ALICE 3 Inner Tracker

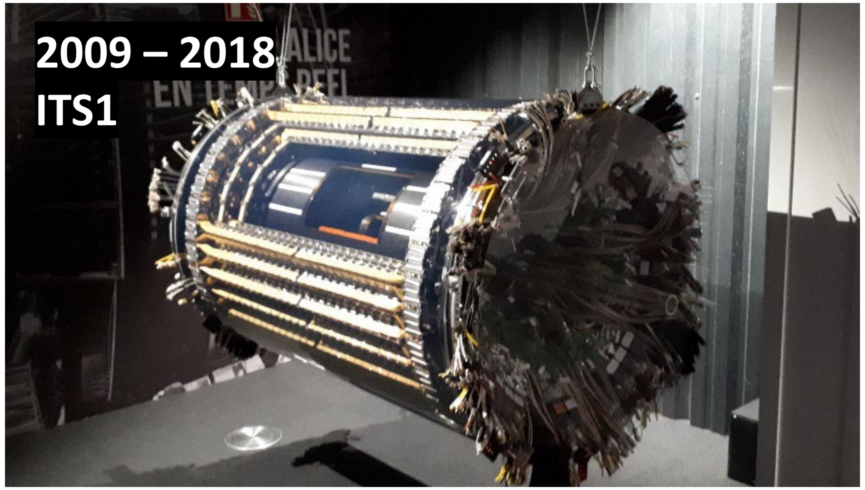
Riunione Referee ALICE – 20-21 Luglio 2023

Giacomo Contin - Università di Trieste & INFN Sezione di Trieste

Outline

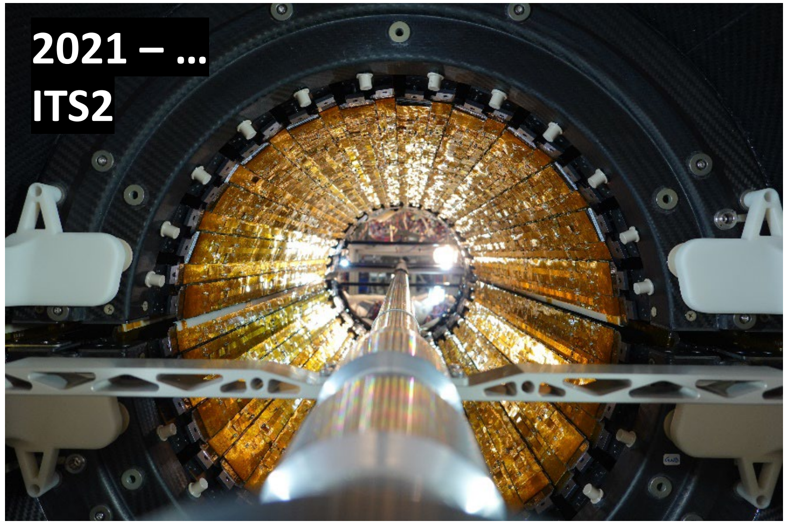
- ITS3 as a first step towards ALICE 3 Inner Tracker
- Planned R&D activities for ALICE 3 Inner Tracker
- Requests for 2024

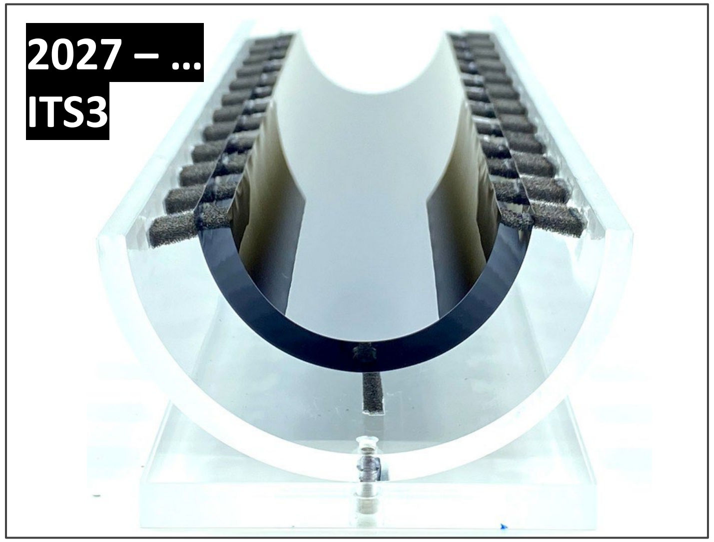
Silicon tracker evolution in ALICE



- **ITS1**: three silicon technologies
  - Hybrid pixels
  - Drift chambers
  - Micro-strips
- Operated for 10 years in ALICE
  - Essential ingredient for its physics output (secondary vertex reconstruction)

- **ITS2**: a large-scale MAPS detector
  - Monolithic Active Pixel Sensors
  - 10 m^2 active area
- Currently taking data

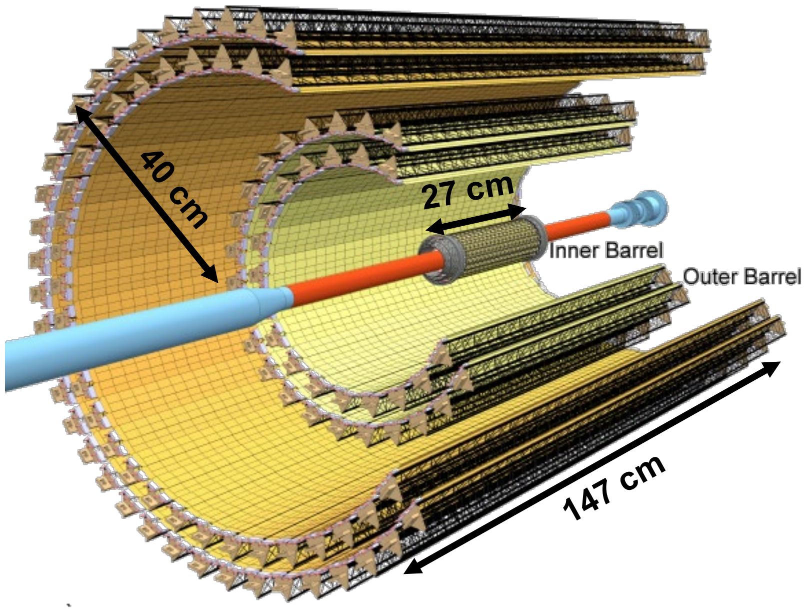




- **ITS3**: wafer-scale, bent silicon
  - Replacing the ITS2 innermost layers
  - Novel detector technology
- R&D endorsed by LHCC and running at full speed
- TDR in preparation

INFN Leadership in all Projects from the start

ITS2: from R&D to detector implementation



ITS2 specifications

7 layers:
all MAPS
10 m^2, 24k chips, 12.5×10^9 Pixels

Innermost layer:
radial distance: 23 mm
material: $X/X_0 = 0.35\%$
pitch: 29 × 27 μm^2

Rate capability: 100 kHz (Pb-Pb)

ITS2 expected performance
pointing resolutions of 15 µm (in r and z) at p_T=1GeV/c
tracking efficiencies > 90% for particles with p_T >200 MeV/c

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Reporting on international high-energy physics

PIXEL PERFECT

Exploring the Hubble tension
A CERN for climate change
Medical technologies

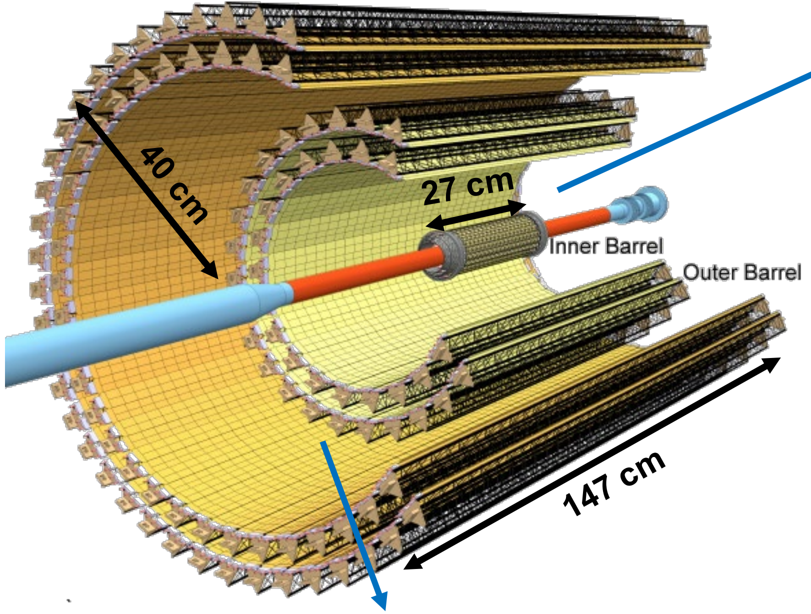
- **ITS2**: the largest detector based on MAPS technology
  - Sensor (ALPIDE) and apparatus **fully developed within ALICE**
  - R&D program started ~12 years ago
  - Construction involved > 10 institutes
  - Currently taking data in ALICE

INFN BA, BR/PV, CA, CT, LNF, PD, TO, TS

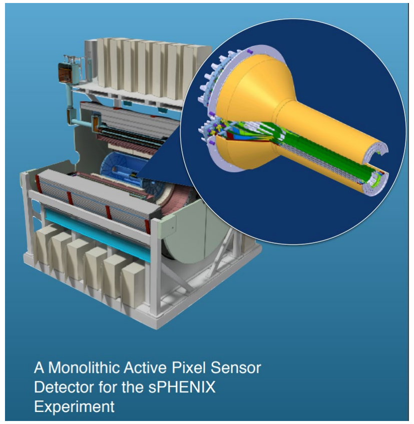
- Safe resource investment for concrete high-quality results

ITS2 technology transfer to other projects

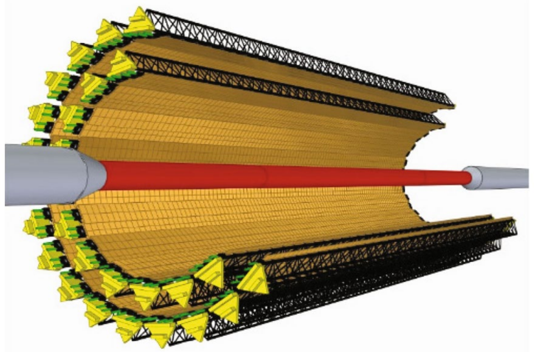
ALICE ITS2



sPHENIX MVTX @RHIC

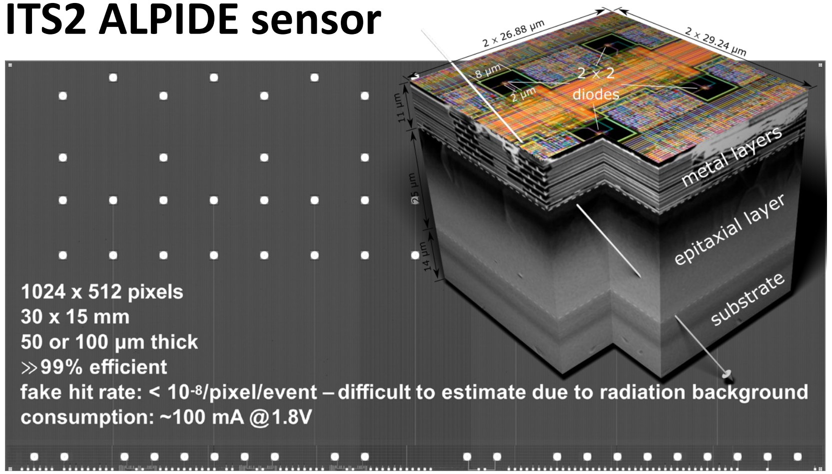


MPD Inner Tracker @NICA



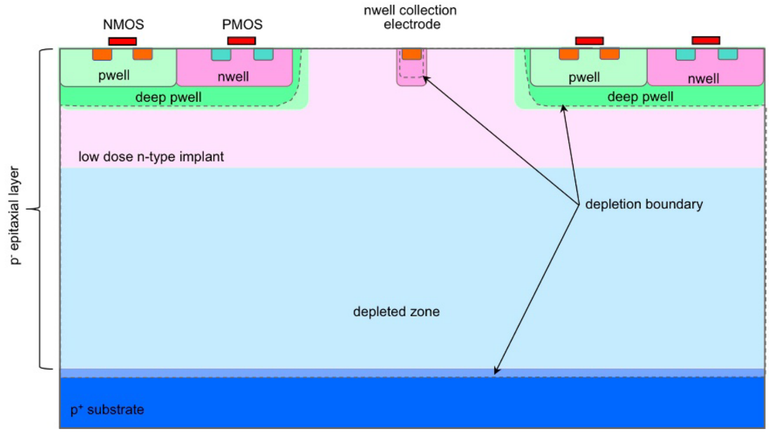
- **Detector replicas** for new experiments

ITS2 ALPIDE sensor

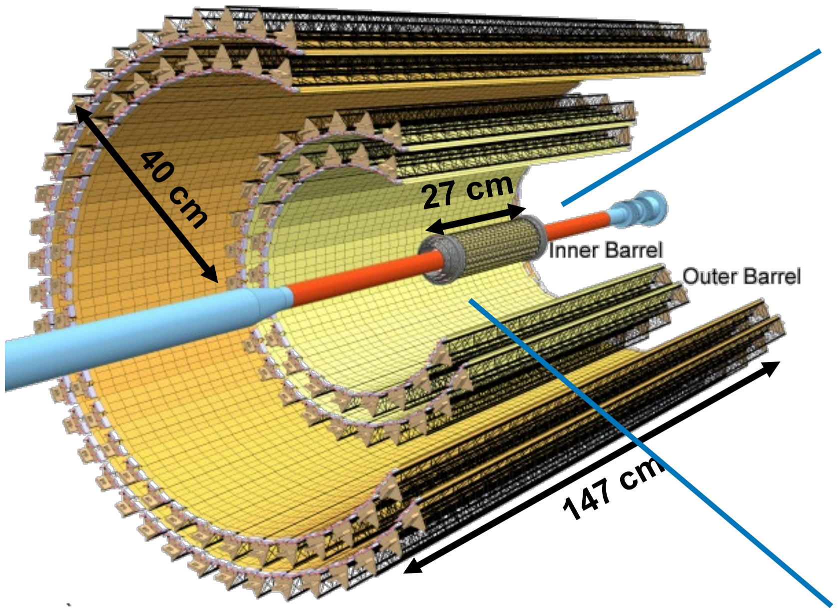


1024 x 512 pixels
30 x 15 mm
50 or 100 µm thick
≫99% efficient
fake hit rate: < 10^{-8}/pixel/event – difficult to estimate due to radiation background
consumption: ~100 mA @1.8V

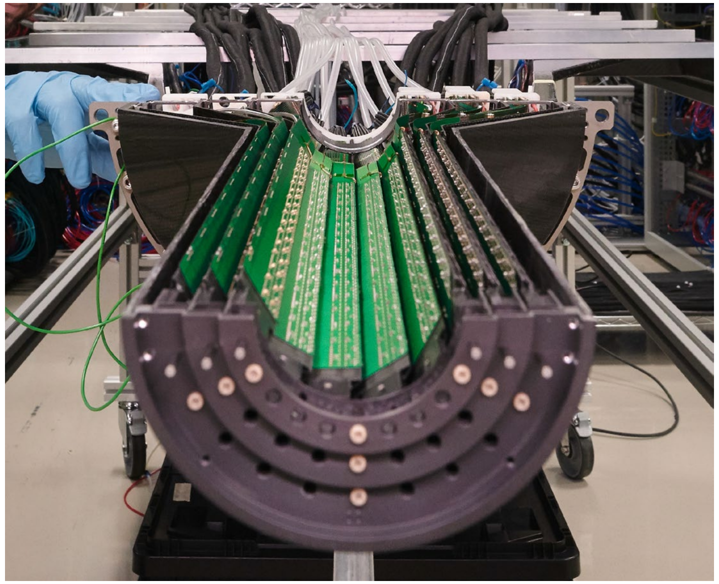
- **Modified process** developed and prototyped within ALPIDE R&D for better timing and radiation hardness
  - Now adopted or considered by future experiments...
    - HADES, CBM, PANDA, NUSTAR, NA61, CSES2-Limadou, iMPACT, COMPASS++/AMBER, pCT, ePIC ...
  - & chip developments:
    - MALTA,
    - CLICpix,
    - FastPix, ...



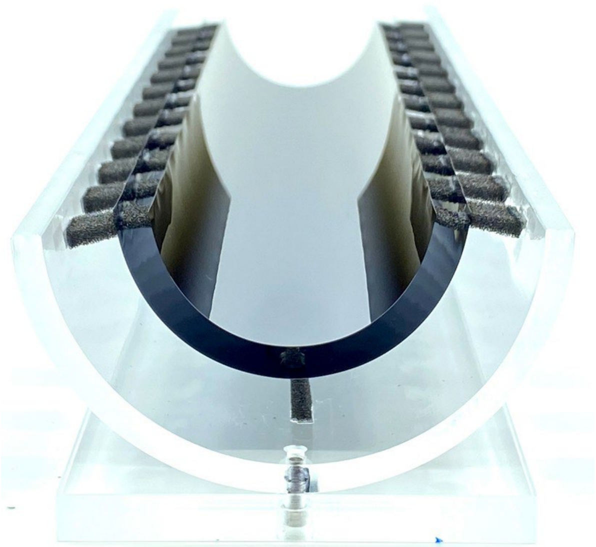
ITS3: wafer-scale sensors with bent geometry



ITS2 Inner Barrel

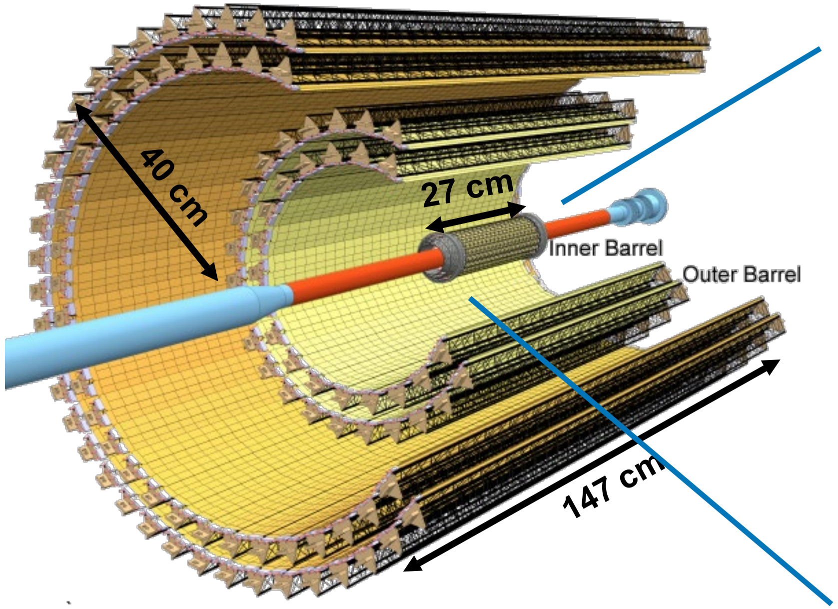


ITS3

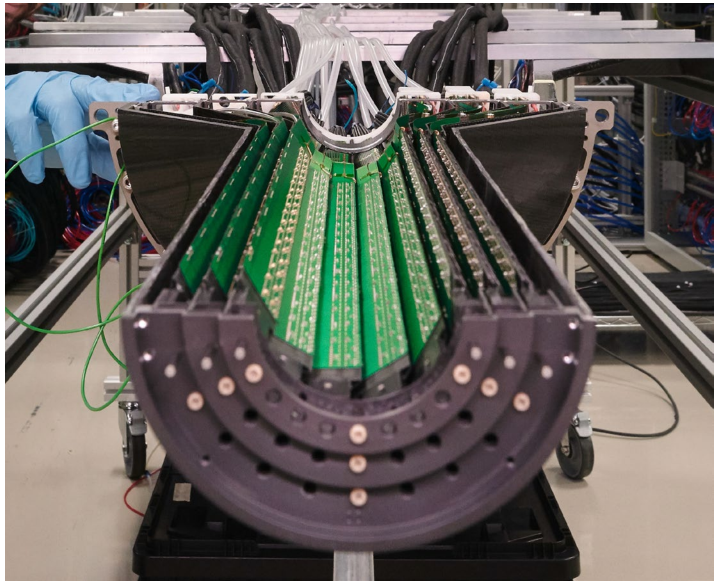


- **Motivation**: further material budget reduction → improve tracking resolution x2 → large physics impact
- **Proposal:** replace detector staves (tiled by several chips) by wafer-scale sensors that are bent around the beam pipe

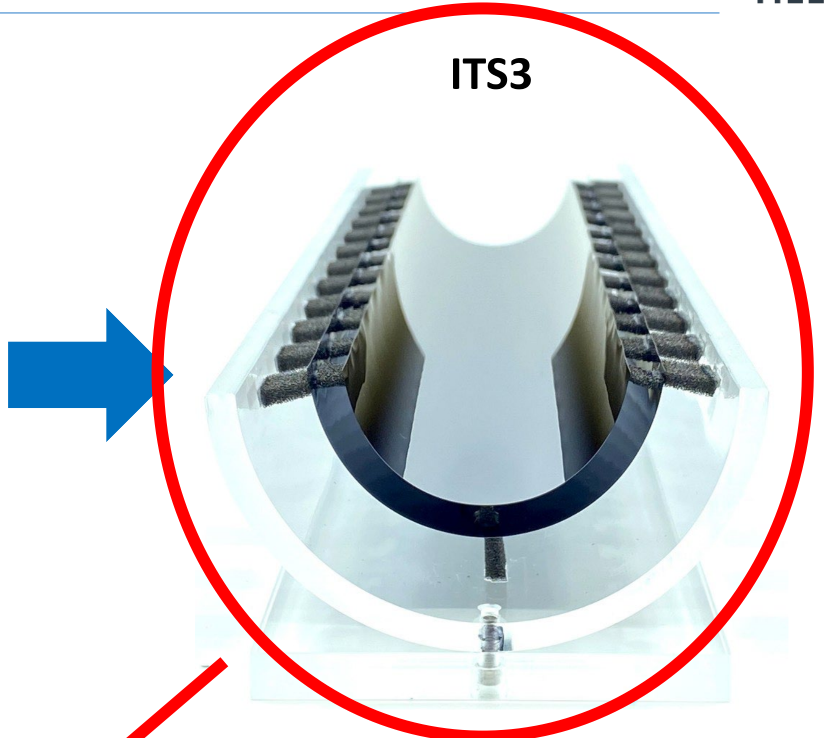
ITS3: wafer-scale sensors with bent geometry



ITS2 Inner Barrel



ITS3



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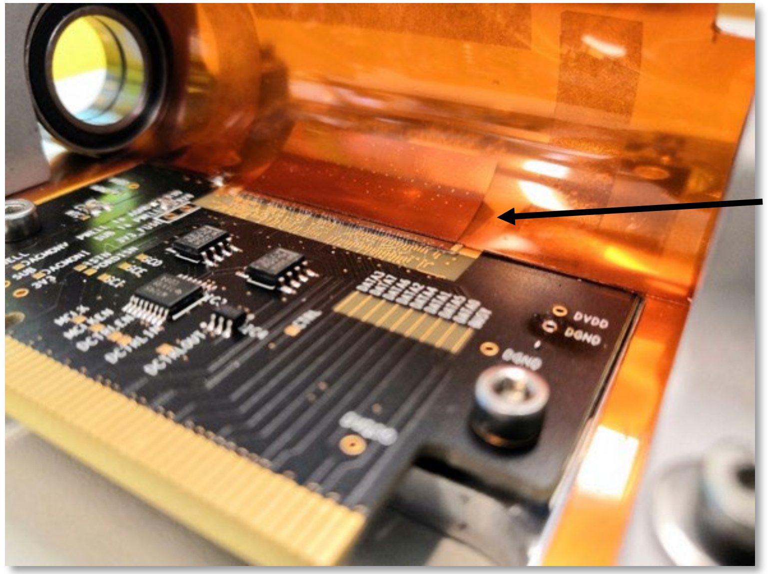
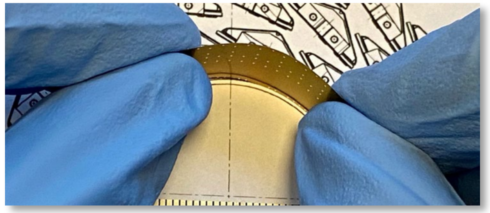
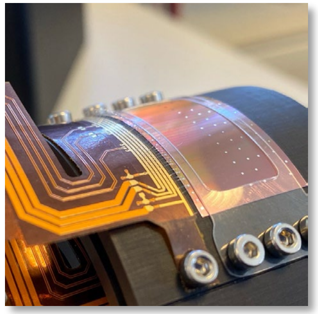
First step towards the ALICE 3 Inner Tracker sensor and detector concept

R&D towards ALICE 3: **bent MAPS sensors**

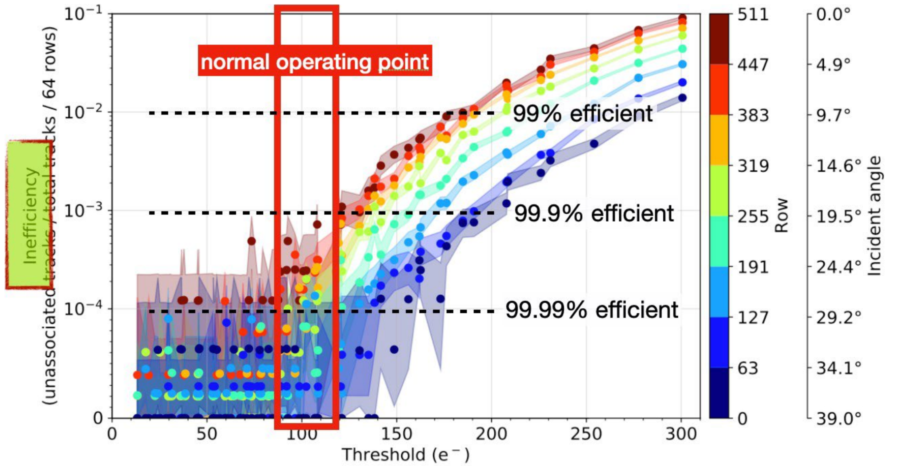


- Silicon becomes flexible below 50 µm thickness
- **Idea:** bend existing MAPS sensors (ALPIDE) and interconnect to readout/control system
- Measure the bent sensor performance and compare with flat sensors

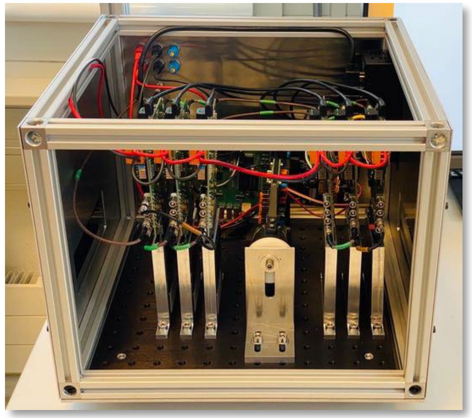




Bent MAPS work!



https://doi.org/10.1016/j.nima.2021.166280



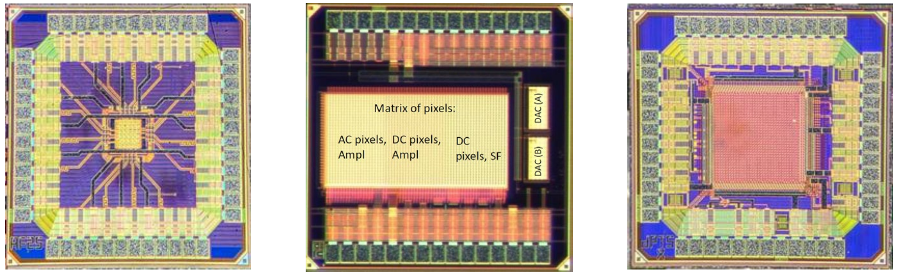
R&D carried out within INFN
- Bending mechanics and procedures
- Curvature precision measurements
- Wire-bonding on curved surface
- Laboratory characterization
- In-beam performance measurements

INFN BA, BO, CA, CT, PD, TO, TS

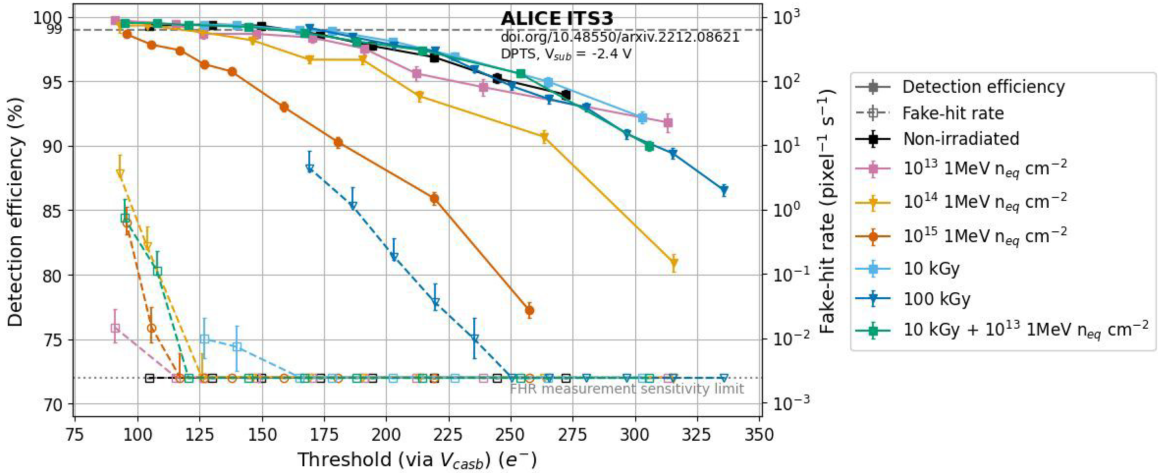
R&D towards ALICE 3: **65 nm CMOS process**

- **65 nm CMOS process** exploration
  - test structures design & characterization with lab measurements and beam tests
  - test system design & production

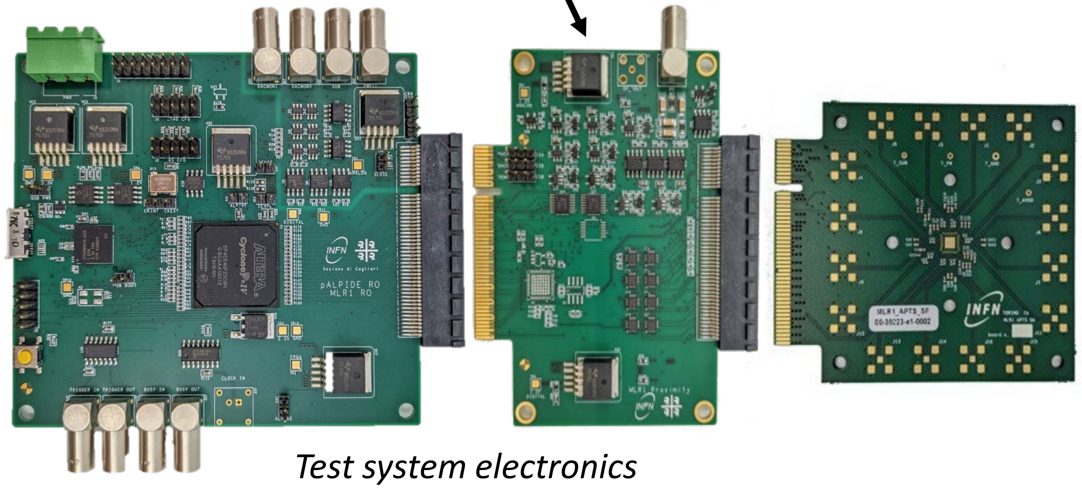
APTS, CE65 and DPTS: 65 nm CMOS test structures



Digital pixel test structure efficient after irradiation



Submitted to NIM A: https://arxiv.org/abs/2212.08621

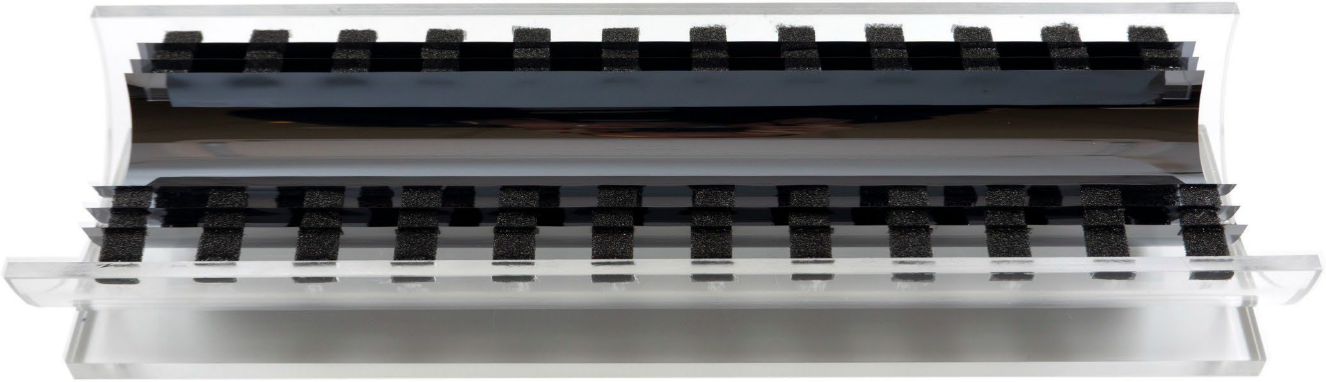


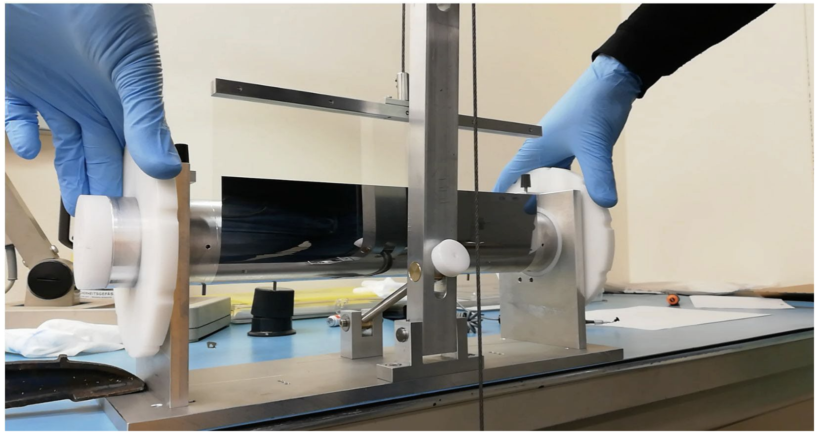
Test system electronics

INFN BA, CA, CT, PD, TO, TS

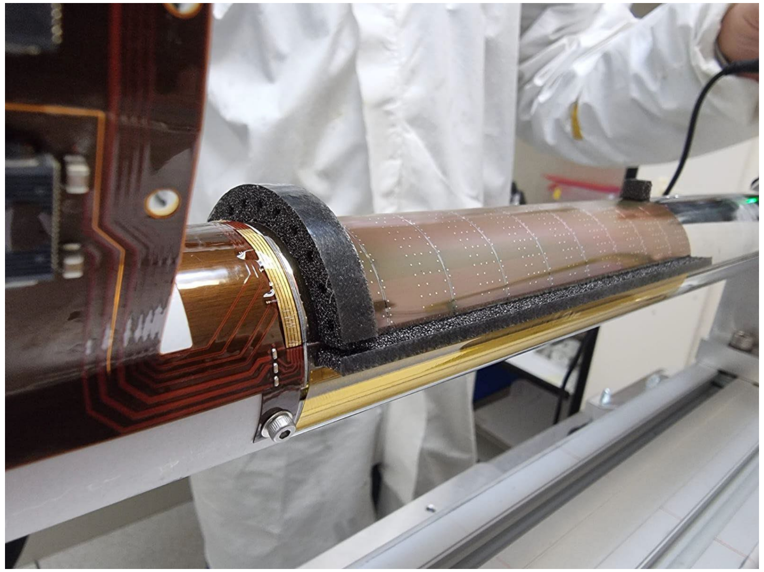
R&D towards ALICE 3: **mechanics & interconnections**

- Large-area bending and mechanical supports

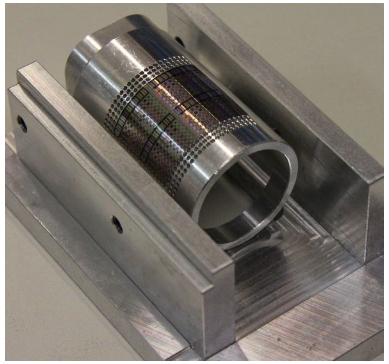




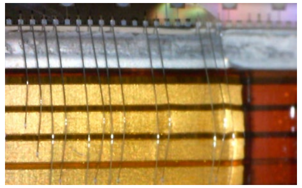
- Full-scale ITS3 Layer prototype in 180 nm CMOS



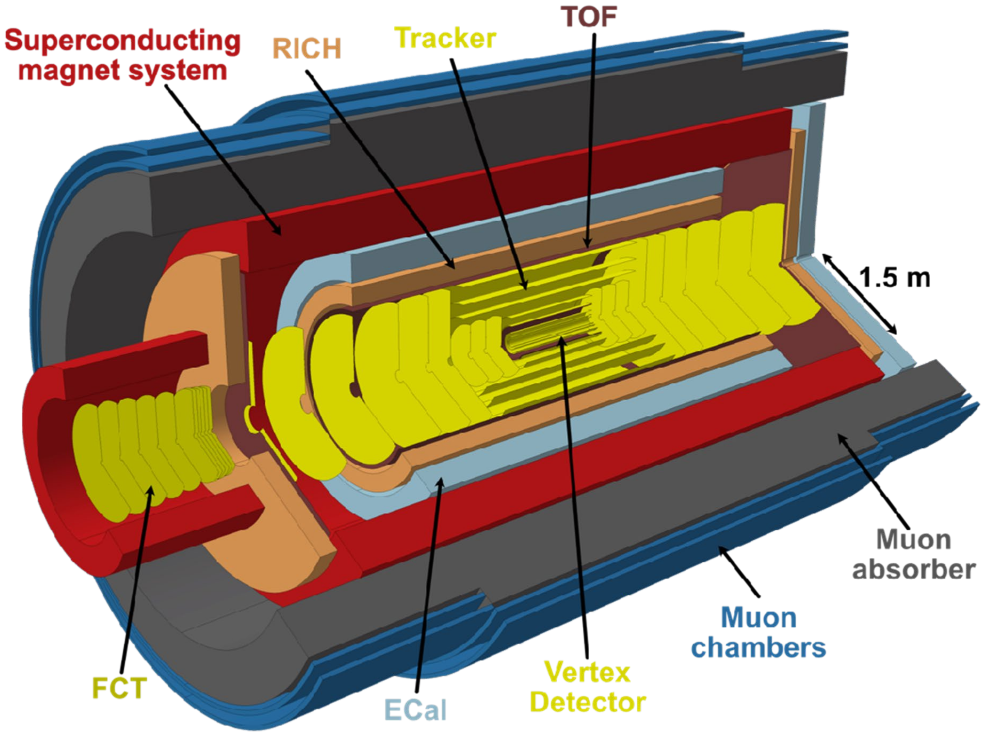
- Bent 65 nm CMOS structure characterization



- Interconnections on bent substrate



INFN BA, TO, TS



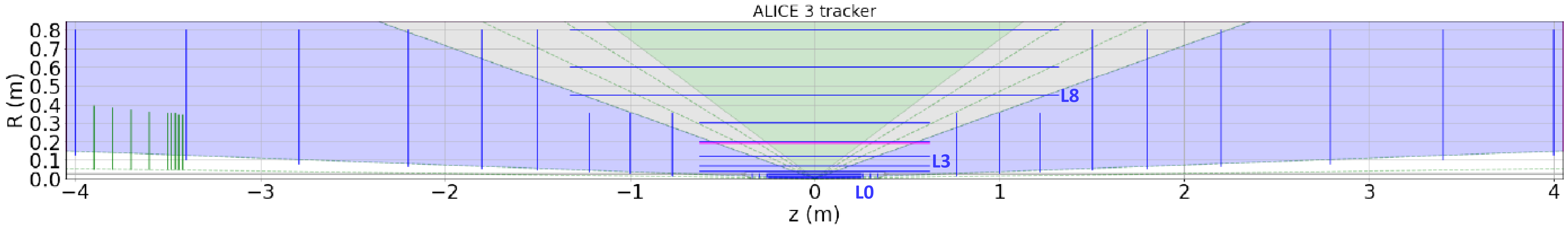
R&D for ALICE 3 Inner Tracker

BA, BS/PV, CA, CT/ME, PD, LNF, TO, TS

giacomo.contin@ts.infn.it

Tracker layout (LoI)

Full Tracker

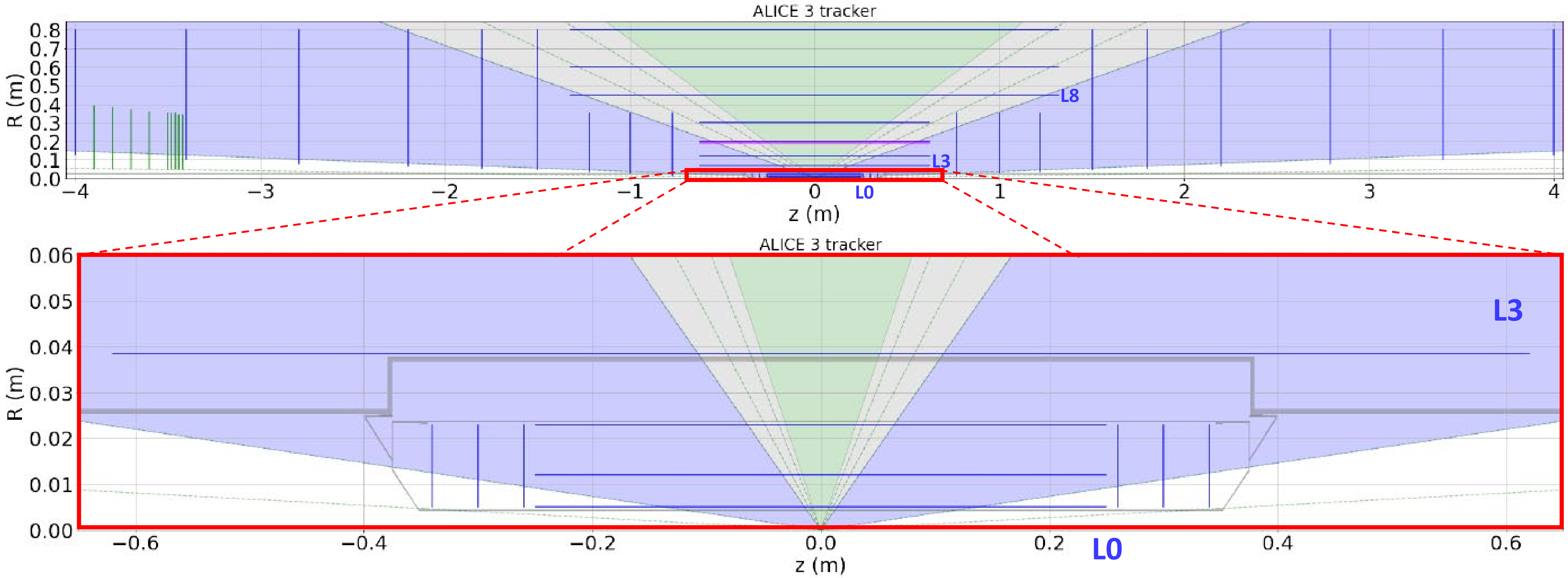


- **11 barrels + 12 discs per side**
- **Main distinction: inside/outside the beampipe**
  - material thickness: 0.1 / 1.0 %X_0
  - intrinsic resolution: 2.5 / 10 µm
- **Barrel lengths and radii, disk positions: not fully optimized yet**

	Layer	Material thickness (%X_0)	Intrinsic resolution (µm)	Barrel layers Length (z) (cm)	Barrel layers Radius (r) (cm)	Forward discs Position (|z|) (cm)	Forward discs R_{in} (cm)	Forward discs R_{out} (cm)
Inside the beam pipe	0	0.1	2.5	50	0.50	26	0.50	3
	1	0.1	2.5	50	1.20	30	0.50	3
	2	0.1	2.5	50	2.50	34	0.50	3
	3	1	10	124	3.75	77	5	35
	4	1	10	124	7	100	5	35
	5	1	10	124	12	122	5	35
	6	1	10	124	20	150	5	80
	7	1	10	124	30	180	5	80
	8	1	10	264	45	220	5	80
	9	1	10	264	60	279	5	80
	10	1	10	264	80	340	5	80
	11	1				400	5	80

Tracker layout (LoI)

Full Tracker



Vertex Layers + L3

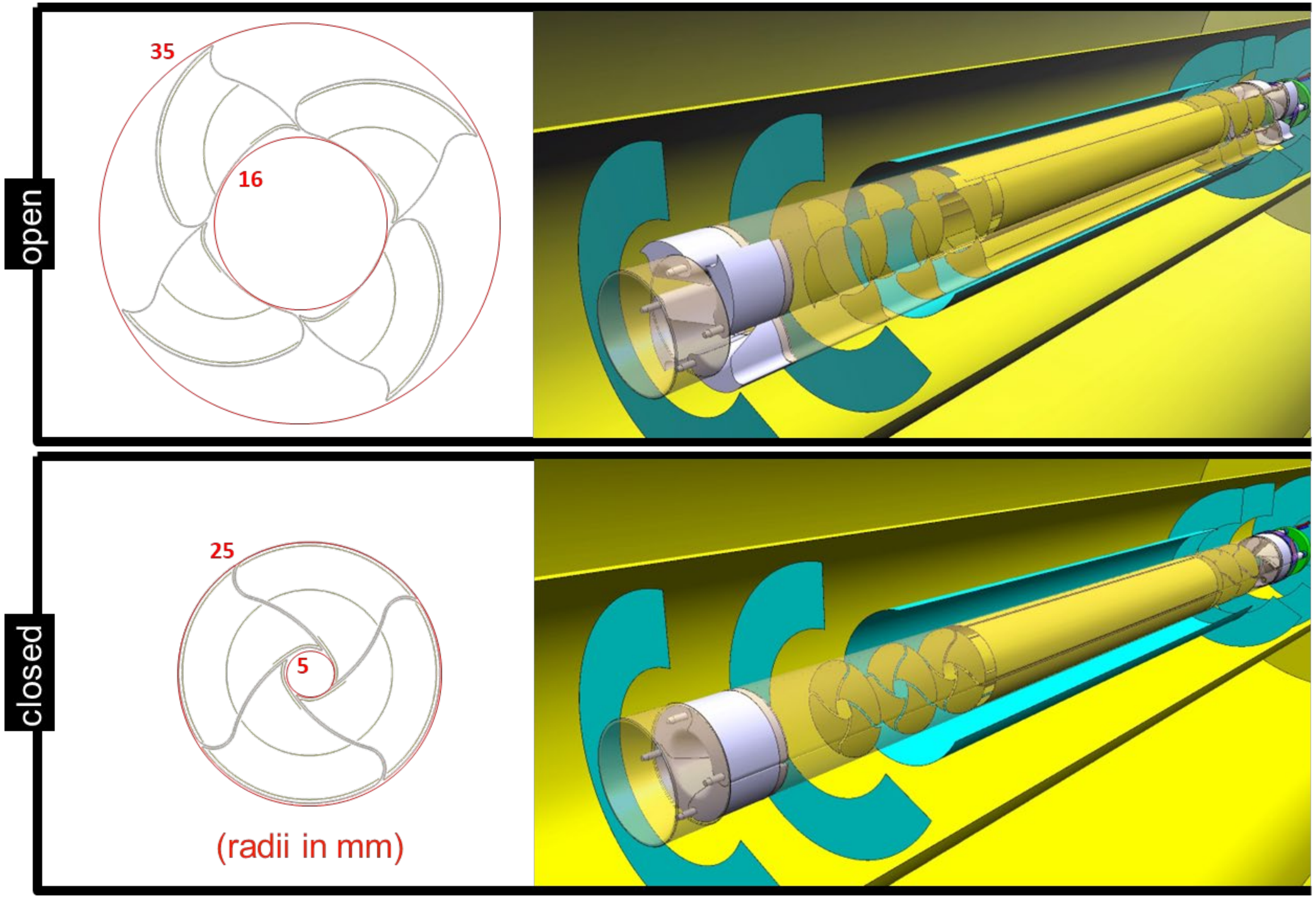
Zoom in on the first 4 layers

ALICE 3 Tracker — **Iris**: inside the beam pipe

- **Curved sensors**
- **5 mm** from IP
  - Crucial to gain highest possible vertex resolution
  - Extremely challenging requirements on sensor
- **Retractable mechanics** inside the beam pipe
- **Vacuum-compatible** services and interconnections

INFN R&D on

Vertex Detector (= Iris)



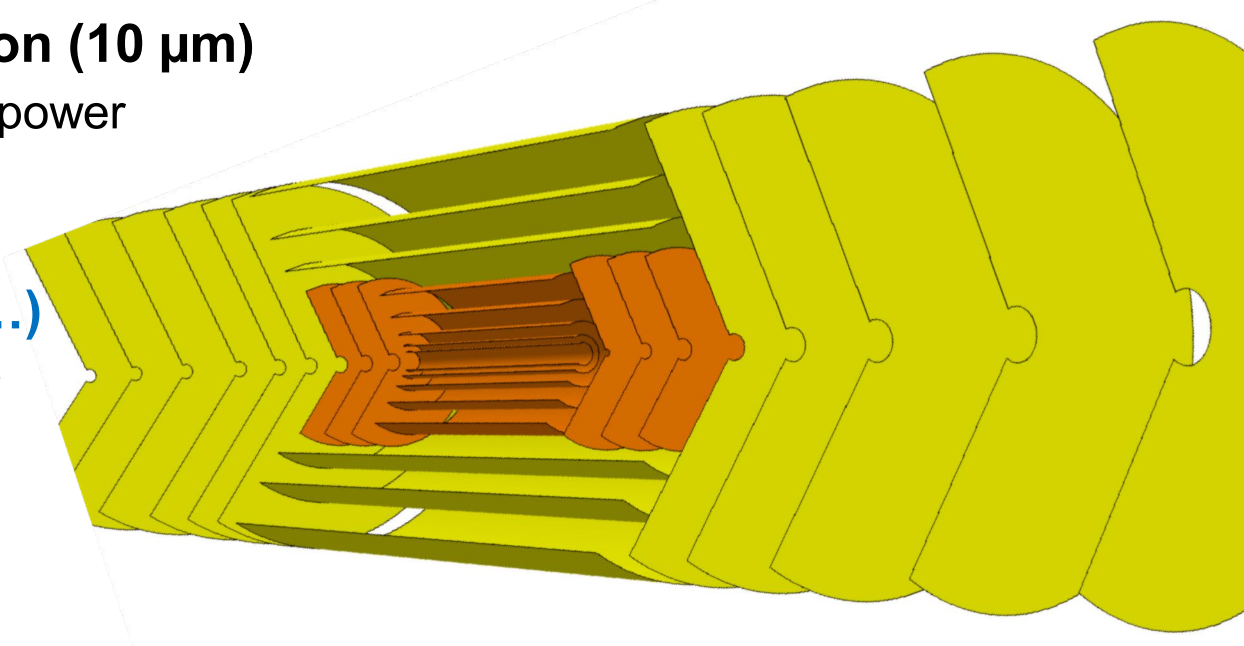
ALICE 3 Tracker — **Outside** the beam pipe

- **~60 m^2 active surface**
  - Heavily relies on a module concept that can be automated/industrialised
  - ITS2 module production for 10 m^2 kept 5 institutes busy for years
- **Low material budget (1% X_0):**
  - Reducing power consumption will be key
  - Powering granularity and services (serial powering, DC/DC, on-detector switches)
- **Less stringent requirement on position resolution (10 μm)**
  - Will allow for larger pixels/grouping of pixels to reduce power
  - Reducing the noise contribution to the bandwidth

- **A specific design for the Middle Layers (L3-L4-…)** with lower material budget and different pixel specs will improve the p_T resolution at very low p_T

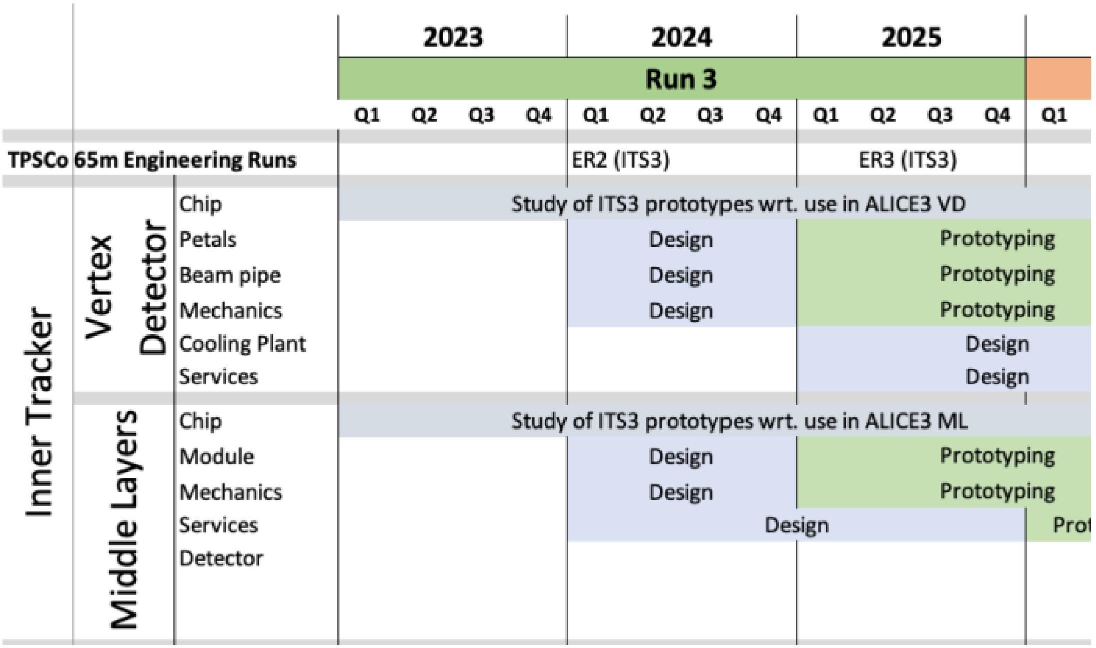
INFN R&D on **Middle Layers**

Physics simulations to define optimal layout are ongoing



R&D INFN su Inner Tracker = Vertex + Middle Layers

- Sviluppo del **sensore ALICE 3 Inner Tracker**
  - Sensore ITS3 e’ il primo passo dello sviluppo del sensore per ALICE 3 Inner Tracker
  - Per 2024 non c’e’ richiesta dedicata per ALICE 3 chip
  - Possibile la caratterizzazione orientata ad ALICE 3
- Indispensabile **anticipare le attivita’ orientate al *risk mitigation*** su chip per ALICE 3
  - Abilita’ del sensore *stitched* ITS di distribuire la tensione di alimentazione su grandi distanze attraverso gli strati metallici interni al silicio e’ ancora sotto esame
  - Strato di ridistribuzione applicato con manifattura additiva



			2023	2024	2025	
			Run 3	Run 3	Run 3	
			Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1 Q2 Q3 Q4	Q1
TPSCo 65m Engineering Runs				ER2 (ITS3)	ER3 (ITS3)	
Inner Tracker	Vertex Detector	Chip	Study of ITS3 prototypes wrt. use in ALICE3 VD			
		Petals		Design	Prototyping	
		Beam pipe		Design	Prototyping	
		Mechanics		Design	Prototyping	
		Cooling Plant			Design	
		Services			Design	
	Middle Layers	Chip	Study of ITS3 prototypes wrt. use in ALICE3 ML			
		Module		Design	Prototyping	
		Mechanics		Design	Prototyping	
		Services		Design		Prot
		Detector				

from preliminary ALICE 3 planning

- Sviluppo **tecnologie compatibili col vuoto** per Iris
  - Meccaniche, sistema di raffreddamento, interconnessioni, materiali e colle

Inner Tracker WG
CERN, Italy, Czech Rep,
Netherlands, Norway, Ukraine

- Esplorazione comparata di **possibili layout dei Middle Layers**

ALICE 3 Inner Tracker **Sensor** development

	Vertex Detector	Outer Tracker	ITS3	ITS2
Pixel size (µm^2)	÷ 9 *O*(10 x 10)	✖2.8 *O*(50 x 50)	*O*(20 x 20)	*O*(30 x 30)
Position resolution (µm)	÷ 2 2.5	✖2 10	5	5
Time resolution (ns RMS)	÷ 10 100	÷ 10 100	O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25 200	÷ 25 200	O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈ $< 10^{-8}$	≈ $< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm^2)	+ 75% 70	67% 20	20 (pixel matrix)	40 / 30**
Particle hit density (MHz / cm^2)	✖20 94	÷ 100 0.06	8.5	5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm^2)	✖3000 1×10^{16}	✖100 2×10^{14}	3×10^{12}	3×10^{12}
Total Ionising Dose (Mrad)	✖1000 300	✖20 5	0.3	0.3

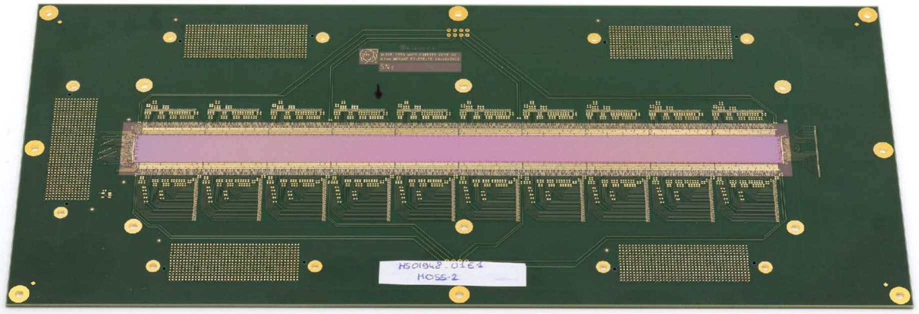
** Innermost layers / outer layers

Different optimisations at different radii

- Improving ITS2/ITS3 performance in all aspects
- Current goals extremely challenging, will be revised based on simulations, results from ITS3 development, and available resources
- **No requests for 2024: ITS3 sensor IS the prototype for ALICE 3**

ALICE 3 IT Sensor risk mitigation: **Redistribution layer**

- In-silicon power distribution over long distances not yet validated
  - If *stitching* yield is sub-optimal for excessive voltage drop across the chip, a **post-processing** of the sensor is needed (measurements are ongoing)



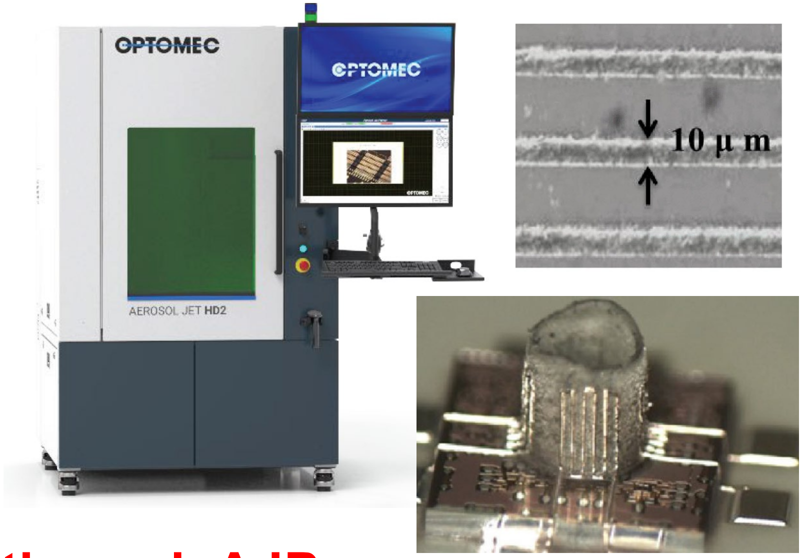
Stitched prototype

Fall-back options:

a) MAPS-foil: embed thin MAPS into polyimide sandwich, developed within ITS3
  - Copper traces deposited on the polyimide and connected to the sensor by through-hole metallization – traditional lithography
  - Adds ~0.05% *X0*, power dissipation not evaluated → not ideal for ALICE 3

b) Application of a **Re-Distribution Layer** (RDL) with additive manufacturing
  - Additional copper and polyamide layer(s) added to the wafer where needed
  - Trade-off between resistance and material budget
  - ***Aerosol Jet Printing (AJP)*** machine available at INFN TS – UniTS:
    - 10 μm spatial resolution, on planar and bent substrate

AJP – conductive traces

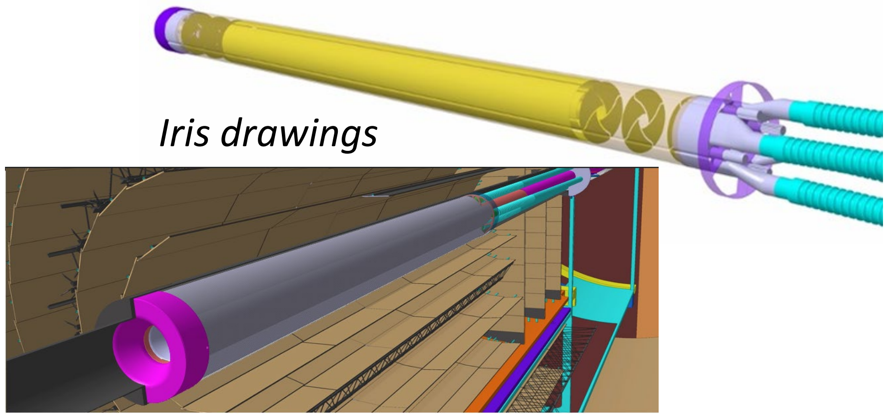


- **Request for 2024: inks to develop conductive traces deposition through AJP**

ALICE 3 Vertex Layers (Iris): **Vacuum technology**

IRIS is constituted by 4 petals

- sensors in each petal are kept in a vacuum case (secondary vacuum, **10^{-10} mbar**) to avoid contamination of primary vacuum

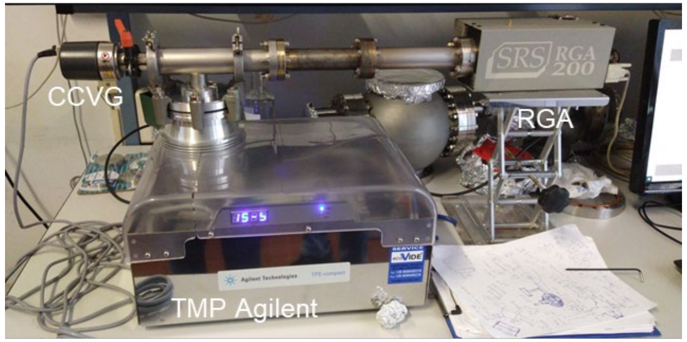


Iris drawings

Foreesen in vacuum studies (**~10^{-10} mbar**):

- outgassing measurements
  - vacuum level comparison
  - a.m.u. behaviour of residual gasses
  - sample weight comparison (*before and after outgassing*)
- Stress measurements on mechanical assembly
  - gluing
  - wire-bonding

Existing facility for vacuum studies (INFN BA)

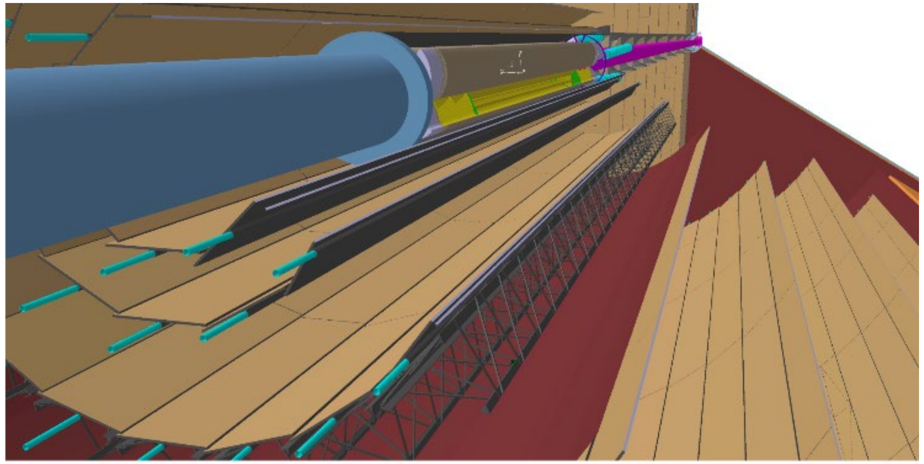


Existing equipment

Requests for 2024: vacuum pump, vacuum chamber baking lamp, vacuum components for ALICE 3-specific upgrade

Options for **Middle layers**: L3-L4(-L5?)

- LoI concept
  - **Traditional stave-based layout** →
    - Same sensor as larger radius layers
    - Mechanics, liquid cooling, interconnection bus
    - 1% X_0 for normal incidence
    - Length = 124 cm
    - Coverage (L4): $|\eta| < 2.9$



Middle Layer layout - LoI concept

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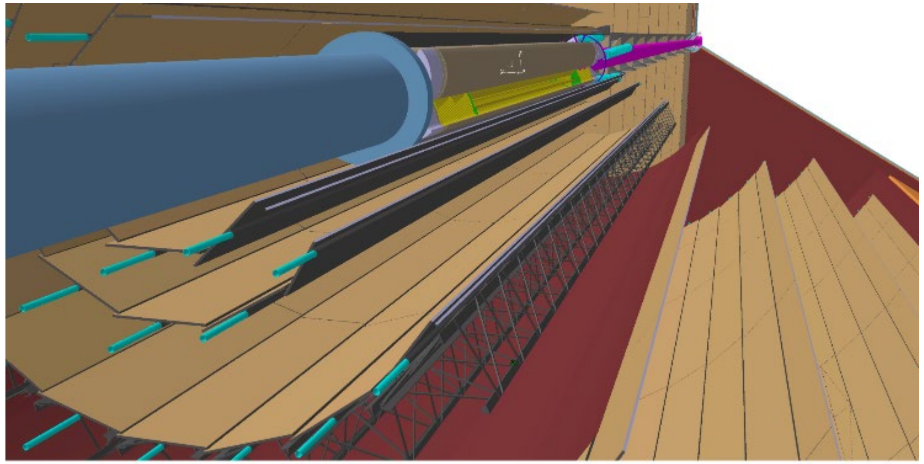
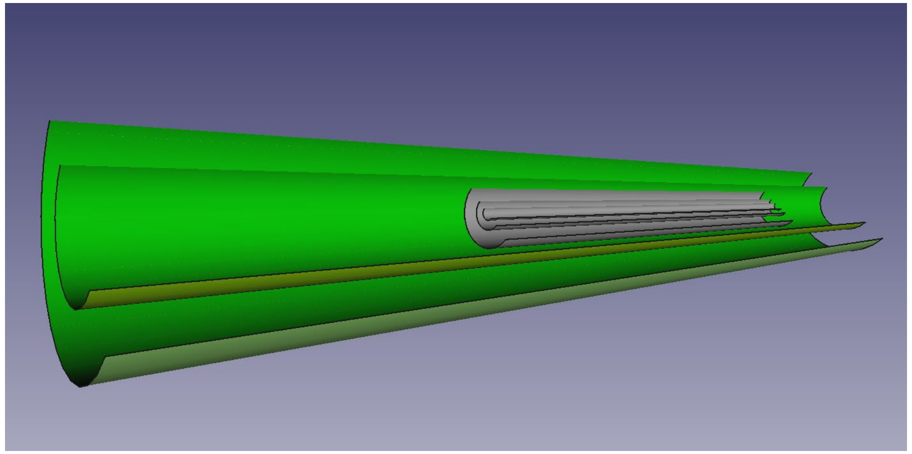


Middle Layer layout - LoI concept

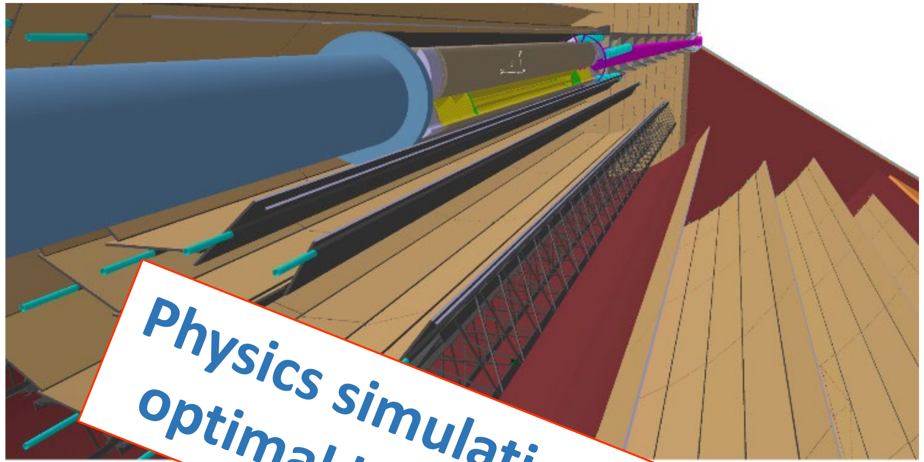
- Possible optimised layout for L3-L4
  - **Flexible sensors with minimal supports** →
    - Same sensor as for the Iris layers
    - Added supports and I/O structures to cover the length
    - **0.1% ~ 0.3% X_0** for normal incidence
    - Length = 100 cm (2x vertex layer length)
    - Coverage (L4): $|\eta| < 2.7$



Middle Layer layout – Optimised layout

Options for **Middle layers**: L3-L4(-L5?)

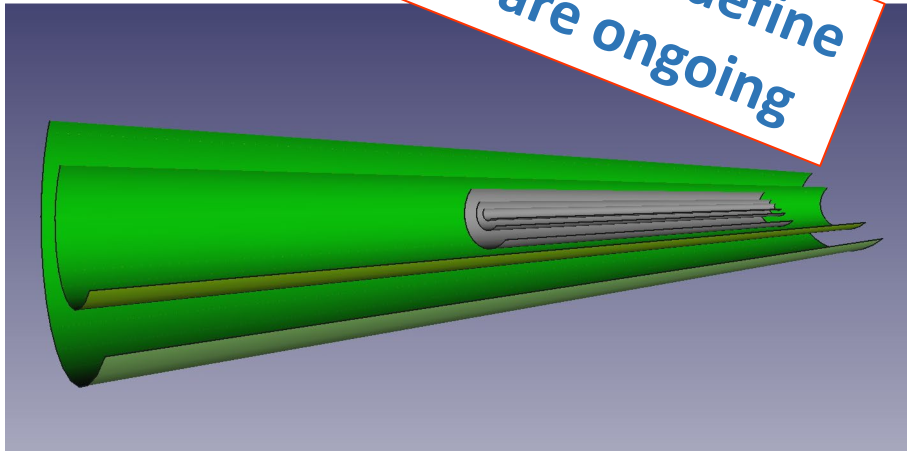
- LoI concept
  - **Traditional stave-based layout** →
    - Same sensor as larger radius layers
    - Mechanics, liquid cooling, interconnection bus
    - 1% X_0 for normal incidence
    - Length = 124 cm
    - Coverage (L4): $|\eta| < 2.9$



Mid

Physics simulations to define optimal layout are ongoing

- Possible optimised layout for L3-L4
  - **Flexible sensors with minimal supports** →
    - Same sensor as for the Iris layers
    - Added supports and I/O structures to cover the length
    - **0.1% ~ 0.3% X_0** for normal incidence
    - Length = 100 cm (2x vertex layer length)
    - Coverage (L4): $|\eta| < 2.7$

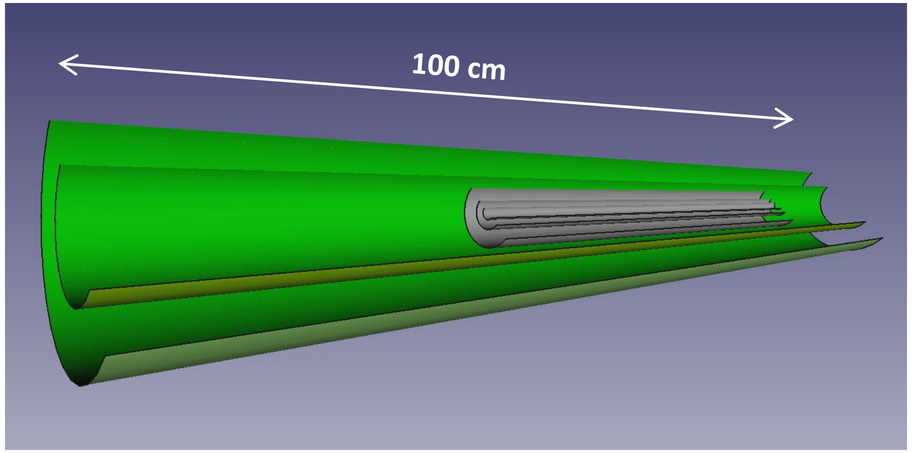


Middle Layer layout – Optimised layout

Optimised layout for **Middle layers**: L3-L4(-L5?)

- Possible optimised layout for L3-L4
  - **Flexible sensors with minimal supports**
    - Same sensor as for the Iris layers
    - Added supports and I/O structures to cover the length
    - **0.1% ~ 0.3%** X_0 for normal incidence
    - Length = 100 cm (2x vertex layer length)
    - Coverage (L4): $|\eta| < 2.7$

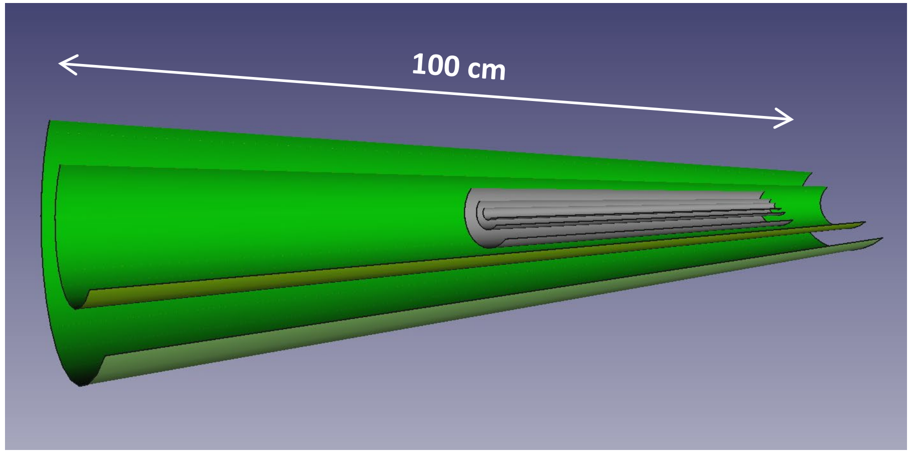
Middle Layer layout – Optimised layout



Optimised layout for **Middle layers**: L3-L4(-L5?)

- Possible optimised layout for L3-L4
  - **Flexible sensors with minimal supports**
    - Same sensor as for the Iris layers
    - Added supports and I/O structures to cover the length
    - **0.1% ~ 0.3%** X_0 for normal incidence
    - Length = 100 cm (2x vertex layer length)
    - Coverage (L4): $|\eta| < 2.7$

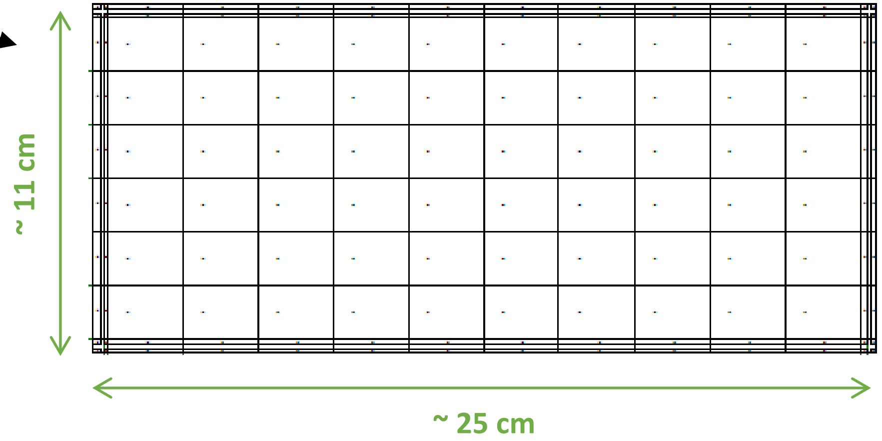
Middle Layer layout – Optimised layout



- Area = 0.239m^2 + 0.440m^2 < **0.7m^2**
  - Layer 3 can be formed with 4x4 sensors* (~25 x 6 cm^2)
  - Layer 4 can be formed with 4x4 sensors* (~25 x11 cm^2)

* = Allowed on 30 cm wafers

Allowed dimensions for stitched sensor on 30 cm wafer



Optimised layout for **Middle layers**: L3-L4(-L5?)

- Possible optimised layout for L3-L4
  - **Flexible sensors with minimal supports**
    - Same sensor as for the Iris layers
    - Added supports and I/O structures to cover the length
    - **0.1% ~ 0.3%** X_0 for normal incidence
    - Length = 100 cm (2x vertex layer length)
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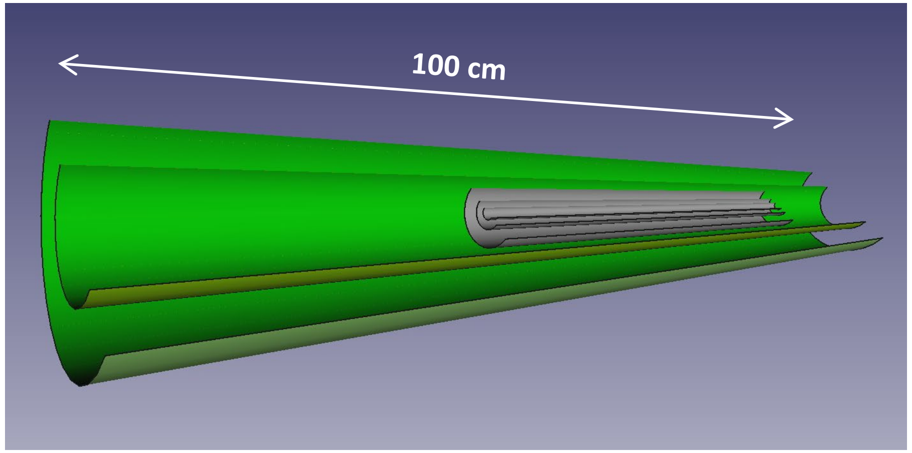
Middle Layer layout – Optimised layout



- Area = 0.239m^2 + 0.440m^2 < **0.7m^2**
  - Layer 3 can be formed with 4x4 sensors* (~25 x 6 cm^2)
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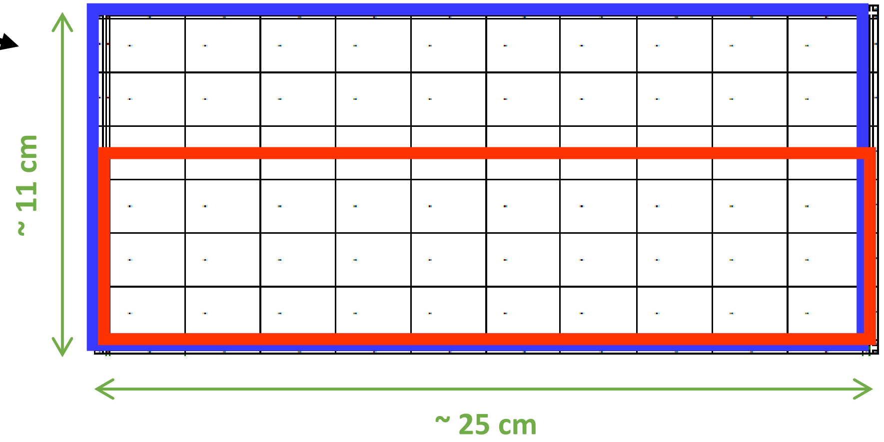

Optimised layout for **Middle layers**: L3-L4(-L5?)

- Possible optimised layout for L3-L4
  - **Flexible sensors with minimal supports**
    - Same sensor as for the Iris layers
    - Added supports and I/O structures to cover the length
    - **0.1% ~ 0.3%** X_0 for normal incidence
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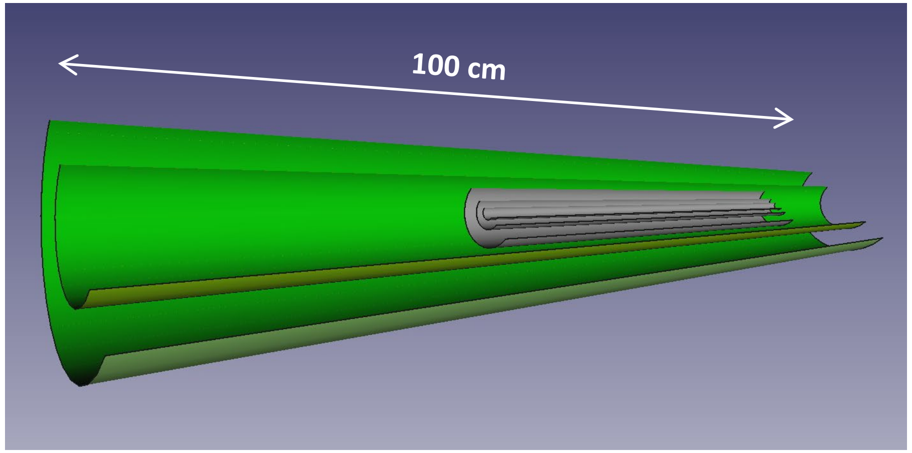
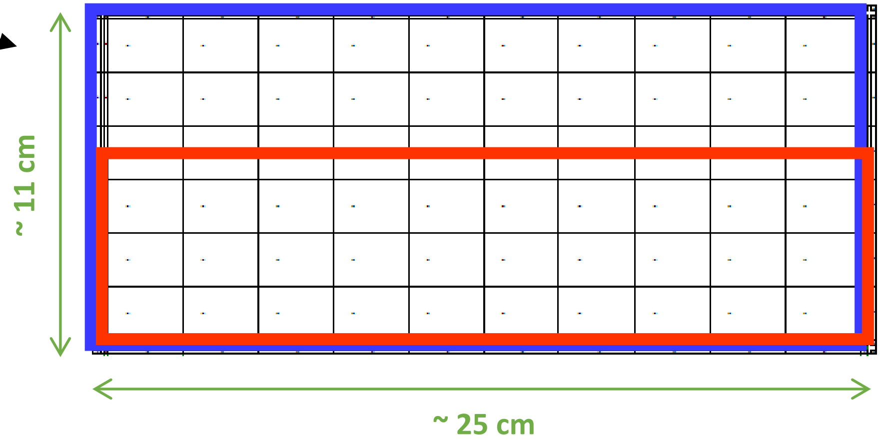
Middle Layer layout – Optimised layout



- Area = 0.239m² + 0.440m² < **0.7m²**
  - Layer 3 can be formed with 4x4 sensors* (~25 x 6 cm²)
  - Layer 4 can be formed with 4x4 sensors* (~25 x11 cm²)

* = Allowed on 30 cm wafers

Allowed dimensions for stitched sensor on 30 cm wafer

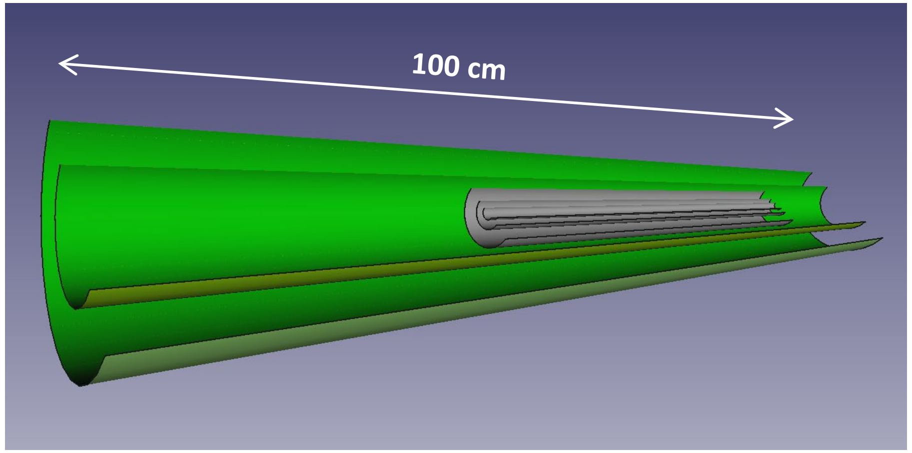


- Material thickness of **0.1%** $\boldsymbol{X_0}$ is in reach
  - Longer sensor chain with simpler mechanics/cooling wrt Vertex
  - ITS3-like assembly
  - Repeated to cover the length
  - **Demonstrate the feasibility!**

Optimised layout for **Middle layers**: L3-L4(-L5?)

- Possible optimised layout for L3-L4
  - **Flexible sensors with minimal supports**
    - Same sensor as for the Iris layers
    - Added supports and I/O structures to cover the length
    - **0.1% ~ 0.3% X_0** for normal incidence
    - Length = 100 cm (2x vertex layer length)
    - Coverage (L4): $|\eta| < 2.7$

Middle Layer layout – Optimised layout



Requests for 2024: carbon foam and carbon fiber to prepare rings and support structures for Middle Layer mechanical prototypes

INFN R&D: Inner Tracker (Vertex + Middle)

- Sensor for Vertex and Middle Layers
  - Main sensor development and characterisation
  - Adaptation for Middle Layers

Covered within ITS3 for 2024

- In-vacuum mechanics, cooling, interconnections

BA + others

- Re-distribution layer for power & interconnections

TS + others

- Middle Layers layout
  - Concepts, feasibility, prototypes

PD, TS
+ others

ALICE 3 Inner Tracker: richieste 2024

Attivita’	Dettaglio	Richiesta 2024 (k€)	Sede
Sviluppo e caratterizzazione sensore	-	0	BA, BS/PV, CA, CT/ME, PD, LNF, TO, TS
Studi di vuoto	Pompa a vuoto, dispositivi di bake-out, componenti	15	BA
Prototipi meccanici Middle layers	Fibra e schiuma di carbonio sagomate	10	TS* (per TS & PD)
Strato ridistribuzione con manifattura additiva	Inchiostri AJP conduttivi/isolanti	7	TS
TOTALE		**32**	
Missioni	Test in vuoto di prototipi	**2**	TS* (per tutti)

Thank you for your attention!

Backup: ALICE 3 tracker – specifications

	Layer ID	Radius [cm]	Length [cm]	< $\|\eta\|$	Area [m²]	Tot Area [m²] up to this Layer	Pixel pitch [um]	Tot Pixels (10^6)	Power density [mW/cm²]	Tot Power (+20%) [W]	Max Hit Rate [10^6/cm²/s]	Required BW for Hits [Gbit/s]	Required BW for Noise [Gbit/s]	Total Installed BW [Gbit/s]
Inside the beam pipe	0	0.5	50	4.6	0.016	0.016	10	157	70	13	94	236	1.0	237
	1	1.2	50	3.7	0.038	0.053	10	377	70	32	16	97	2.4	99
	2	2.5	50	3.0	0.079	0.132	10	785	70	66	3.8	48	5.0	53
Middle Layers	3	3.8	100	3.3	0.239	0.371	10	2388	70	201	1.7	65	15.3	80
	4	7.0	100	2.7	0.440	0.811	10	4398	70	369	0.48	34	28.1	62
	5	12.0	124	2.3	0.935	1.745	50	374	20	224	0.16	24	2.4	26
	6	18.0	124	1.9	1.402	3.148	50	561	20	337	0.058	13	3.6	17
	7	30.0	124	1.4	2.337	41.972	50	935	20	561	0.026	10	6.0	16
	8	45.0	264	1.8	7.464	49.437	50	2986	20	1791	0.012	14	19.1	33
	9	60.0	264	1.5	9.953	59.389	50	3981	20	2389	6.50E-03	10	25.5	36
	10	80.0	264	1.2	13.270	72.659	50	5308	20	3185	3.70E-03	8	34.0	42

- Hit density decreases by *O*(10^4) from layer 0 to layer 10
- Bandwidth dominated by the vertex detector
- Noise performance critical for the outer most layers

- Bandwidth:16 bit / hit, single pixel clusters
- Radiation load: 50 months of 24 MHz pp interactions
- Fake-hit rate: 10-8 / pixel / event at 40 MHz readout rate

Main R&D items for the ALICE 3 Tracker (I)

- Sensor development (ALICE 3 ER1’ foreseen by 2027)
  - Challenging requirements:
    - Highest possible vertex resolution (Vertex Detector)
    - High radiation tolerance (Vertex Detector)
    - High Speed front-end circuit
    - High Data Bandwidth to handle
    - Extremely low noise (Outer Tracker)
    - Low power consumption (extremely low for Outer Tracker)
    - Single-point failure tolerance

  - At least two sensor versions need to be developed
    - Common development with fork-off?
    - Existing low-performance technology for Outer Tracker?
    - Is a third version needed for Middle Layers?
    - *In collaboration with CERN and other Institutions (ITS2/ITS3 model)*

Main R&D items for the ALICE 3 Tracker (II)

- Iris development (L0-L1-L2, inside the beam pipe)
  - Vacuum-compatible technology
  - Retractable mechanics
  - Flexible sensors
  - *INFN groups with significant experience, strong commitment from CERN*

- Middle layers (L3-L4, outside the beam pipe)
  - Bent silicon to equip ~0.7 m^2 with low-material supports and I/O structures
  - Substantial data bandwidth and power consumption
  - *Well-defined item matching INFN groups' expertise*

- Sensor characterization
  - Crucial for the sensor development
  - ITS3 experience shows that a large effort is needed
  - *Easy to contribute for small/medium-sized groups*

Resources ramping up in 2024-2028

- 8 groups involved:

  Bari, Brescia/Pavia, Cagliari, Catania/Messina, Frascati, Padova, Torino, Trieste

- **~15 FTE** (total of 25 collaborators*) for detector R&D and construction
  - 4-5 on **sensor design**
    - 3 designers already integrated in the ITS3 design, more to come
    - Need to focus on ALICE 3-specific design quite soon
  - 6-7 on **sensor characterisation**
    - 6 groups already active participants in ITS3 test system development and sensor characterisation
  - 4 on **integration and mechanics**
    - Experience on ITS2 mechanical structure and ITS3 integration

** including Researchers, Postdocs, PhD students, Engineers, Technicians*

- Adequate contribution to simulation and physics studies

News on avaliable infrastructures

- Well equipped laboratories and workshops in most of the sites
  - (Automatic) probe stations, bonding facilities, CMMs, radiation sources, mechanical workshops

- Additional infrastructures
  - Vacuum laboratory, assembly clean room @ Bari
  - Assembly clean room, X-ray facility, soon cyclotron @ Padova
  - Beam test facility, assembly clean room @ Frascati
  - Assembly clean room, X-ray facility @ Torino
  - X-ray facility, future sensor and AM laboratory @ Trieste
  - …

- **FTE and infrastructures availability expected to grow once the project starts**

giacomo.contin@ts.infn.it