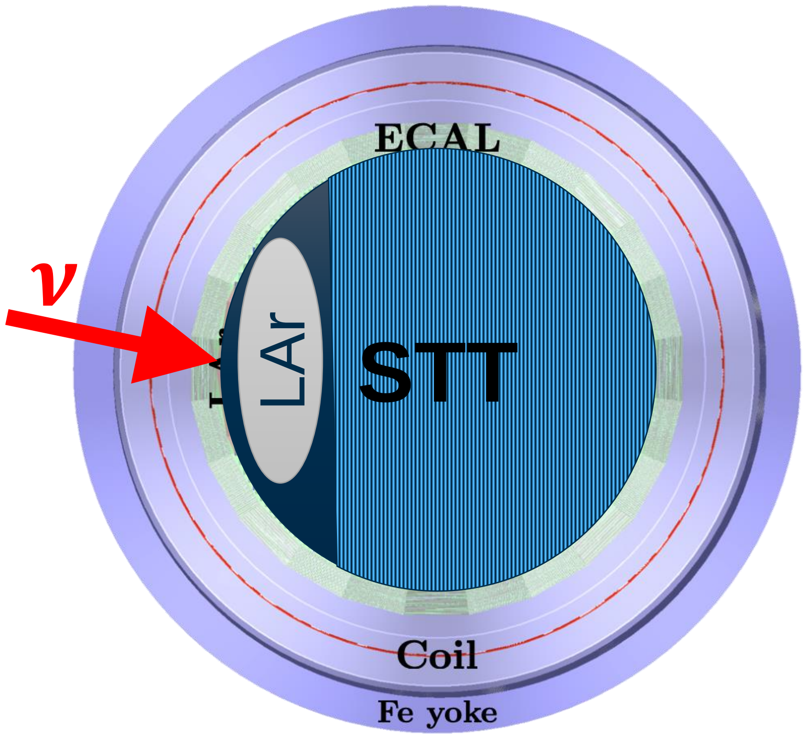
S. Di Falco (INFN – Pisa), G. Sirri (INFN – Bologna)

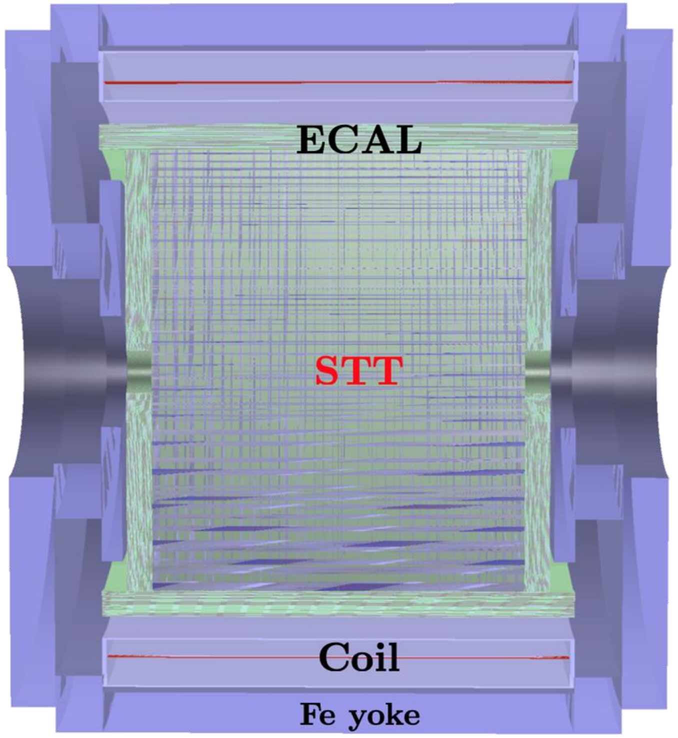
DUNE-IT Meeting, LNF 2022.11.07

STT = tracker + target

RECAP

low-density target and high resolution tracking detector inside the SAND magnetized volume





key feature:
capability to perform accurate measurements of (anti)neutrino interactions on hydrogen (free proton)

SAND physics program - “solid” hydrogen concept

RECAP

STT provides a **compact modular layout** with a flexible design to control configurations, chemical composition and mass of neutrino targets similar to $e^{\pm}$ DIS experiments

“solid” hydrogen concept:

model independent subtraction of measurements on dedicated graphite (pure C) targets from main CH_2 target **to extract** high statistics samples of ν ($\overline{\nu}$) CC **interactions on H** by a kinematical analysis

Keep under control systematic uncertainties:
- Flux measurements
- Constrain models on nuclear effects

arXiv:1910.05995

SAND physics program

RECAP

Reducing **systematics** for long baseline **oscillation analysis**:

- Flux measurements
- Constraints on the nuclear effects in Ar using a combination of different nuclear targets

SAND will turn the ND site to **a physics facility** for **precision measurements** and searches exploring many different topics:

- Precision **isospin** physics
- Measurements of $\sin^2\theta_w$ and **electroweak** physics
- Measurements of **strangeness** content of the nucleon ($s(x)$, $\bar{s}(x)$, Δs, etc)
- Study of QCD and **structure** of nucleons and nuclei
- Measurements of nuclear physics and ν-nucleus **interactions**
- Search for **new physics**: sterile neutrinos, NSI, etc…

Ruolo cruciale degli STT

arXiv:1910.05995
Nucl. Phys. A765, 126(2006), hep-ph/0412425
Phys. Rev. D76, 094023 (2007), hep-ph/0703033

SAND STT Working Group

Activities related to the design and construction of the STT for SAND.

The assigned goals is the completion of the detector installation
and its readiness for operation.

Initial WG chairs: G. Sirri, S. Di Falco, R. Petti

Gruppo di lavoro attivo da Aprile 2022

Dedicated **mailing list** DUNE-ND-SAND-STT

Material presented and discussed during WG meetings available on Indico:
https://indico.fnal.gov/category/1402/

By-weekly regular meetings on Wednesday at 11am Central Time

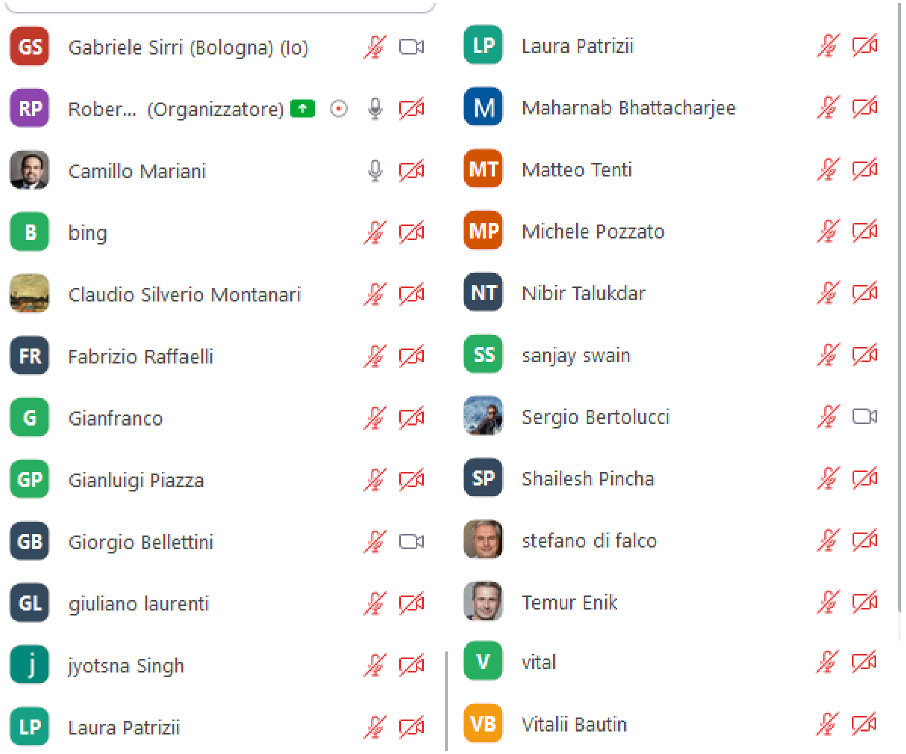
STT WG Meeting

By-weekly regular meetings on Wednesday at 11am Central Time

Iniziale espressione di interesse

Institution	Name		Institution	Name
BNL	M. Diwan		INFN-Lab. Naz. Di Frascati	L. Benussi
FNAL	C. Montanari		INFN/UNIV-Genova	M. Pallavicini
IIT Guwahati	B. Bhuyan		INFN/UNIV-Genova	T. Sergi
IIT Guwahati	S. Pincha		INFN/UNIV-Napoli	M. D'Aniello
IIT Guwahati	A. Nath		INFN-Pisa	S. Di Falco
NISER	S. Swain		INFN-Pisa	F. Raffaelli
NISER	P. Mal		INFN-Pisa	E. Pedreschi
Panjab University	V. Bhatnagar		INFN-Pisa	F. Spinella
Panjab University	S. S. Chauhan		Università di Pisa	R.Ciolini
Panjab University	R. Gaba		Università di Pisa	S. Donati
University of Lucknow	J. Singh		Università di Pisa	V. Giusti
University of Lucknow	R. B. Singh		Università di Pisa	A. Gioiosa
University of Lucknow	P. S. Chouhan		Università di Pisa	L. Morescalchi
INFN/UNIV-Bologna	G. Laurenti		Università di Pisa	D. Pasciuto
INFN/UNIV-Bologna	G. Sirri		Università di Pisa	N. Chitirasreemadam
INFN/UNIV-Bologna	M. Tenti		Università di Pisa	A. Alves
INFN/UNIV-Bologna	A. Cervelli		INFN-Lab. Naz. Del Sud	P. Sapienza
INFN/UNIV-Bologna	G. Ingratta		INFN-Lab. Naz. Del Sud	S. Biagi
INFN/UNIV-Bologna	L. Patrizii		INFN-Lab. Naz. Del Sud	S. Viola
INFN/UNIV-Bologna	G. Piazza		INFN-Lab. Naz. Del Sud	G. Riccobene
INFN/UNIV-Bologna	C. Guadalini		INFN-Lab. Naz. Del Sud	F. Noto
INFN/UNIV-Bologna	A. Badiali		Univ. of South Carolina	R. Petti
			Univ. of South Carolina	M. Joshi
			Univ. of South Carolina	D. Rocheleau

STT WG Meeting più partecipato (2022-04-13)



In media partecipano **10-15 persone** compresi colleghi di DUBNA e GTU Georgia e altri.

Istituti coinvolti

The following institutions are currently contributing
or have expressed interest in contributing to the STT activities:

- **Georgia**: Georgian Technical University (GTU);
- **Germany**: University of Hamburg;
- **India**: IIT Guwahati, NISER, Panjab University, University of Lucknow;
- **Italy**: INFN/Univ. Bologna, Genova, Pisa; INFN/Lab. Frascati, Catania;
- **JINR** Joint Institute for Nuclear Research, Dubna;
- **USA**: BNL, Duke University, University of South Carolina, Virginia Tech.

C’è ancora incertezza sulla suddivisione di risorse e costi $$$.

Main Tasks and tentative schedule

The main tasks have been identified and an initial tentative schedule has been defined, to be updated following the progress made:

- **Design and prototyping**: to be completed by the beginning of 2024;
- **Preparation** of **production sites**: partially in parallel with the design and prototyping, to be completed by mid 2024;
- **Procurement** and detector fabrication: expected to take about four years until the end of 2027;
- **Installation** in the magnet: the modularity of STT allows some flexibility on the installation schedule, effectively providing some margin on the overall production schedule;
- **Service connection** and **commissioning**: the detector is expected to be operational by the end of 2029 in order to be ready for the first neutrino beam.

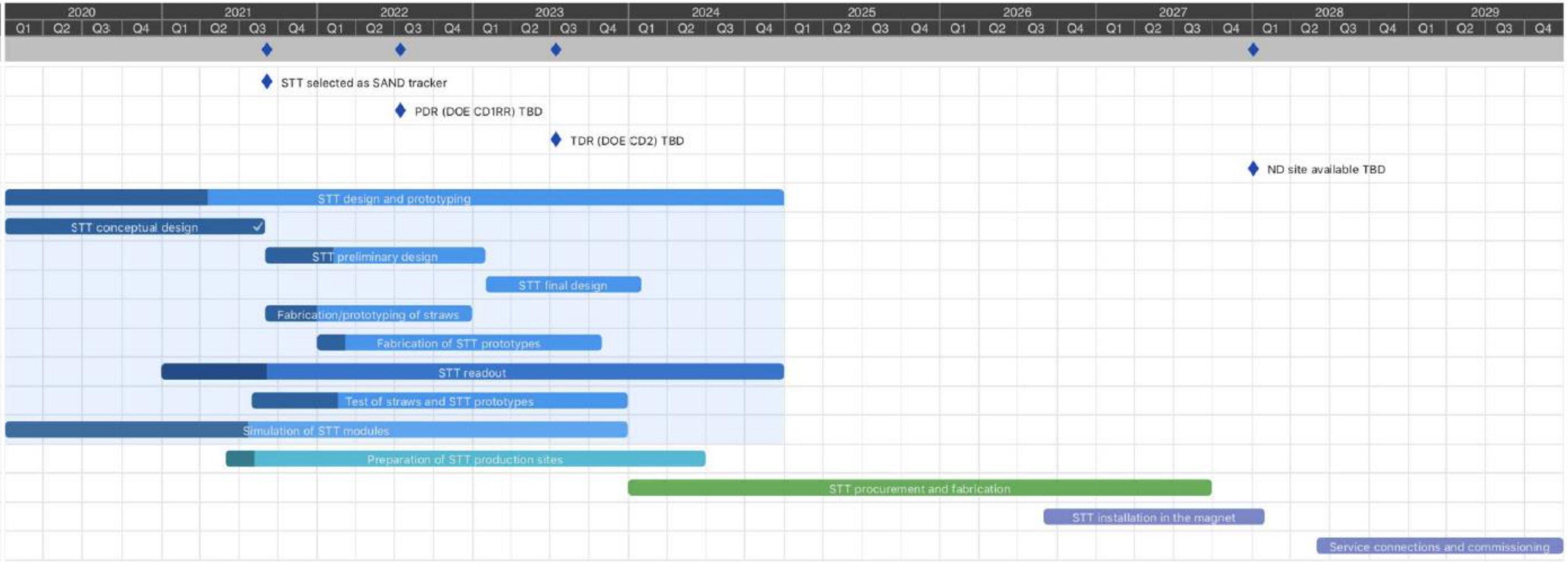
Uncertainties on the timeline are associated to the current global constraints (pandemic, conflict, supplies, etc.)

WBS

✦ *Preliminary schedule* and related deliverables:

- *Identified main tasks and tentative timeline (to be revised following inputs/developments);*
- *Uncertainties on availability of ND site and current situation (covid19, conflict, supplies, etc.).*

WBS	Task	Start	Finish
		Jan 1, 2020	Dec 31, 2029
1	STT selected as SAND tracker	Sep 2, 2021	Sep 2, 2021
2	PDR (DOE CD1RR) TBD	Jul 12, 2022	Jul 12, 2022
3	TDR (DOE CD2) TBD	Jul 12, 2023	Jul 12, 2023
4	ND site available TBD	Jan 1, 2028	Jan 1, 2028
5	**STT design and prototyping**	**Jan 1, 2020**	**Dec 31, 2024**
5.1	STT conceptual design	Jan 1, 2020	Sep 1, 2021
5.2	STT preliminary design	Sep 2, 2021	Jan 31, 2023
5.3	STT final design	Feb 1, 2023	Jan 31, 2024
5.4	Fabrication/prototyping of straws	Sep 2, 2021	Dec 31, 2022
5.5	Fabrication of STT prototypes	Jan 1, 2022	Oct 31, 2023
5.6	STT readout	Jan 1, 2021	Dec 31, 2024
5.7	Test of straws and STT prototypes	Aug 1, 2021	Dec 31, 2023
5.8	Simulation of STT modules	Jan 1, 2020	Dec 31, 2023
6	Preparation of STT production sites	Jun 1, 2021	Jun 30, 2024
7	STT procurement and fabrication	Jan 1, 2024	Sep 30, 2027
8	STT installation in the magnet	Sep 1, 2026	Jan 31, 2028
9	Service connections and commissioning	Jun 1, 2028	Dec 31, 2029



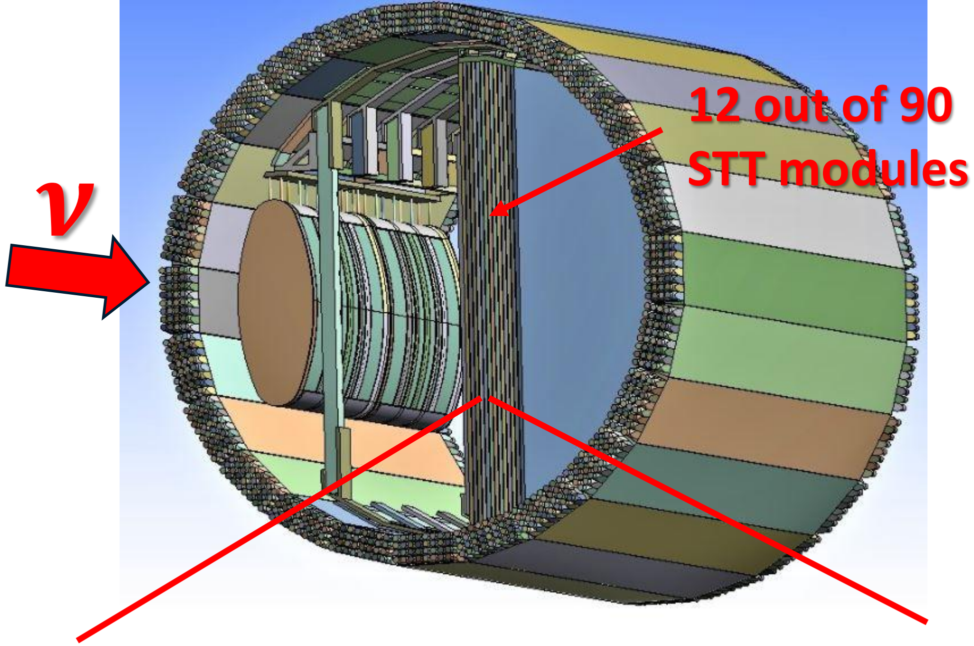
STT basic design

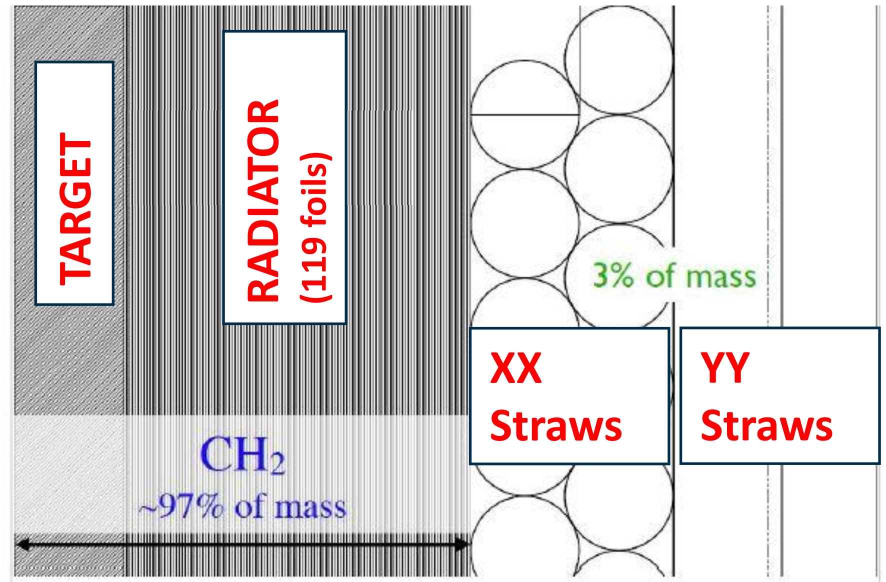
SAND – STT Inner tracker

The internal magnetized volume of SAND will be instrumented with an Inner Tracker to:

- separate neutrino and antineutrino events (**charge ID**),
- identify primary leptons (**beam flavor composition**),
- reconstruct event-by-event and all charged and neutral (π^0, n) **particles tracks**

90 modules with planes of 5 mm diameter **straw tubes** (Xe/CO_2 gas at 1.9 atm) arranged in XXYY layers, radiator of polypropylene foils and a target (CH_2, C,…)

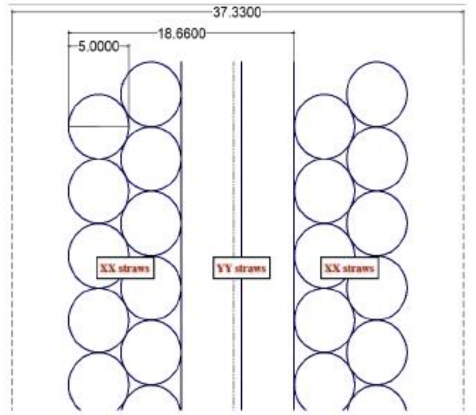


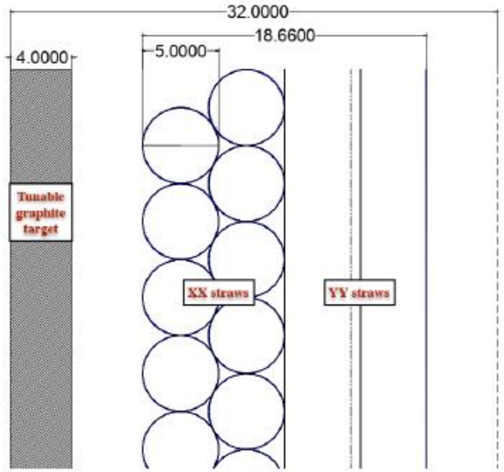


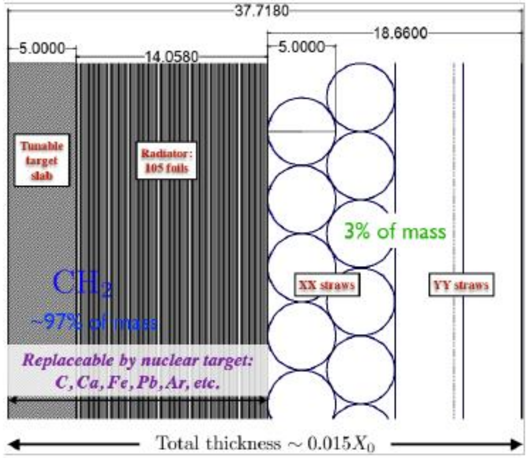
fiducial volume mass 4.7 t CH_2, 557 kg C

SAND Geometry: Straw tube tracker

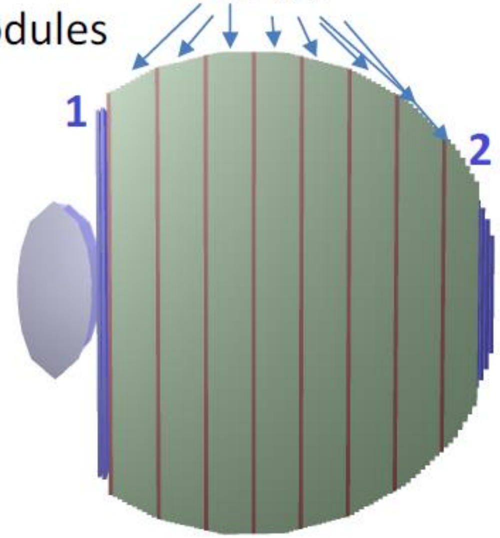
3 TYPES OF MODULES







- position resolution on single hit: 200 um in y , 10 um in z
- time resolution on single hit: 1 ns
- average density ~ 0.18 g/cm^3
- radiation length x0~ 2.6 m
- tracking sampling 0.15 (0.36)%x0 ⊥ (||)

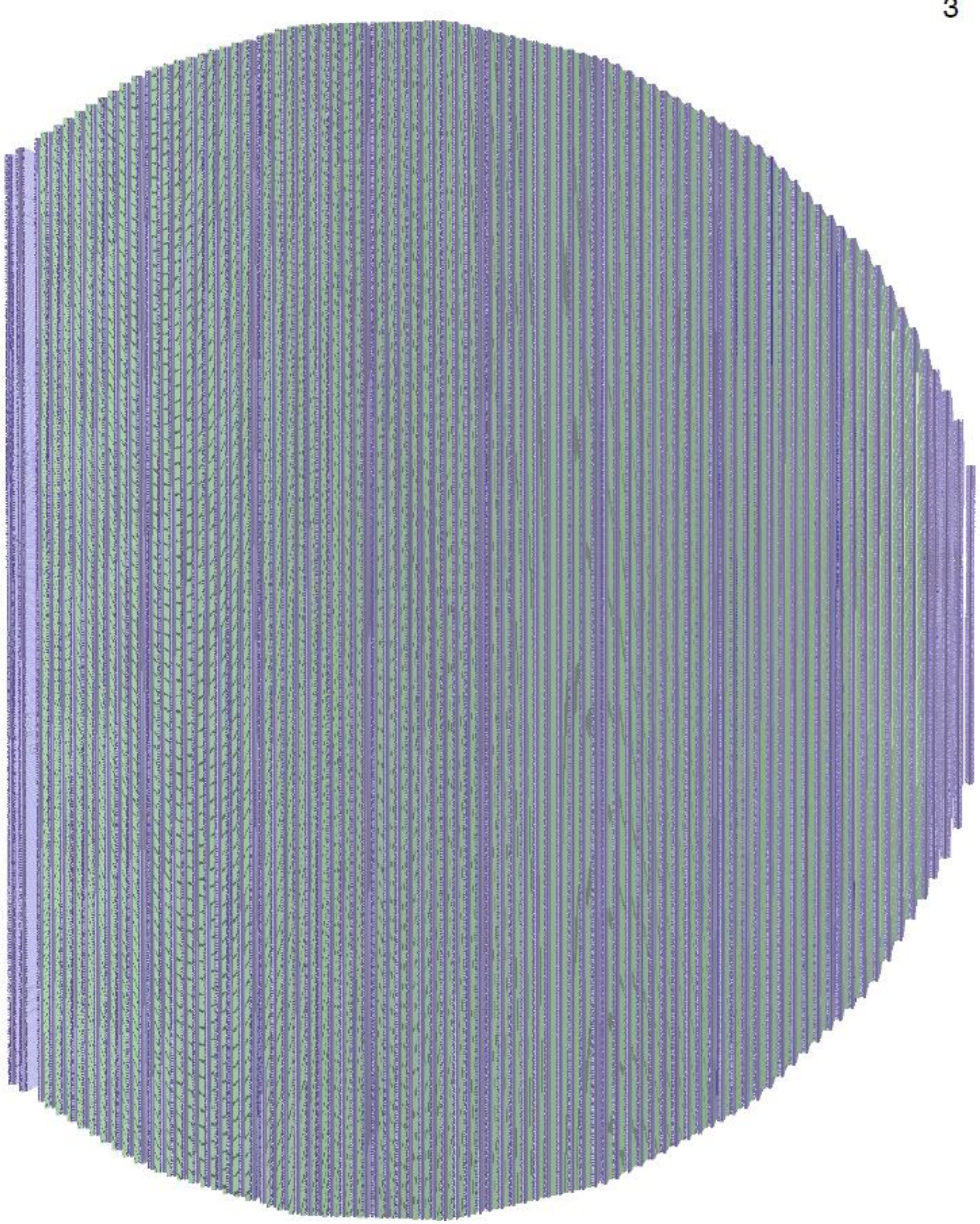


STT FOR SAND

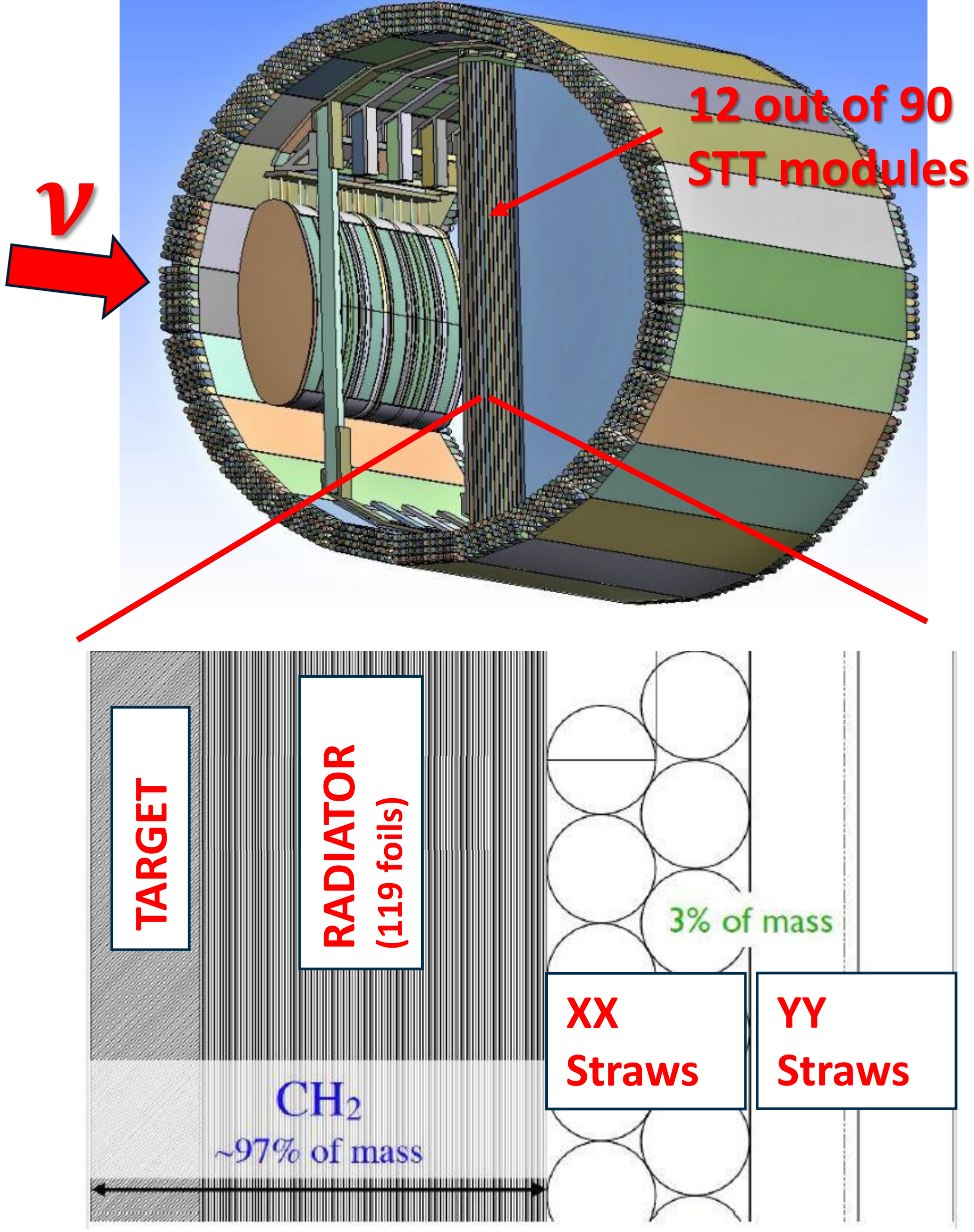
70 CH_2 modules
8 C modules
6 tracking modules

~220,000 straws
average straw length 3.2 m
maximal straw length 3.8 m
internal gas volume ~14 m^3
nominal gas pressure ~2 bar

FV mass:
~4.7 t CH_2
~600 kg C



SAND – STT Inner tracker



fiducial volume mass 4.7 t CH_2, 557 kg C

The design provides accurate control of **configuration**, **chemical composition**, and **mass** and allows

- **Accurate** reconstruction of **transverse plane kinematics** variables from particle 4-momenta
  $(\delta p/p \leq 3\,\%\,,\,\delta\theta/\theta \leq 1.5\,\%)$
- $\boldsymbol{e/\pi}$ **separation** via transition radiation ($e/\pi \sim 10^{-3}$) and $p/\pi/K$ identification with dE/dx and range
- **4**$\boldsymbol{\pi}$ **detection of** $\boldsymbol{\pi^0}$ from γ conversion (~ 49 %) within STT volume
- Neutron detection is ensured by combination of STT with ECAL

Progress since Jan 2022

PROTOTYPING & TESTS

Demonstrate all aspects of the STT design in increasing order of complexity:

- **Produce straws** of required quality & maximal length with ultrasonic welding (UW) — **OK**
  Validation of model production lines at JINR (5m) and GTU (2m)
- **Verify** UW **straws** fulfill **requirements** from STT conceptual design & assembly procedure — **OK**
  Measurement of maximal internal pressure, radial and longitudinal deformations vs. pressure, relaxation vs. time and humidity, gas tightness, etc.
- **Verify** XXYY straw **layer assembly** — **OK**
  Gluing and pressure tests of 1m × 1m XXYY test assembly
- **Verify assembly procedure** of XXYY straws to frame, gas tightness, etc. — **In progress**
  Mockup prototype(s) with plexiglass frame (in progress)
- **Verify module design** with C-composite frame and related performance
  Complete 1.2m × 0.8m prototype with XXYY straws and actual STT frame design
- **Verify full scale module** (module 0) with maximal straw length and complete assembly
  Complete 4m × 0.5m prototype with XXYY straws and C-composite frame

PROTOTYPING & TESTS

Demonstrate readout performance:

- Verify **charge measurement** with 55Fe **source** & cosmics **OK**
  Readout small STT prototype with Mu2e FE boards with VMM3/VMM3a ASICs
- Verify **time measurement** with **signal generator** **OK**
- Verify **time and charge measurement** at testbeam **In progress**
  Readout small STT prototype with FE boards with VMM3/VMM3a ASICs

- Investigation of **alternative ASIC**…. ASIC TIGER from INFN-TO)

Progress made towards the **STT preliminary design** includes studies of

- the gas **sealing**, the straw **deformations** under different operating conditions and for the various steps of the **assembly** procedure

  The measured deformations as a function of the inner gas pressure were found in agreement with the calculations. Measurements of the gas leakage in the straws were performed over an extensive period of time to evaluate the rate of diffusion through the straw walls, which help to define the STT requirements in terms of gas tightness.

- various aspects of the **mechanical design** of the tracking part of the STT modules.
  → presentazione di Fabrizio

- **Test Beam** e Prototyping
  → presentazione di Stefano

Gas System

- A possible **design** for the complete **STT gas system** was presented **by the CERN gas group** based on existing functional modules from various straw detectors operating at CERN.
- The gas system does not require the developments of new components and can be built and tested at CERN over a period of six months.

talk of Roberto Guida (CERN) at STT-WG 2022-06-22

GAS System per ND280 –TPC

Conclusions

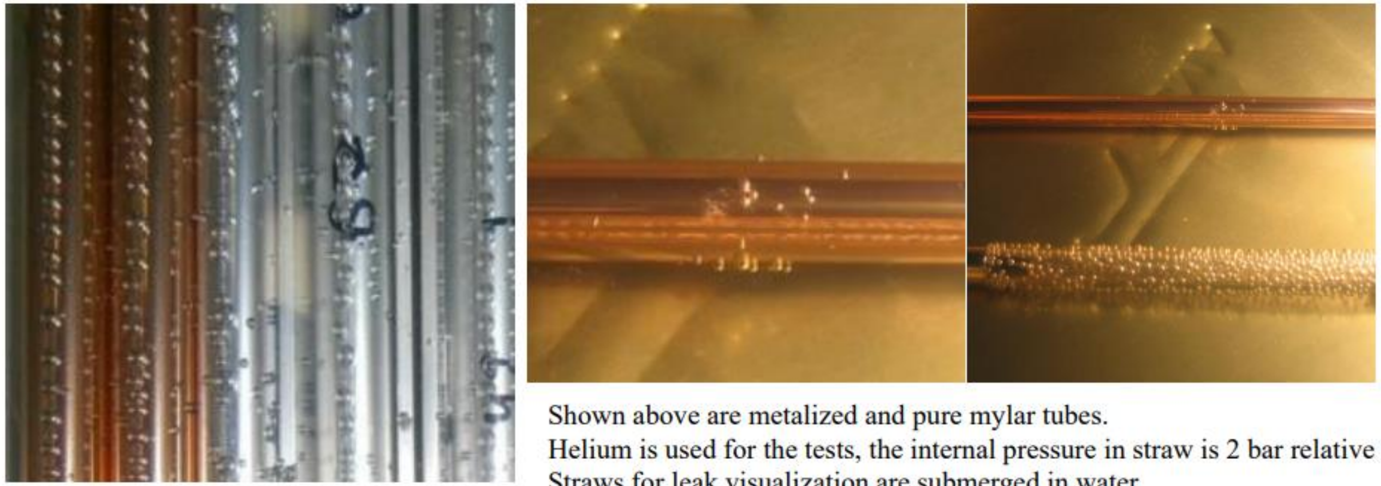
- The development, construction and operation of the gas systems for the LHC experiments has contributed to the creation of CERN expertise in this domain
- Gas systems are designed and built according to functional modules:
  - Simplified maintenance and operation activities for the team
  - Fully automated systems with remote control/monitoring
  - impressive reliability level
- Approximate cost and resource estimate presented
  - Very important to have one experienced technical engineer or equivalent and one software expert following production and test phases to ensure the start up of a good knowledge transfer process in view of maintenance and operation in USA. We need to build an onsite expertise to ensure good operation conditions.
  - Assuming 100% availability of all people involved and team fully competent/trained the full process will take about 50 weeks
  - 1 month commissioning at production site needed (not included in the 50 weeks)
- Cost estimate based on CERN gas team present knowledge. In case DUNE would express wish for CERN to build the system, the following steps would be needed:
  1) Agreement with the EP department about the CERN contribution to DUNE
  2) Assessment of timing and schedule compatibility with team present activities (To be considered the critical period LHC-LS3: 2025-2027).
  3) Collaboration agreement between DUNE and EP-DT in form of a Workpackage, specifying the injected DUNE resources (personnel, funds) and the EP-DT deliverables and milestones.

22/06/2022 R. Guida CERN/EP-DT-FS Gas Systems Project 17

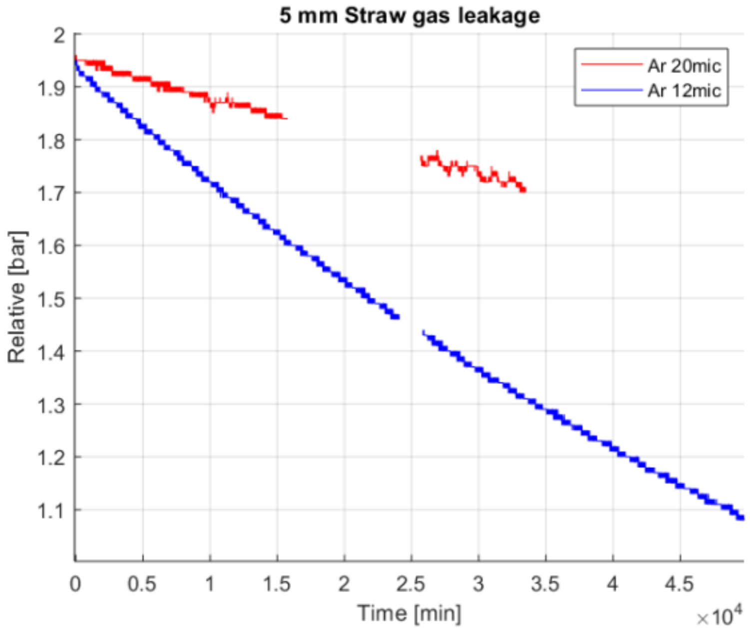
Gas Leakage

[talk of Nika Tsverava (GTU) at STT-WG 2022-05-11]

Visual demonstration test of gas diffusion in straw tubes using helium



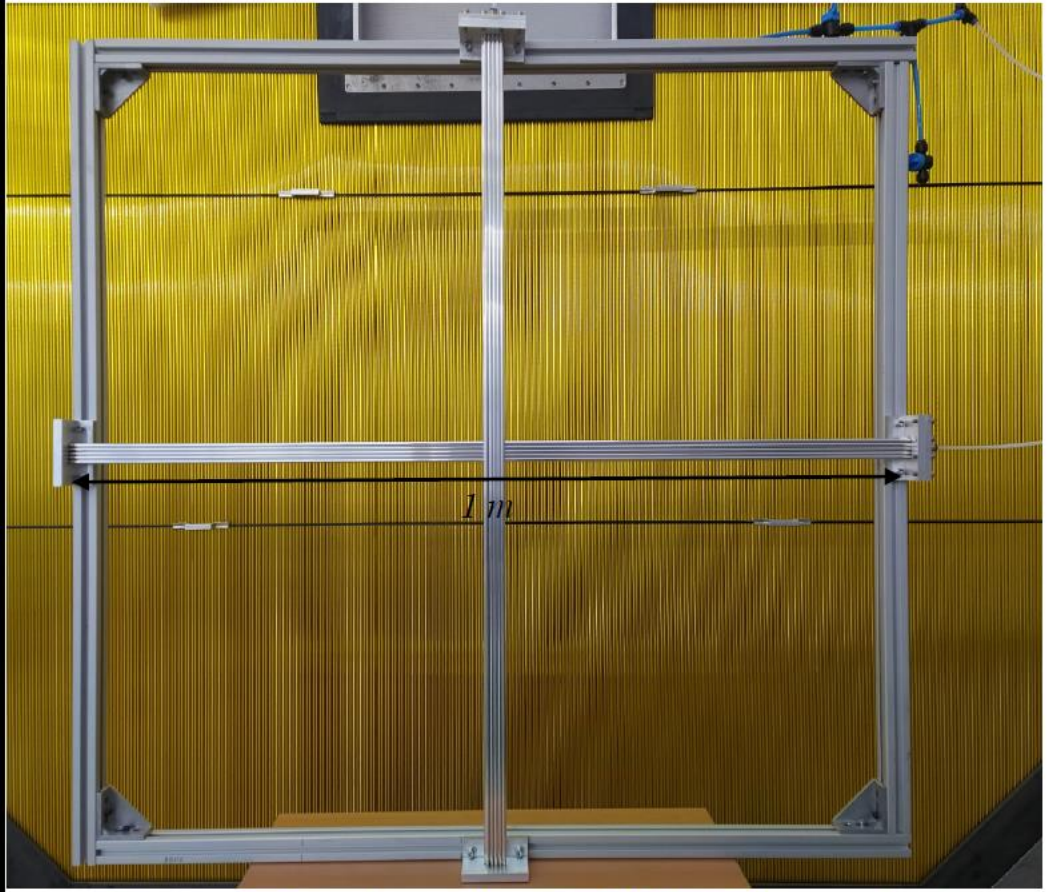
Shown above are metalized and pure mylar tubes.
Helium is used for the tests, the internal pressure in straw is 2 bar relative
Straws for leak visualization are submerged in water
In metal-free tubes, we have an equal distribution of the diffusion process
In metalized straws mainly weld area is a place for gas leak since the metal layer is a difficult barrier to gas diffusion then mylar



Gas leak test for 12/20 µm 5 mm diameter straw tubes of 1 m length
By rough calculations loss is: 0.01 bar/day for 20 µm and 0.03 bar/day for 12 µm

Gluing and Pressure Tests

- **Gluing** and **pressure tests** were performed on a XXYY four layer assembly using 1m long straws.
- After being glued together the straws were pressurized and successfully cycled multiple times between 1 bar a d 5 bar (nominal operating pressure 2 bar) without damages.
- The tests allowed to validate the XXYY straw assembly and the gluing procedure of the straws.



Straws glued together with epoxy ELK5 (~ 20cm spacing)

8

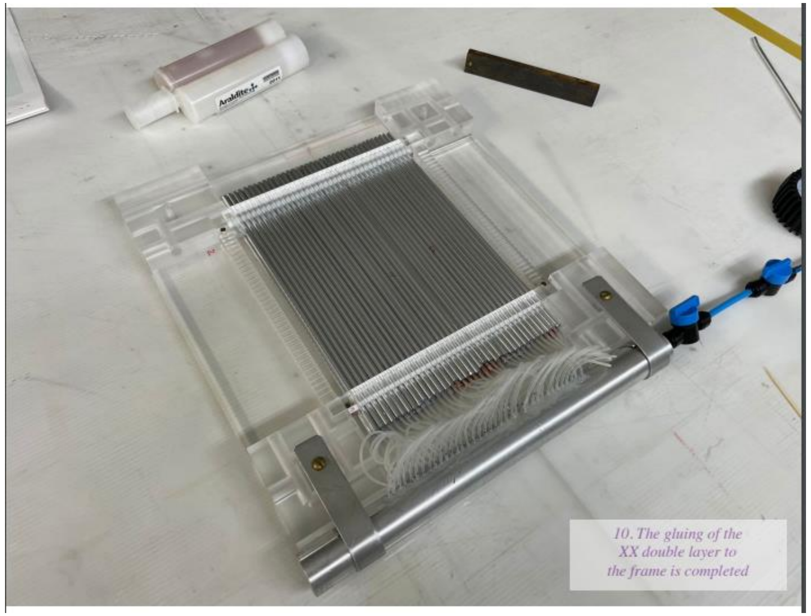
T. Enik (JINR)

Cycled multiple times
complete glued XXYY assembly
from 1 bar to 5 bar:
no problems nor apparent damages
for the straw assembly

Mockup Assembly

- In order to validate the assembly of the straws to the mechanical frame, and the corresponding gas tightness and assembly tolerances, **a small mockup** prototype is being **produced**.
- All required components have been procured, including a plexiglass mockup frame based on the design currently implemented for the STT modules, and the straws produced with the ultrasonic welding technology.

→ Temur talk at STT WG 2022-08-10



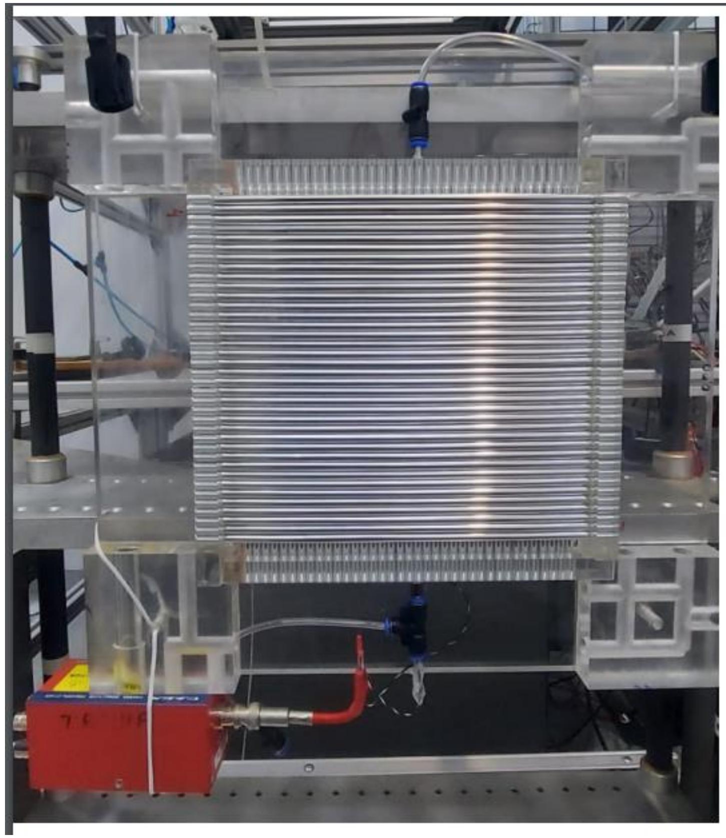
Mockup Assembly (towards 1.2m x 0.8m prototype)

- **Steps of the assembly procedure** have been tested and the full mockup prototype completed during the summer.

→ Talk of Temur at STT WG 2022-09-07
→ Talk of Temur at STT-WG 2022-10-10

- Results are **critical to validate the assembly procedure** envisaged for the STT modules and to finalize the design of the following 1.2m x 0.8m prototype, which will be based on a C-composite frame similar to the one planned for the final STT.

  The **main outcome** from the mockup prototype will be a detailed and tested assembly procedure for the STT modules.



Instrumented one straw with 20 μm wire (50 g tension) and tested with ^{55}Fe source at STT operating conditions

Test Beam of VMM3 front-end readout

- A small **STT prototype** with XX + YY straw layers was **exposed** to high energy **muons** and **pions** at CERN to evaluate the performance of the VMM3 front-end readout with the straws.
- The testbeam activity took place at the H4 beamline at CERN and covered an extended period of time from 25 April to 3 May 2022 and from 18 May to 8 June 2022. The readout of the straws was performed using a front-end board from the Mu2e experiment and the setup included three trigger scintillators, as well as three Micromega trackers equipped with APV readout.
- The **primary goal** is to evaluate the resolution on the drift time in the straws. Other studies include the measurement of the energy deposition dE/dx in the straws by different particles.
- A large amount of usable data was collected with different configurations and geometries of the setup. Results from the testbeam are critical for the choice of the ASIC to be used in the front-end readout of STT.
  The analysis of the testbeam data is currently in progress.

Fallback solution…

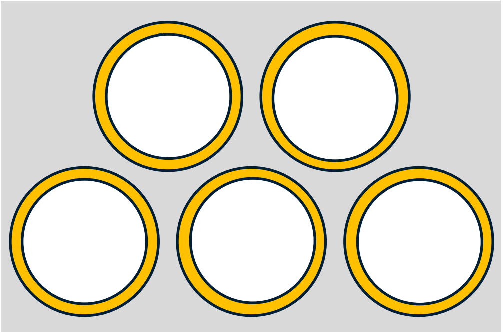
- Ci sono idee che potrebbero essere utili per migliorare le **performance**, **semplificare** alcuni aspetti di **integrazione** e **ridurre** il numero di **canali**.

- Insieme al prototipo 120 x 80 si vuole realizzare un secondo prototipo in cui sono implementate alcune di queste idee.

- Riteniamo critico mettere in produzione un **framework di analisi end-to-end** che permetta di validare le performance di eventuali variazioni al design rispetto agli obiettivi scientifici di SAND, in particolare sugli item di fisica che riguardano le **interazioni su idrogeno**.

- target di spessore diverso (piu' spessi upstream e meno spessi downstream)

- eliminazione del transition detector
- tubi distanziati
- tubi con diametro maggiore
- raffreddamento dell’elettronica autonomo



- camera a drift multifili (con varie ipotesi sul setup)

altre slides

MOCKUP PROTOTYPE(S)

- *Mockup prototype(s) 35cm × 35cm for preliminary validation tests:*
  - *Completed design of mock frame (Hamburg, UofSC);*
  - *Machining of first plexiglass mockup frame being completed in Hamburg;*
  - *Required straws produced by GTU (4.9mm diameter, 20 μm walls);*
  - *End-plugs machined from simplified design;*
  - *Assembly of first mockup prototype at JINR.*

- *Main goals of mockup prototype(s):*
  - *Validate assembly procedure using same geometry/frame as in STT;*
  - *Test the connection/gluing of straws to the frame;*
  - *Test sealing and gas leaks vs. internal pressure;*
  - *Evaluate different design options.*

- *Additional mockup prototypes expected to be built at various collaborating institutions following the completion of the first one at JINR.*

PREPARATION FOR 1.2m × 0.8m PROTOTYPE

- *Prototype 1.2m × 0.8m based on design & parts as in full scale STT modules:*
  - *Build at JINR with help from GTU & other institutions;*
  - *Maximal size compatible with existing tooling & similar to NA64 detectors recently built at JINR;*
  - *4 straw layers XXYY: 672 straws total, no target, no radiator;*
  - *C-composite frame and assembly as in STT modules.*

  ⟹ *Aim to build the prototype in 2022 (summer?)*

- *FE analysis of deformations induced by gas pressure, wire and straw tension:*
  - *Removable lids giving access to gas manifolds and FE boards, gas tightness (O-rings, etc.);*
  - *Connection of individual straws to C-composite frame and related gas sealing;*
  - *Study interplay between internal overpressure and wire/straw tension.*

- *Evaluating options for procurement of required components.*

- *Contributing institutions:*
  JINR, GTU, IIT Guwahati, Panjab, Duke, INFN, Hamburg, UofSC.

PRELIMINARY ESTIMATE OF Xe LOSSES

✦ *Consider current default STT configuration:*

- *Maximal number of modules with Xe: 70 filled with Xe/CO_2 70/30;*
- *Total Xe gas volume: 14 m^3 × 70/84 × 0.7 ∼ 8 m^3;*
- *Total length of straws filled with Xe: 590 km.*

✦ *Assume diffusion rate measured by GTU with Ar gas:*

- 1.53×10^{-5} *liter/day/m at internal relative pressure of 1.9 bar*
  $\longrightarrow 8 \times 10^{-6}$ *liter/day/m at 1 bar relative (nominal operating condition);*
- *Expected yearly gas losses for an Ar volume equivalent to the Xe volume:*
  1.53×10^{-5} *l/day/m* $* 5.9 \times 10^5$ *m* $* 0.7 * 365$ *day* = 2.3 m^3*/year at 1.9 bar relative*
  8×10^{-6} *l/day/m* $* 5.9 \times 10^5$ *m* $* 0.7 * 365$ *day* = 1.2 m^3*/year at 1 bar relative.*

✦ *Expected exponential dependence upon the square of the atomic radius of gas:*

- *Scaling factor Xe/Ar for diffusion rates 0.11-0.14;*
- *Expected yearly Xe gas losses: 2.3 m^3/year × 0.14 ∼ 0.3 m^3/year at 1.9 bar relative pressure.*

$\Longrightarrow$ *Operating costs to replace Xe gas lost at $15/l about $4,500/year*

SIGNAL/HV CONNECTION OF STRAWS

22

R. Petti (UofSC)

✦ *Preliminary configuration considered:*

- *Total of about 1,720 flexible PCBs, each connecting 128 straws;*
- *Maximal length about 1.5m, minimal about 0.35m, average about 1m;*
- *Base Kapton film: 50 μm thick;*
- *Cu traces: 5 μm thick, 100 μm wide;*
- *Petal connections: 3mm external diameter, Ni (1 μm) + Au (0.05 μm) coating;*
- *HIROSE 140 pin connector on the side of the FE boards;*
- *Coverlay coating on single side with Cu traces, 50 μm thick.*

$\Longrightarrow$ *Need to evaluate cross-talk and optimize trace layout accordingly*

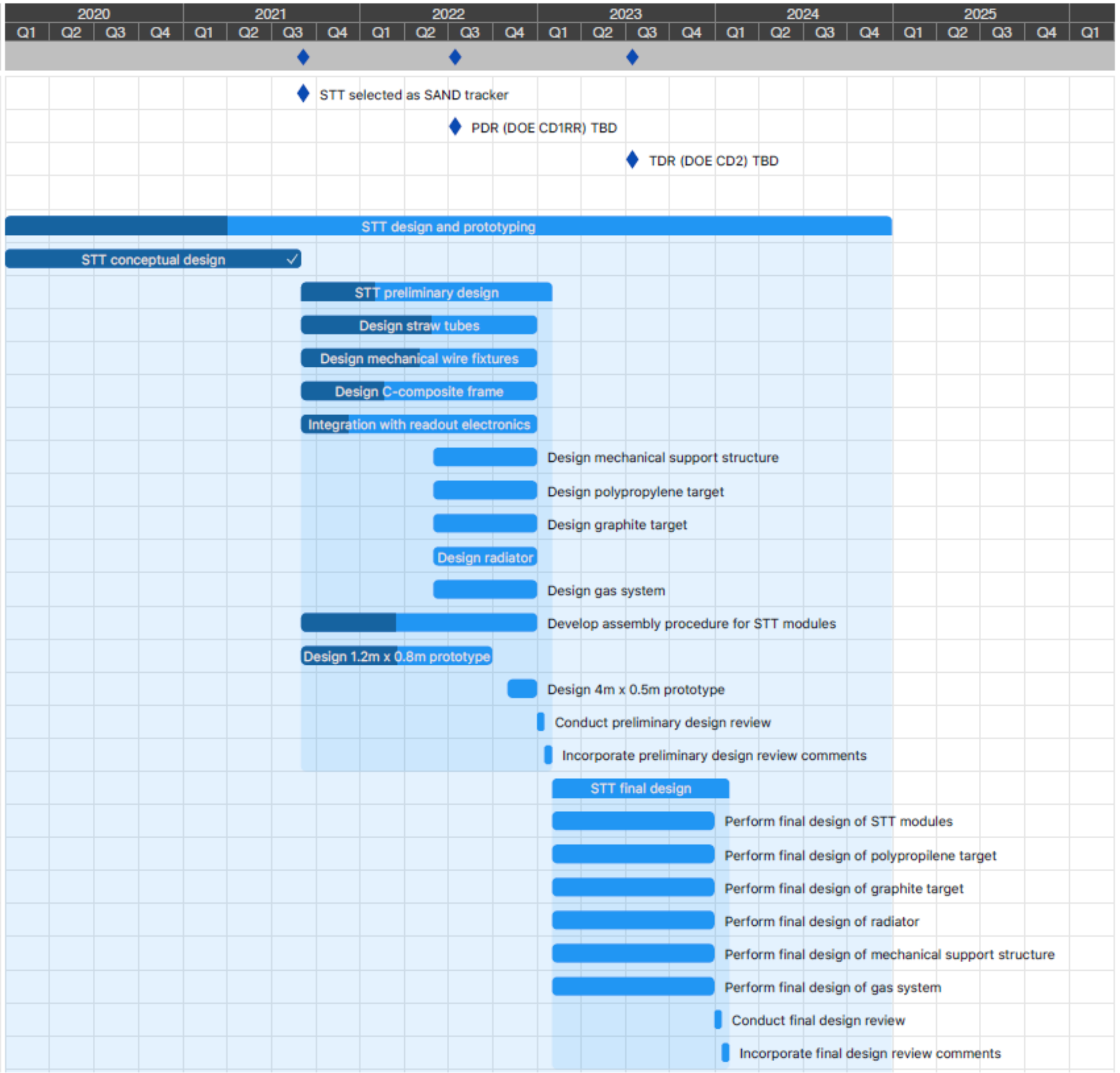
✦ *Confirmed technical feasibility and preliminary quote obtained:*

- *CERN: 345 CHF / flexible PCB, minimum lead time 1 year for full production (3 FTEs);*
- *Requested quotes from commercial companies for comparison.*

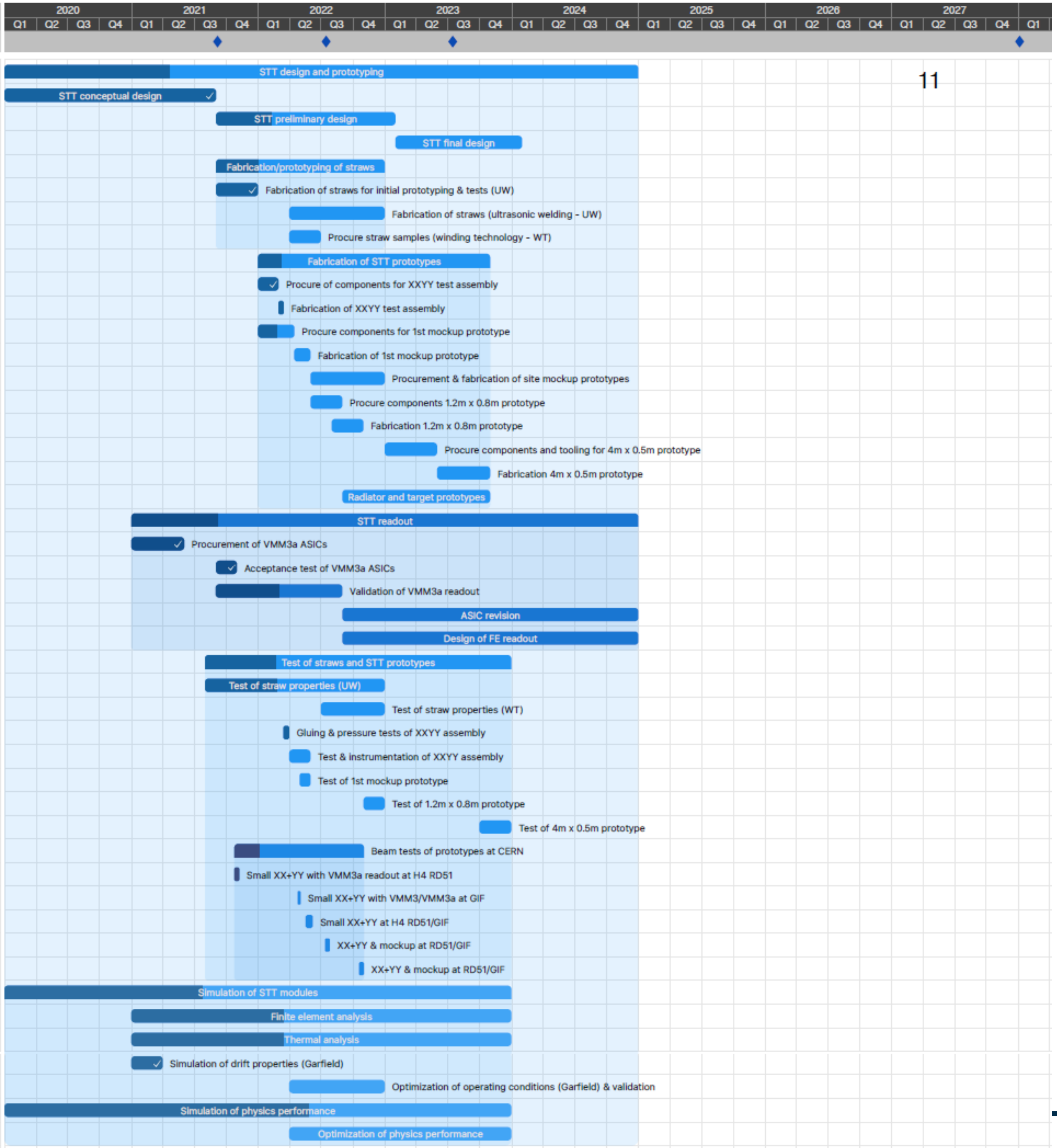
DESIGN ACTIVITIES

5

WBS	Task	Start	Finish
		Jan 1, 2020	Dec 31, 2029
1	STT selected as SAND tracker	Sep 2, 2021	Sep 2, 2021
2	PDR (DOE CD1RR) TBD	Jul 12, 2022	Jul 12, 2022
3	TDR (DOE CD2) TBD	Jul 12, 2023	Jul 12, 2023
4	ND site available TBD	Jan 1, 2028	Jan 1, 2028
5	**STT design and prototyping**	**Jan 1, 2020**	**Dec 31, 2024**
5.1	STT conceptual design	Jan 1, 2020	Sep 1, 2021
5.2	**STT preliminary design**	**Sep 2, 2021**	**Jan 31, 2023**
5.2.1	Design straw tubes	Sep 2, 2021	Dec 31, 2022
5.2.2	Design mechanical wire fixtures	Sep 2, 2021	Dec 31, 2022
5.2.3	Design C-composite frame	Sep 2, 2021	Dec 31, 2022
5.2.4	Integration with readout electronics	Sep 2, 2021	Dec 31, 2022
5.2.5	Design mechanical support structure	Jun 1, 2022	Dec 31, 2022
5.2.6	Design polypropylene target	Jun 1, 2022	Dec 31, 2022
5.2.7	Design graphite target	Jun 1, 2022	Dec 31, 2022
5.2.8	Design radiator	Jun 1, 2022	Dec 31, 2022
5.2.9	Design gas system	Jun 1, 2022	Dec 31, 2022
5.2.10	Develop assembly procedure for STT modules	Sep 2, 2021	Dec 31, 2022
5.2.11	Design 1.2m x 0.8m prototype	Sep 2, 2021	Sep 30, 2022
5.2.12	Design 4m x 0.5m prototype	Nov 1, 2022	Dec 31, 2022
5.2.13	Conduct preliminary design review	Jan 1, 2023	Jan 15, 2023
5.2.14	Incorporate preliminary design review comments	Jan 16, 2023	Jan 31, 2023
5.3	**STT final design**	**Feb 1, 2023**	**Jan 31, 2024**
5.3.1	Perform final design of STT modules	Feb 1, 2023	Dec 31, 2023
5.3.2	Perform final design of polypropilene target	Feb 1, 2023	Dec 31, 2023
5.3.3	Perform final design of graphite target	Feb 1, 2023	Dec 31, 2023
5.3.4	Perform final design of radiator	Feb 1, 2023	Dec 31, 2023
5.3.5	Perform final design of mechanical support structure	Feb 1, 2023	Dec 31, 2023
5.3.6	Perform final design of gas system	Feb 1, 2023	Dec 31, 2023
5.3.7	Conduct final design review	Jan 1, 2024	Jan 15, 2024
5.3.8	Incorporate final design review comments	Jan 16, 2024	Jan 31, 2024



WBS	Task	Start	Finish
		Jan 1, 2020	Dec 31, 2029
5	**STT design and prototyping**	**Jan 1, 2020**	**Dec 31, 2024**
5.1	STT conceptual design	Jan 1, 2020	Sep 1, 2021
5.2	STT preliminary design	Sep 2, 2021	Jan 31, 2023
5.3	STT final design	Feb 1, 2023	Jan 31, 2024
5.4	**Fabrication/prototyping of straws**	**Sep 2, 2021**	**Dec 31, 2022**
5.4.1	Fabrication of straws for initial prototyping & tests (UW)	Sep 2, 2021	Dec 31, 2021
5.4.2	Fabrication of straws (ultrasonic welding - UW)	Apr 1, 2022	Dec 31, 2022
5.4.3	Procure straw samples (winding technology - WT)	Apr 1, 2022	Jun 30, 2022
5.5	**Fabrication of STT prototypes**	**Jan 1, 2022**	**Oct 31, 2023**
5.5.1	Procure of components for XXYY test assembly	Jan 1, 2022	Feb 28, 2022
5.5.2	Fabrication of XXYY test assembly	Mar 1, 2022	Mar 15, 2022
5.5.3	Procure components for 1st mockup prototype	Jan 1, 2022	Apr 15, 2022
5.5.4	Fabrication of 1st mockup prototype	Apr 15, 2022	May 31, 2022
5.5.5	Procurement & fabrication of site mockup prototypes	Jun 1, 2022	Dec 31, 2022
5.5.6	Procure components 1.2m x 0.8m prototype	Jun 1, 2022	Aug 31, 2022
5.5.7	Fabrication 1.2m x 0.8m prototype	Aug 1, 2022	Oct 31, 2022
5.5.8	Procure components and tooling for 4m x 0.5m prototype	Jan 1, 2023	May 31, 2023
5.5.9	Fabrication 4m x 0.5m prototype	Jun 1, 2023	Oct 31, 2023
5.5.10	Radiator and target prototypes	Sep 1, 2022	Oct 31, 2023
5.6	**STT readout**	**Jan 1, 2021**	**Dec 31, 2024**
5.6.1	Procurement of VMM3a ASICs	Jan 1, 2021	Jun 1, 2021
5.6.2	Acceptance test of VMM3a ASICs	Sep 2, 2021	Oct 31, 2021
5.6.3	Validation of VMM3a readout	Sep 1, 2021	Aug 31, 2022
5.6.4	ASIC revision	Sep 1, 2022	Dec 31, 2024
5.6.5	Design of FE readout	Sep 1, 2022	Dec 31, 2024
5.7	**Test of straws and STT prototypes**	**Aug 1, 2021**	**Dec 31, 2023**
5.7.1	Test of straw properties (UW)	Aug 1, 2021	Dec 31, 2022
5.7.2	Test of straw properties (WT)	Jul 1, 2022	Dec 31, 2022
5.7.3	Gluing & pressure tests of XXYY assembly	Mar 15, 2022	Mar 31, 2022
5.7.4	Test & instrumentation of XXYY assembly	Apr 1, 2022	May 31, 2022
5.7.5	Test of 1st mockup prototype	May 1, 2022	May 31, 2022
5.7.6	Test of 1.2m x 0.8m prototype	Nov 1, 2022	Dec 31, 2022
5.7.7	Test of 4m x 0.5m prototype	Oct 1, 2023	Dec 31, 2023
5.7.8	**Beam tests of prototypes at CERN**	**Oct 25, 2021**	**Nov 1, 2022**
5.7.8.1	Small XX+YY with VMM3a readout at H4 RD51	Oct 25, 2021	Nov 7, 2021
5.7.8.2	Small XX+YY with VMM3/VMM3a at GIF	Apr 25, 2022	May 3, 2022
5.7.8.3	Small XX+YY at H4 RD51/GIF	May 18, 2022	Jun 7, 2022
5.7.8.4	XX+YY & mockup at RD51/GIF	Jul 13, 2022	Jul 26, 2022
5.7.8.5	XX+YY & mockup at RD51/GIF	Oct 19, 2022	Nov 1, 2022
5.8	**Simulation of STT modules**	**Jan 1, 2020**	**Dec 31, 2023**
5.8.1	Finite element analysis	Jan 1, 2021	Dec 31, 2023
5.8.2	Thermal analysis	Jan 1, 2021	Dec 31, 2023
5.8.3	Simulation of drift properties (Garfield)	Jan 1, 2021	Mar 31, 2021
5.8.4	Optimization of operating conditions (Garfield) & validation	Apr 1, 2022	Dec 31, 2022
5.8.5	Simulation of physics performance	Jan 1, 2020	Dec 31, 2023
5.8.6	Optimization of physics performance	Apr 1, 2022	Dec 31, 2023



PRODUCTION SITES, PROCUREMENT & FABRICATION

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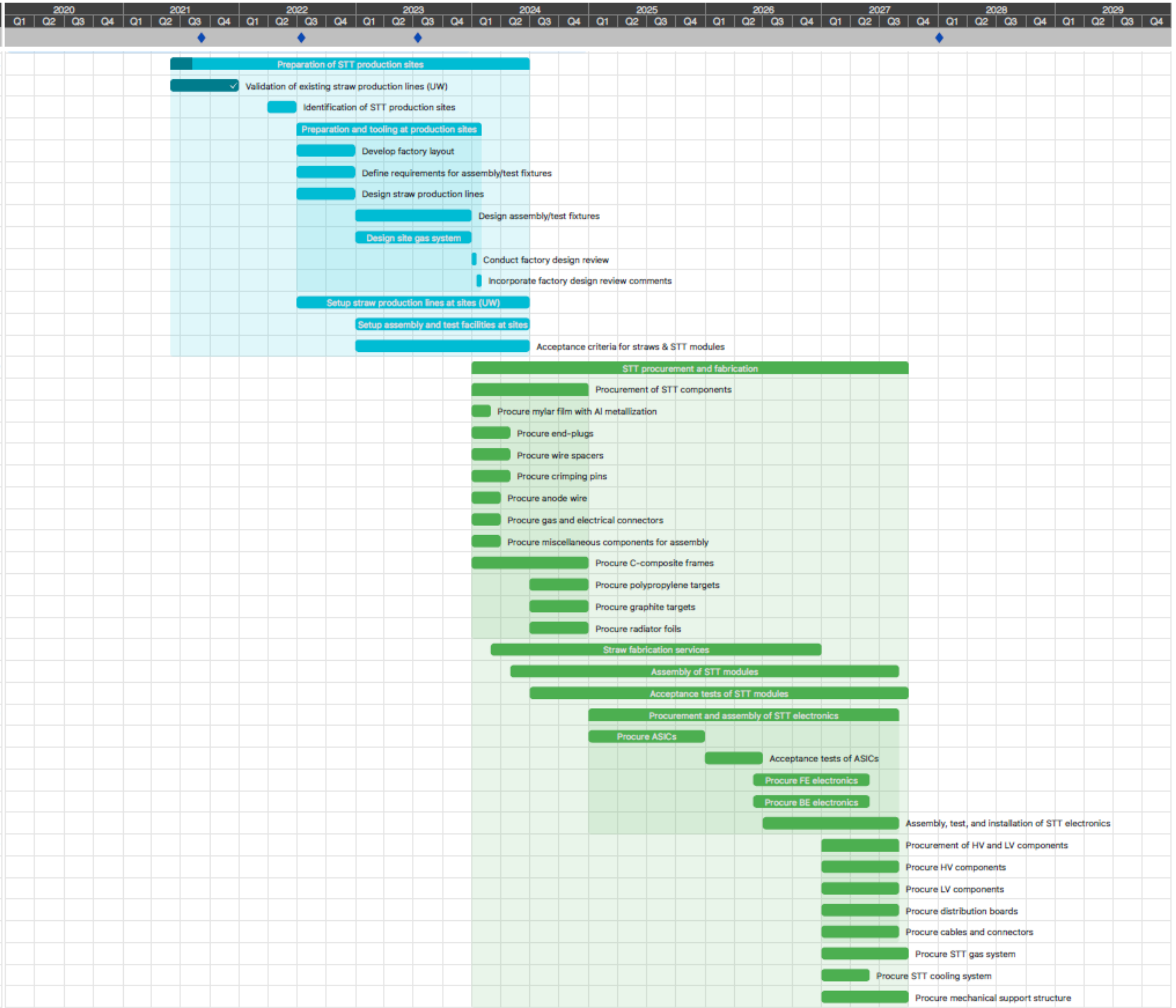
WBS	Task	Start	Finish
		Jan 1, 2020	Dec 31, 2029
6	**Preparation of STT production sites**	**Jun 1, 2021**	**Jun 30, 2024**
6.1	Validation of existing straw production lines (UW)	Jun 1, 2021	Dec 31, 2021
6.2	Identification of STT production sites	Apr 1, 2022	Jun 30, 2022
6.3	**Preparation and tooling at production sites**	**Jul 1, 2022**	**Jan 31, 2024**
6.3.1	Develop factory layout	Jul 1, 2022	Dec 31, 2022
6.3.2	Define requirements for assembly/test fixtures	Jul 1, 2022	Dec 31, 2022
6.3.3	Design straw production lines	Jul 1, 2022	Dec 31, 2022
6.3.4	Design assembly/test fixtures	Jan 1, 2023	Dec 31, 2023
6.3.5	Design site gas system	Jan 1, 2023	Dec 31, 2023
6.3.6	Conduct factory design review	Jan 1, 2024	Jan 15, 2024
6.3.7	Incorporate factory design review comments	Jan 16, 2024	Jan 31, 2024
6.4	Setup straw production lines at sites (UW)	Jul 1, 2022	Jun 30, 2024
6.5	Setup assembly and test facilities at sites	Jan 1, 2023	Jun 30, 2024
6.6	Acceptance criteria for straws & STT modules	Jan 1, 2023	Jun 30, 2024
7	**STT procurement and fabrication**	**Jan 1, 2024**	**Sep 30, 2027**
7.1	**Procurement of STT components**	**Jan 1, 2024**	**Dec 31, 2024**
7.1.1	Procure mylar film with Al metallization	Jan 1, 2024	Feb 29, 2024
7.1.2	Procure end-plugs	Jan 1, 2024	Apr 30, 2024
7.1.3	Procure wire spacers	Jan 1, 2024	Apr 30, 2024
7.1.4	Procure crimping pins	Jan 1, 2024	Apr 30, 2024
7.1.5	Procure anode wire	Jan 1, 2024	Mar 31, 2024
7.1.6	Procure gas and electrical connectors	Jan 1, 2024	Mar 31, 2024
7.1.7	Procure miscellaneous components for assembly	Jan 1, 2024	Mar 31, 2024
7.1.8	Procure C-composite frames	Jan 1, 2024	Dec 31, 2024
7.1.9	Procure polypropylene targets	Jun 30, 2024	Dec 31, 2024
7.1.10	Procure graphite targets	Jun 30, 2024	Dec 31, 2024
7.1.11	Procure radiator foils	Jun 30, 2024	Dec 31, 2024
7.2	Straw fabrication services	Mar 1, 2024	Dec 31, 2026
7.3	Assembly of STT modules	May 1, 2024	Aug 31, 2027
7.4	Acceptance tests of STT modules	Jul 1, 2024	Sep 30, 2027
7.5	**Procurement and assembly of STT electronics**	**Jan 1, 2025**	**Aug 31, 2027**
7.5.1	Procure ASICs	Jan 1, 2025	Dec 31, 2025
7.5.2	Acceptance tests of ASICs	Jan 1, 2026	Jun 30, 2026
7.5.3	Procure FE electronics	Jun 1, 2026	May 31, 2027
7.5.4	Procure BE electronics	Jun 1, 2026	May 31, 2027
7.5.5	Assembly, test, and installation of STT electronics	Jul 1, 2026	Aug 31, 2027
7.6	**Procurement of HV and LV components**	**Jan 1, 2027**	**Aug 31, 2027**
7.6.1	Procure HV components	Jan 1, 2027	Aug 31, 2027
7.6.2	Procure LV components	Jan 1, 2027	Aug 31, 2027
7.6.3	Procure distribution boards	Jan 1, 2027	Aug 31, 2027
7.6.4	Procure cables and connectors	Jan 1, 2027	Aug 31, 2027
7.7	Procure STT gas system	Jan 1, 2027	Sep 30, 2027
7.8	Procure STT cooling system	Jan 1, 2027	May 31, 2027
7.9	Procure mechanical support structure	Jan 1, 2027	Sep 30, 2027



INSTALLATION & COMMISSIONING

WBS	Task	Start	Finish
		Jan 1, 2020	Dec 31, 2029
1	STT selected as SAND tracker	Sep 2, 2021	Sep 2, 2021
2	PDR (DOE CD1RR) TBD	Jul 12, 2022	Jul 12, 2022
3	TDR (DOE CD2) TBD	Jul 12, 2023	Jul 12, 2023
4	ND site available TBD	Jan 1, 2028	Jan 1, 2028
5	STT design and prototyping	Jan 1, 2020	Dec 31, 2024
6	Preparation of STT production sites	Jun 1, 2021	Jun 30, 2024
7	STT procurement and fabrication	Jan 1, 2024	Sep 30, 2027
8	**STT installation in the magnet**	**Sep 1, 2026**	**Jan 31, 2028**
8.1	Shipping of STT modules to Fermilab	Sep 1, 2026	Oct 1, 2027
8.2	Test of STT modules on surface	Apr 1, 2027	Oct 31, 2027
8.3	Installation of STT targets	May 1, 2027	Nov 30, 2027
8.4	Installation of STT modules in magnet	Jun 1, 2027	Jan 31, 2028
9	**Service connections and commissioning**	**Jun 1, 2028**	**Dec 31, 2029**
9.1	Installation of STT gas system	Jun 1, 2028	Sep 28, 2028
9.2	Installlation of the HV and LV components	Jul 30, 2028	Sep 25, 2028
9.3	Cabling and gas connections	Sep 28, 2028	Dec 29, 2028
9.4	Commissioning of STT	Dec 30, 2028	May 31, 2029
9.5	Alignment with cosmics	Jun 1, 2029	Dec 31, 2029