

ePIC Silicon Vertex Tracker Project R&D

Status Report and Proposal

eRD104: Services Reduction

eRD111: Modules, Mechanics, Cooling and Integration

eRD113: Sensor Development and Characterization

Ernst Sichtermann (LBNL)

for the ePIC SVT Detector Subsystem Collaboration

Outline

- **Introduction**
- Status of R&D for the ePIC SVT
- Proposal and request for FY24
- Outlook

ePIC Silicon Vertex Tracker Collaboration



ePIC Silicon Vertex Tracker Collaboration

- The overarching goal is the development and construction of a full tracking and vertexing detector subsystem for the ePIC project detector based on 65nm MAPS sensors
- ePIC SVT DSC has its origins in the EIC Silicon Consortium,
- MIT, Oxford, and Purdue have joined during the past period,
- Productive work with the EIC project in areas ranging from agreements with ALICE/CERN on sensor development to service estimates and routing, work package structure, etc.
- Kickoff meeting provides an overview — <https://indico.bnl.gov/event/19823/>

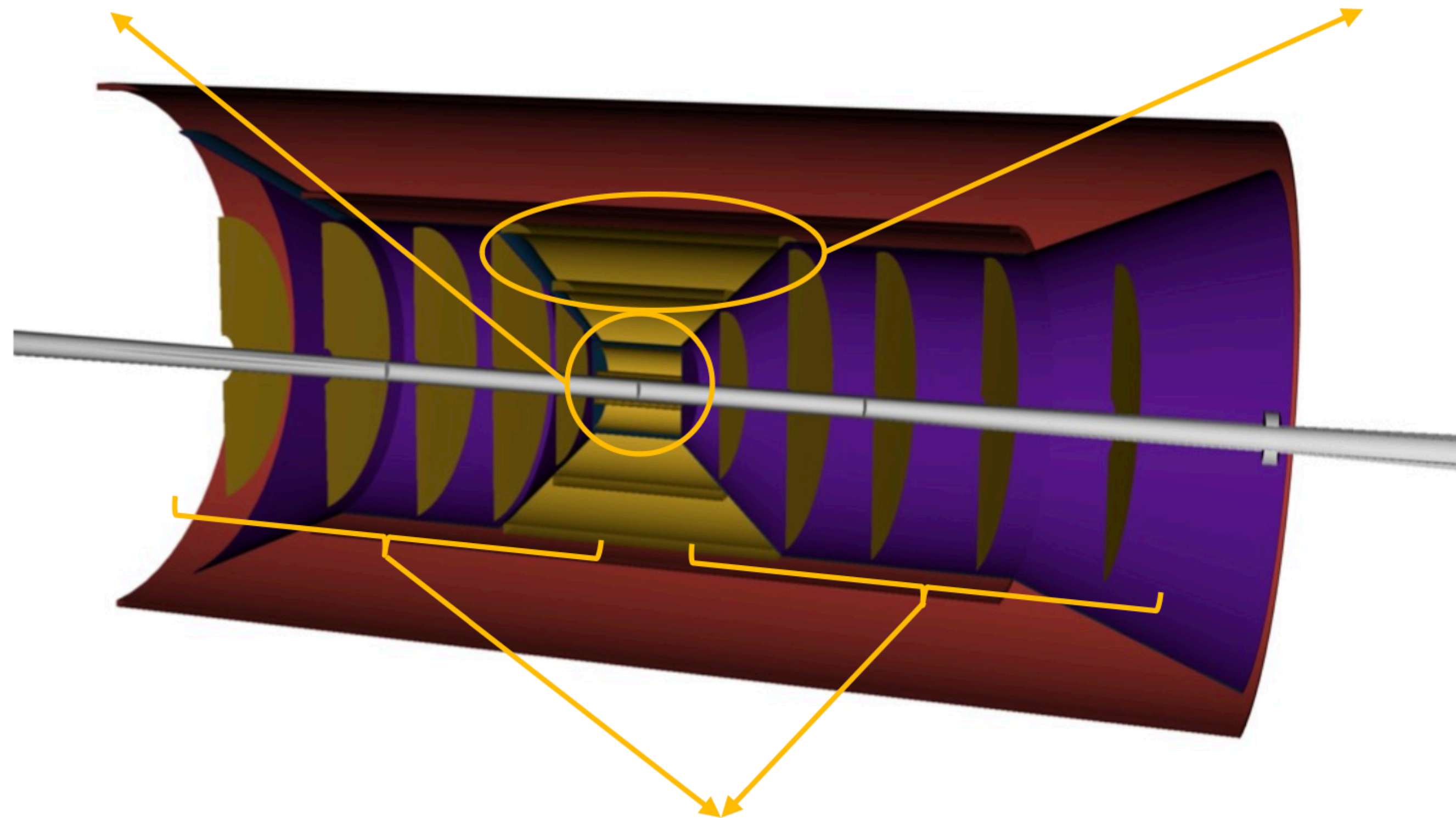
ePIC Silicon Vertex Tracker

Inner Barrel (IB)

- Two curved silicon vertex layers,
- One curved dual-purpose layer,

Outer Barrel (OB)

- One stave-based sagitta layer,
- One stave-based outer layer,



Total active area ~ 8.5 m²
Radius ~ 0.45 m
Length ~ 2.5 m

Well integrated, large acceptance, high granularity, and low-mass subsystem,

New generation MAPS technology to satisfy the requirements — based off the ALICE-ITS3 development.

Electron/Hadron Endcaps (EE, HE)

- Five disks on either side of the Interaction Region,

Note that the ePIC SVT concept and geometrical configuration is largely unchanged; there are, however, changes e.g. because of sensor development. The surrounding ePIC tracking configuration has evolved; MPGDs are the topic of eRD108 and are outside the scope of eRD104, eRD111, and eRD113.

ePIC Silicon Vertex Tracker R&D

Project R&D for the ePIC SVT is organized in three areas:

- **eRD104** — services reduction
 - Investigates methods to significantly reduce the services load;
 - Powering system
 - Readout system
- **eRD111** — modules, mechanics, cooling, and integration
 - Development of a full tracking detector solution composed of next-generation 65 nm MAPS;
 - Forming modules from stitched sensors
 - Barrel and Disks
 - Cooling
 - Mechanics and integration
- **eRD113** — sensor development and characterization (started in FY23)
 - Development of the EIC MAPS;
 - Sensor design
 - Sensor Characterization

In addition, the SVT relies on Project Engineering and Design support and in-kind contributions.

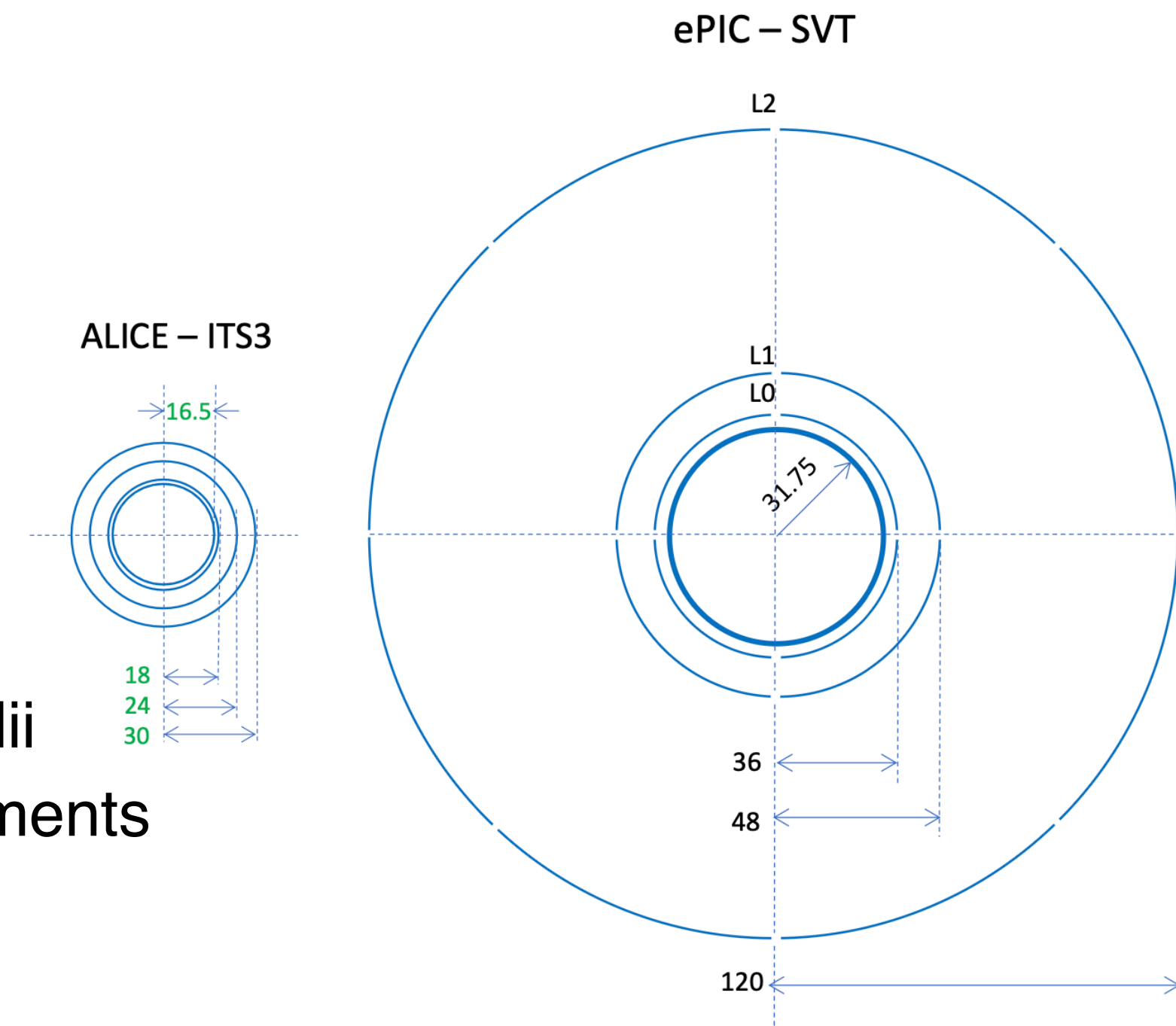
The SVT does *not* rely on the Generic EIC-related R&D Program, c.f. https://www.jlab.org/research/eic_rd_prgm. However, several members of the ePIC SVT DSC are part of submitted proposals to that program.

ePIC SVT

At a high level, the ePIC SVT thus requires us to develop:

1. ITS3-like Inner-Barrel layers

- Re-use the ITS3 sensor as is
- Adapt the ITS3 detector concept to the EIC:
 - Mechanics of bent layers — sensor and support — for the larger EIC radii
 - Services and cooling design and routing for the EIC acceptance requirements
 - Considerations related to in-situ beam-pipe bake-out at the EIC



2. EIC variant for the staves in the Outer Barrel and the Endcap Disks

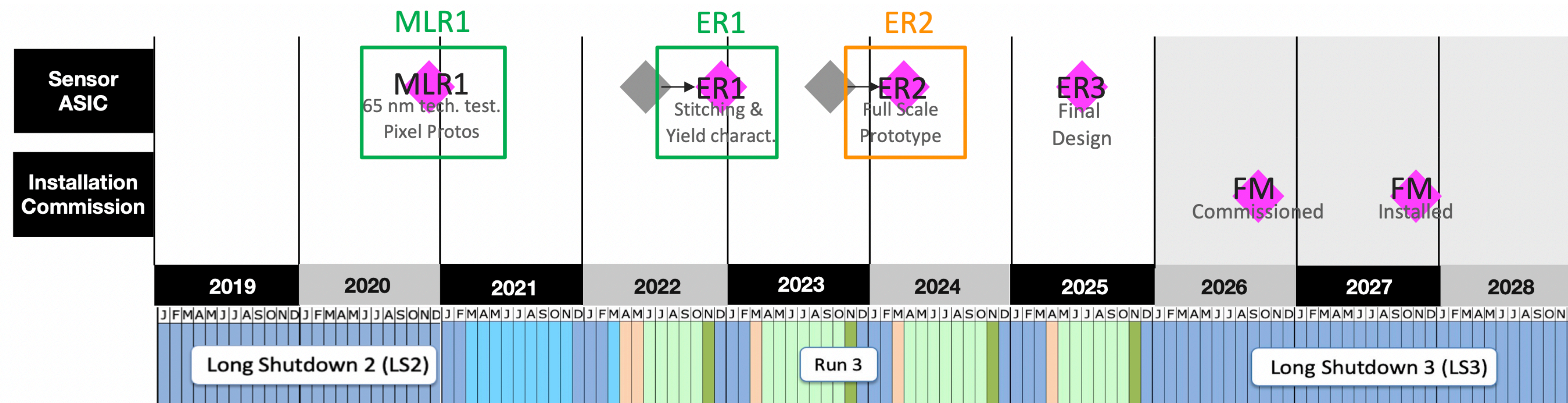
- EIC Large Area Sensor (LAS), i.e. ITS3 sensor size optimized for large-area coverage, yield, and cost
 - EIC LAS will be stitched, but not to wafer scale; functionality and interfaces stay largely unchanged
 - Size(s) of the EIC LAS to be defined by requirements for full coverage and yields, cost
- More conventional carbon composite mechanical support structures with integrated cooling

ePIC SVT Sensor — ITS3

Management of the relationship with ITS3 is critical to eRD113 and the success of the ePIC SVT.

EIC project / ePIC and CERN / ALICE met in April 2023 at CERN — **agreement to share sensor.**

ITS3 development timeline:

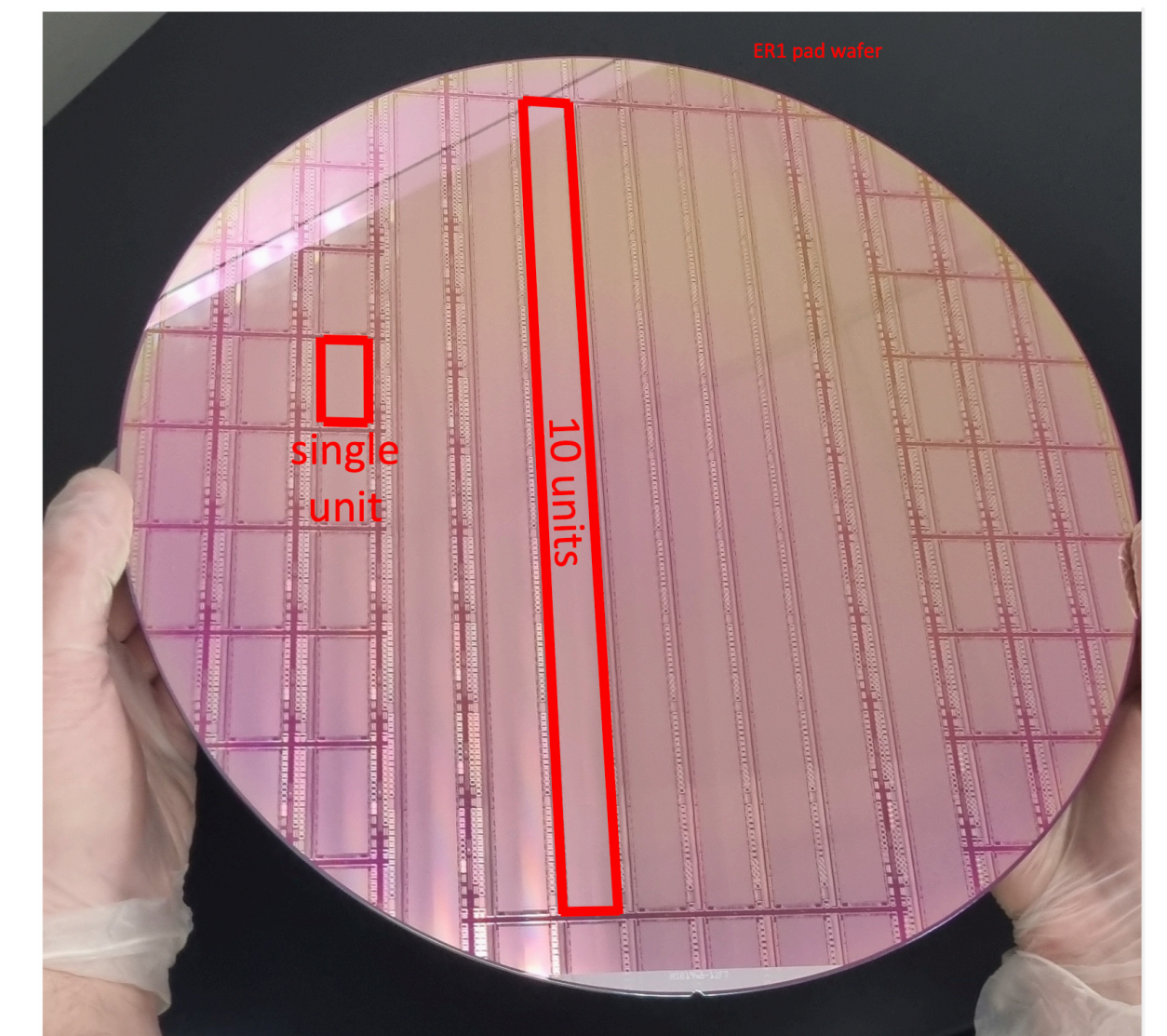
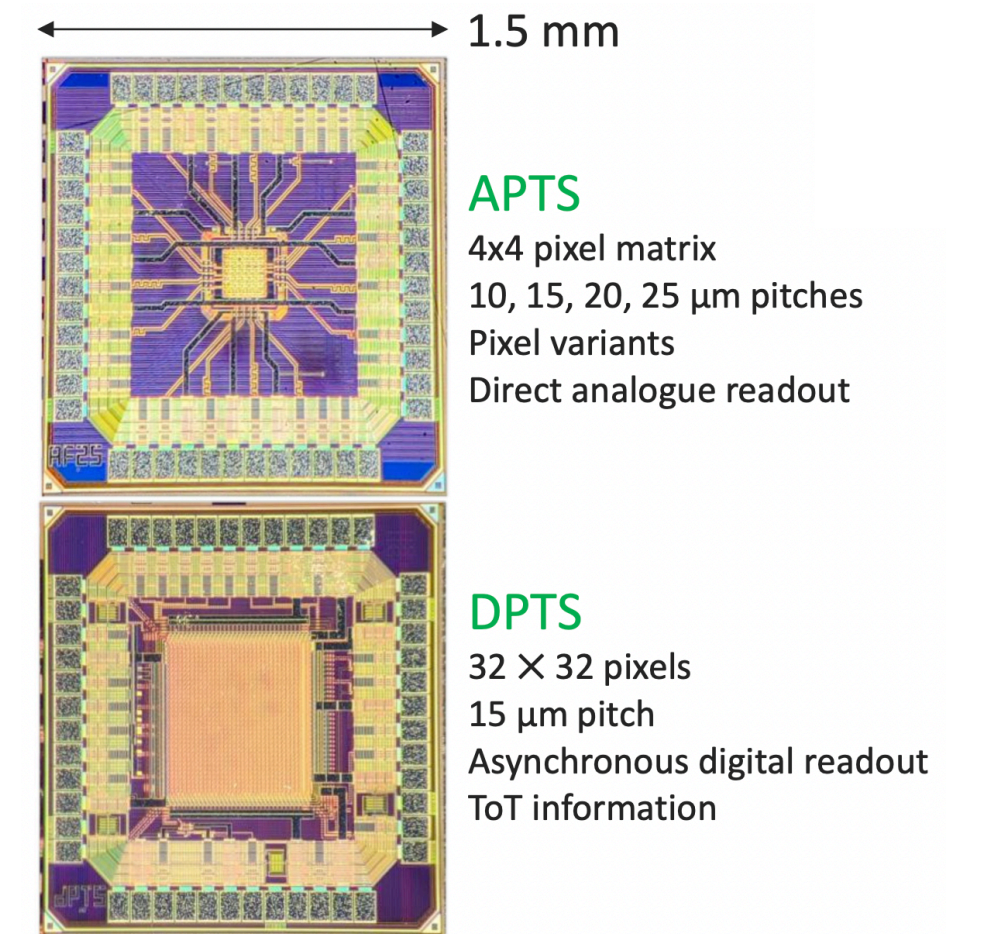


Source: Gianluca Aglieri Rinella, Walter Snoeys — <https://indico.cern.ch/event/1280150/>

ePIC SVT sensor timeline: the EIC LAS will be based off the ER2 and ER3 designs.

Intermezzo — MLR1, ER1, ER2, ...

- MLR1 — Q4 2020
 - Technology exploration — first submission in 65 nm CMOS imaging
 - Prototype circuit blocks for future sensors
 - Includes Analog and Digital Pixel Test Structures (APTS, DPTS)
- ER1 — Q4 2022
 - MOSS and MOST sensors; exploratory designs to learn and prove stitching, methodology, constraints, yield
 - First, single unit MOSS was powered and responded correctly to slow control commands
- ER2 — Q1 2024
 - Sensor design aims to satisfy ITS3 requirements
 - *Not* a direct evolution of MOSS / MOST; substantial redesign of existing circuits, new features
- ER3 — Q2 2025
 - Final ITS3 design / production



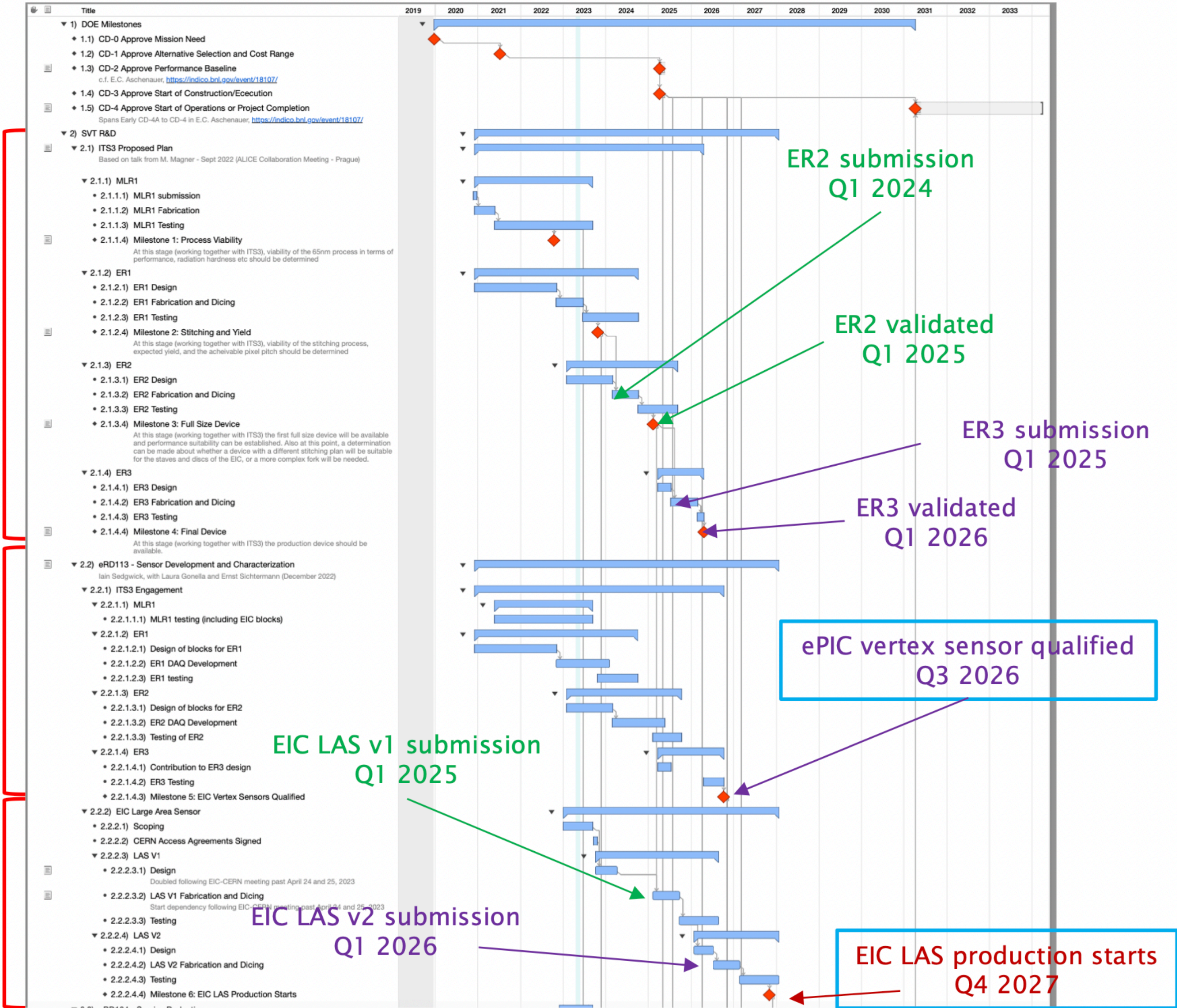
Source: Gianluca Aglieri Rinella, Walter Snoeys — <https://indico.cern.ch/event/1280150/>

ePIC SVT Sensor — development schedule

ITS3 schedule

EIC contributions to ITS3 submissions

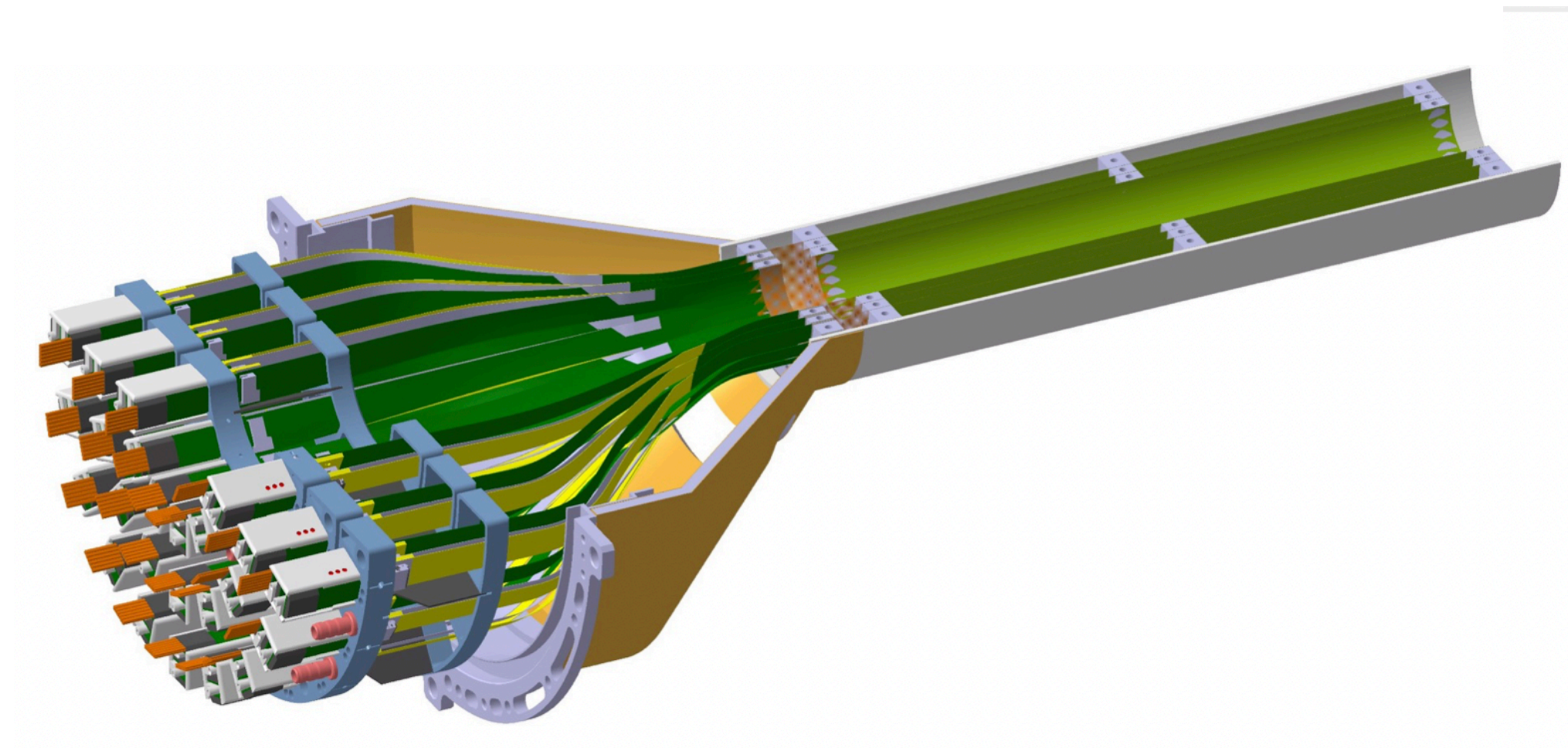
EIC LAS design



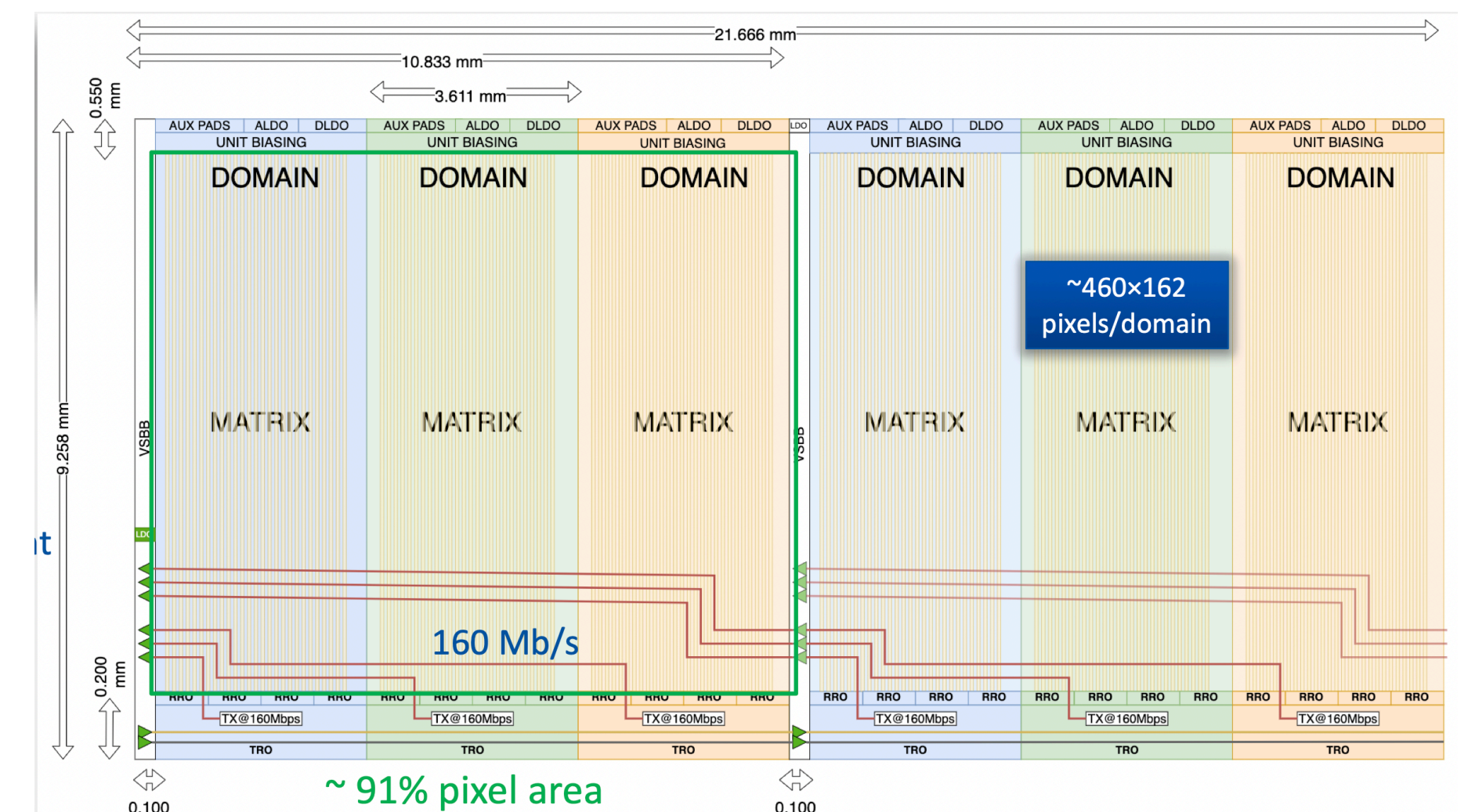
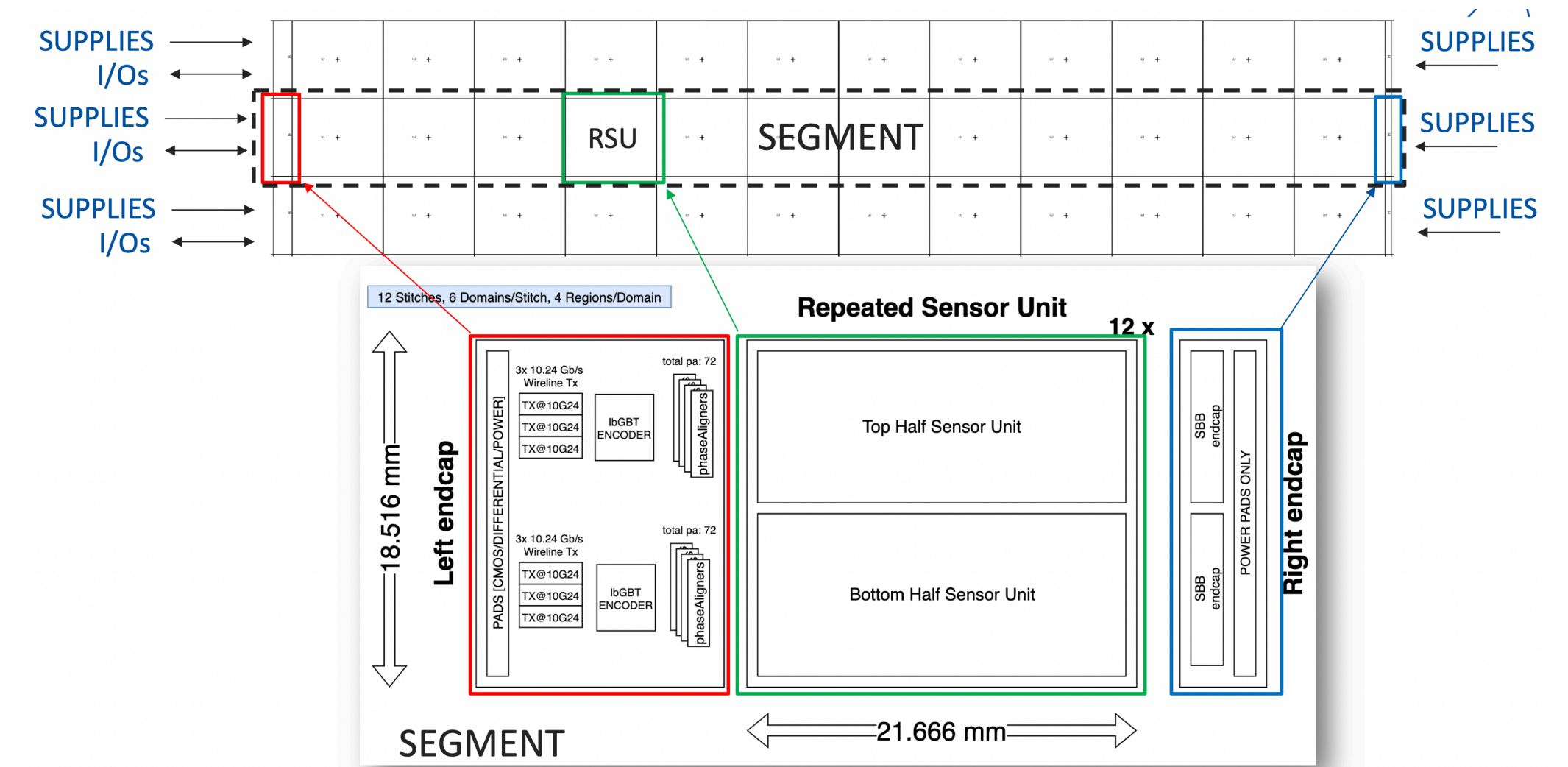
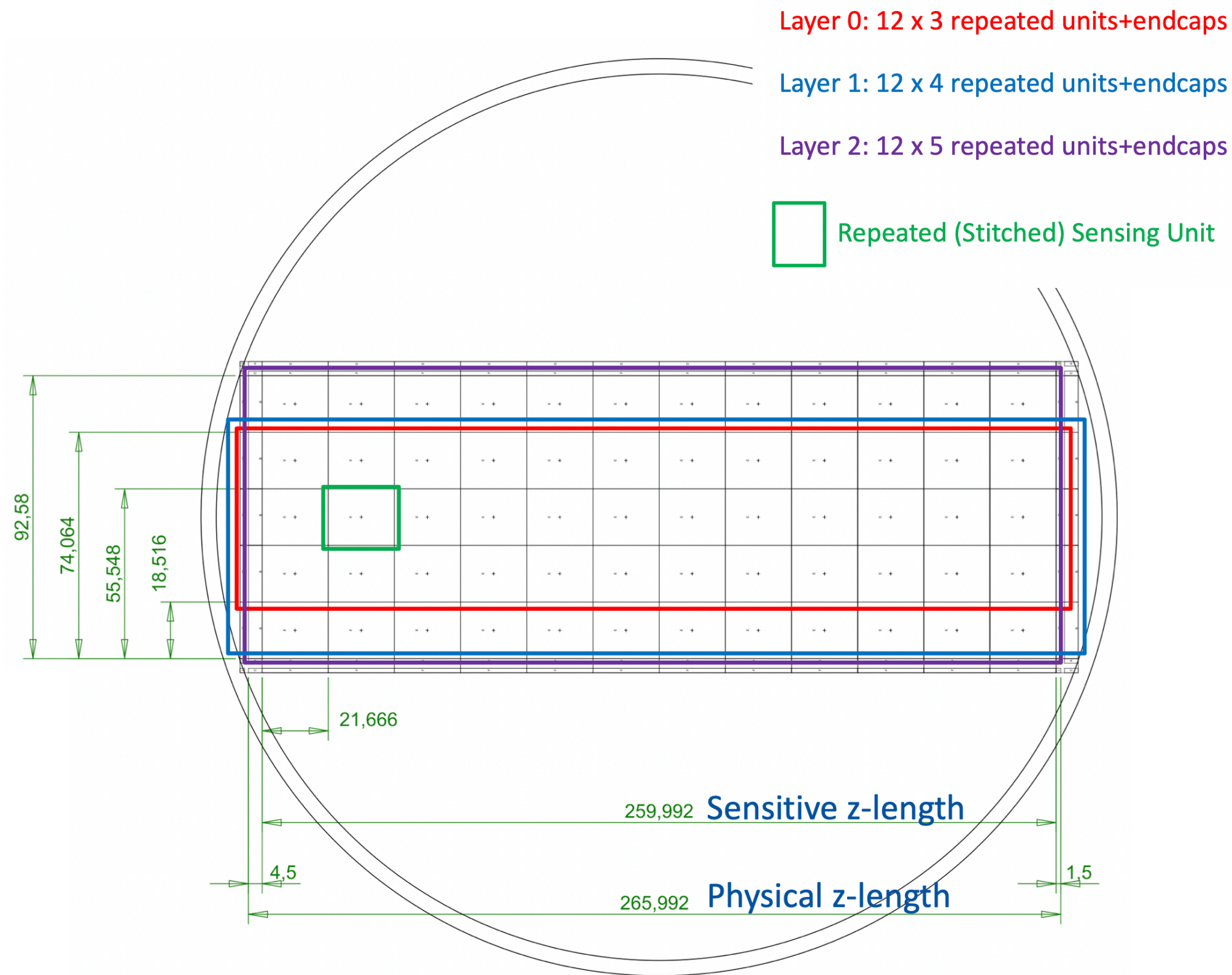
ITS3 implications — ePIC SVT Sensor

ITS3 in a nutshell:

- Made with 6 curved wafer-scale single-die Monolithic Active Pixel Sensors
- No flex circuits in the active area; power and data transfer on the chip to/from the short edge
- Cooled by air flow; dissipate less than 20 mW/cm² (in the sensitive area)
- LoI CERN-LHCC-2019-018 / LHCC-I-034



ITS3 ER2 implications — ePIC SVT Sensor



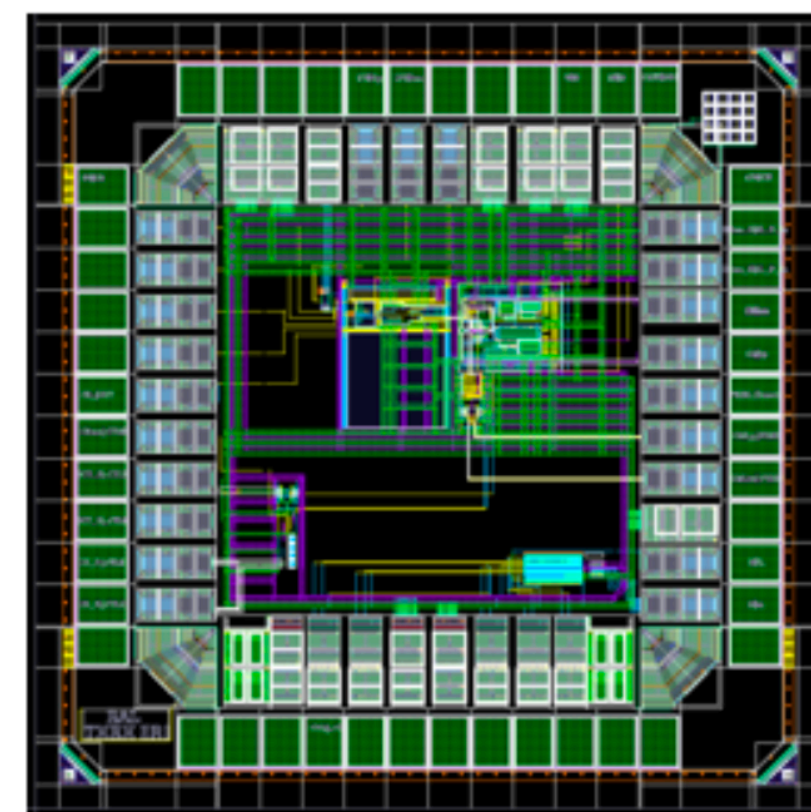
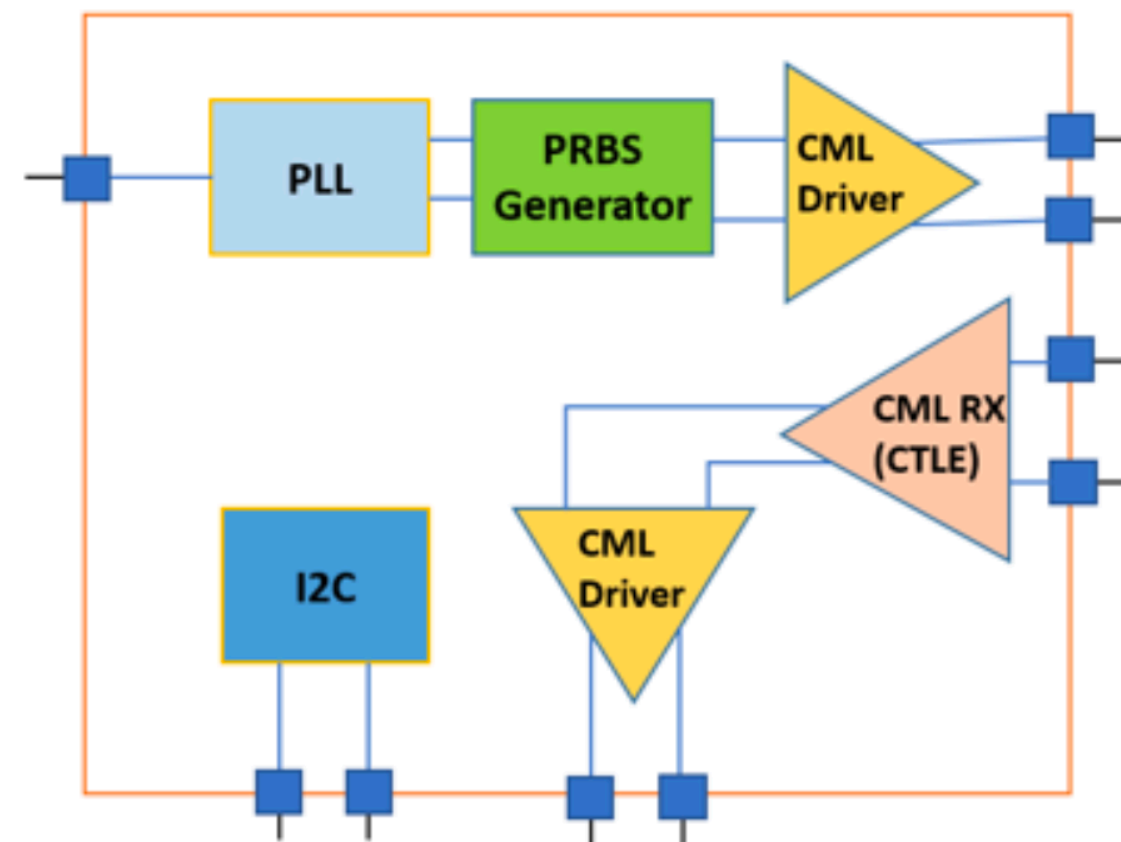
Rapidly evolving ER2 design,
 Foundry rules will limit the EIC LAS to 2 or 3 variants,
 Likely, limit EIC LAS variant(s) to six RSUs or fewer,
 Serial powering, data multiplexing.

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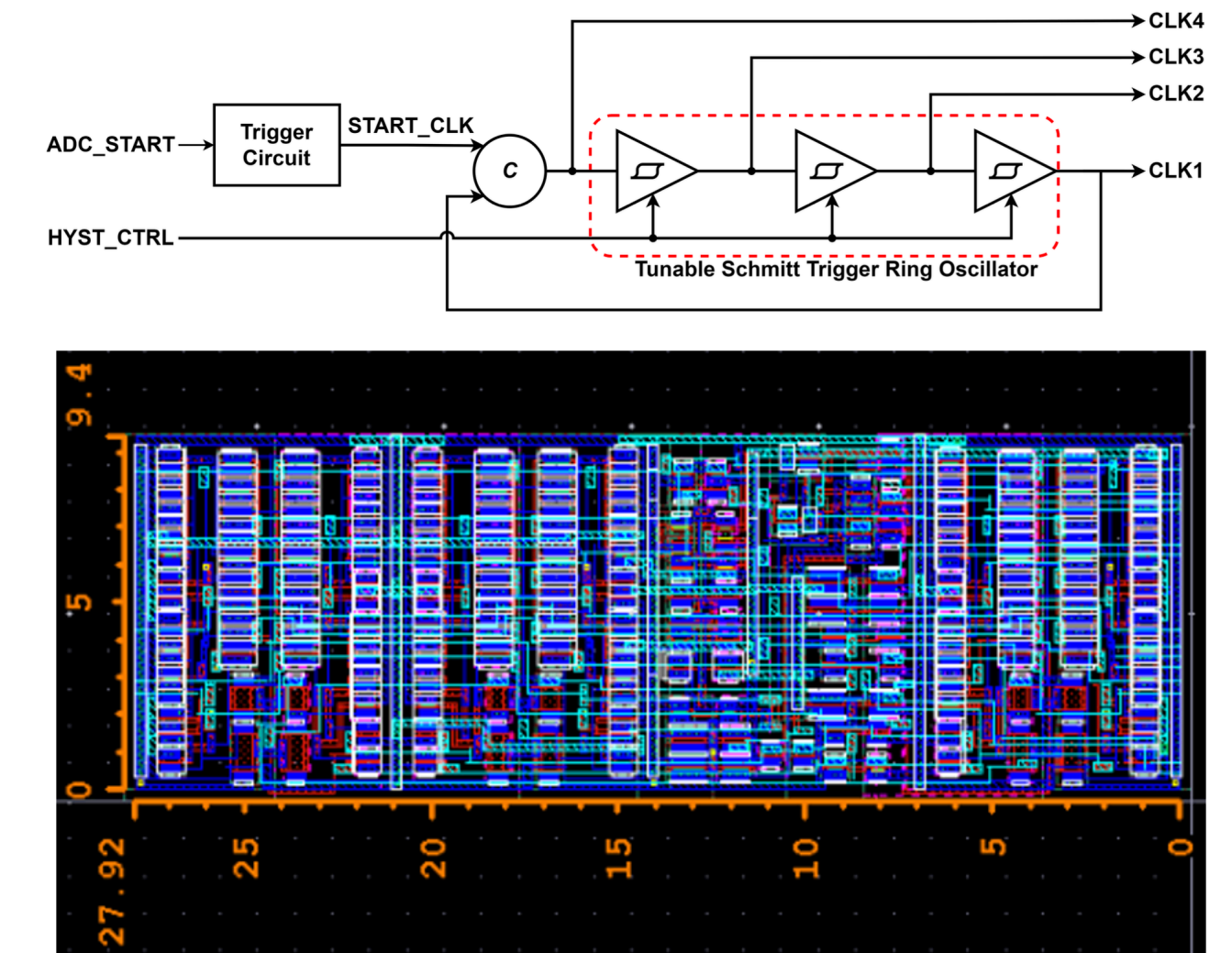
ePIC SVT — Sensor Design

- RAL, BNL, and LBNL are involved in the design of the ePIC SVT sensor,
- RAL has contributed structures to the past ITS3 submissions — made possible with resources from the former eRD18/25 project and the UKRI-STFC Infrastructure fund,
 - MLR1 — circuit blocks for high-speed off-sensor data transmission up to 2 Gbps
 - ER1 (FY23) — continuation of high-speed off-sensor data transmission (PLL, CML receiver); design of low speed on-sensor data transmission (I2C); redesign of standard cells for DFM



ePIC SVT — Sensor Design

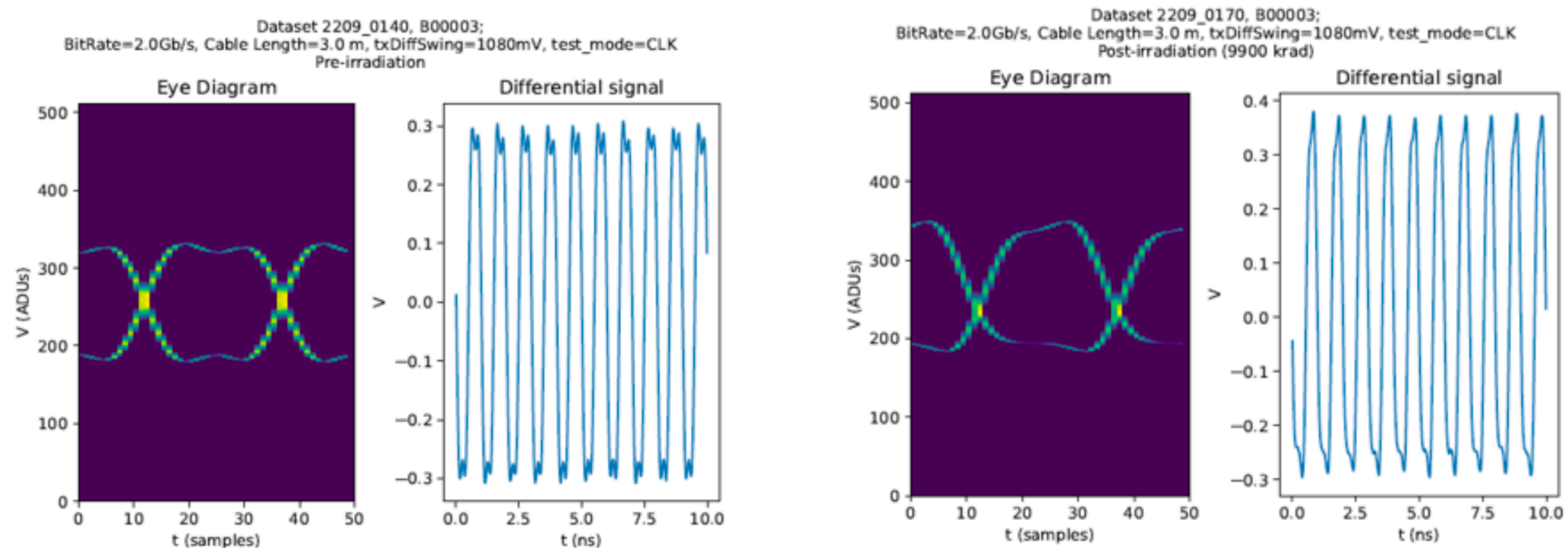
- RAL, BNL, and LBNL are involved in the design of the ePIC SVT sensor,
- ePIC contributions to ER2 design under discussion with ITS3 designers
 - DFM / low power standard cells — RAL, BNL, LBNL
 - Monitoring Analog-to-Digital Converter — BNL
 - SRAM design — LBNL
 - Voltage regulation — RAL, BNL
- Design ongoing or starting on ePIC specific developments for EIC LAS
 - Shunt LDO regulator development for current-based serial powering scheme underway at RAL
 - Generation of sensor bias voltage from sensor low voltage — BNL
 - Integrated data multiplexing — BNL
- Early to late Q2 timeline of eRD113 project funding and PED has affected start on FY23 goals at BNL and LBNL; goals will carry over into FY24.



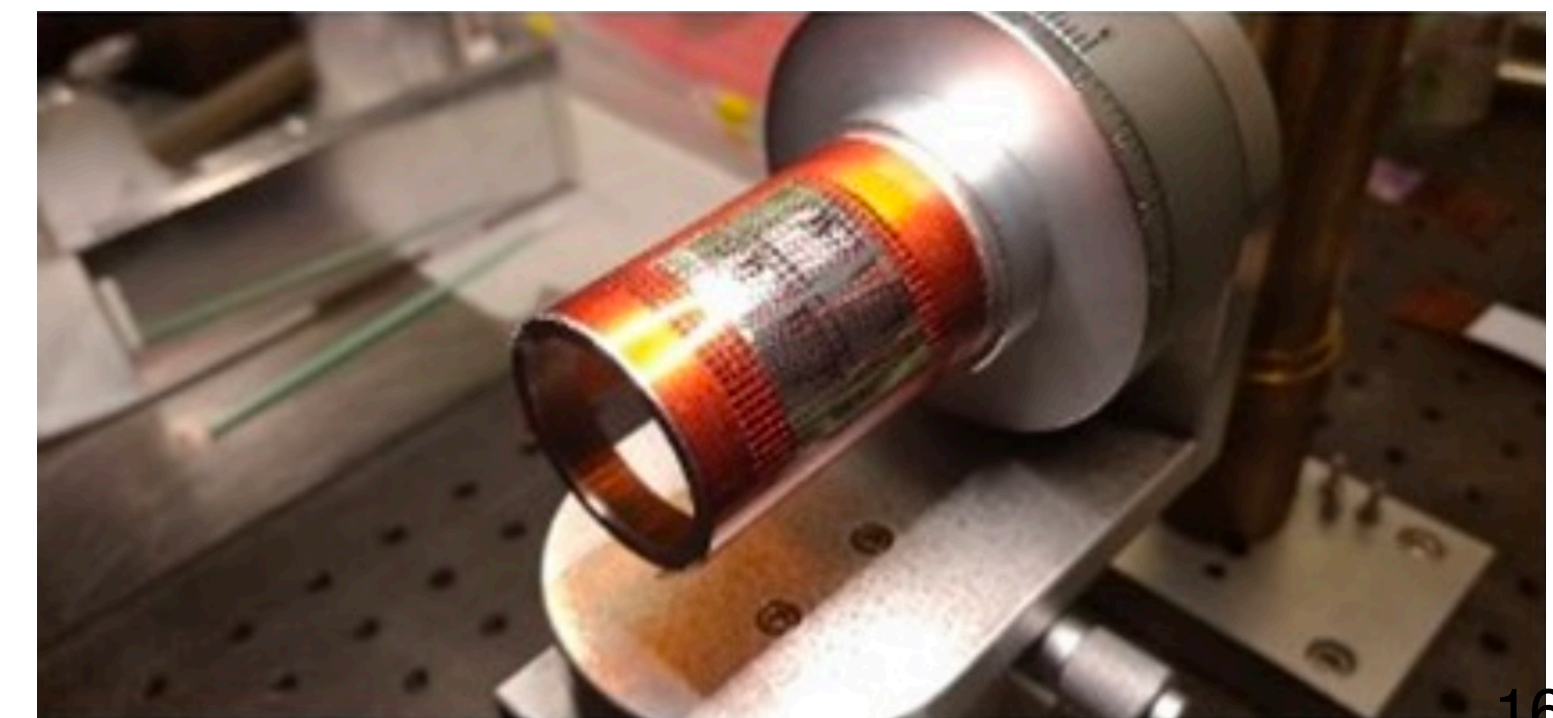
Monitoring ADC: on-demand clock component

ePIC SVT — Sensor Characterization

- INFN groups, UK groups, ORNL and LBNL are involved in characterization of ITS3 submissions,
- UK groups have characterized MLR1 RAL blocks; involved in testing of APTS and DPTS

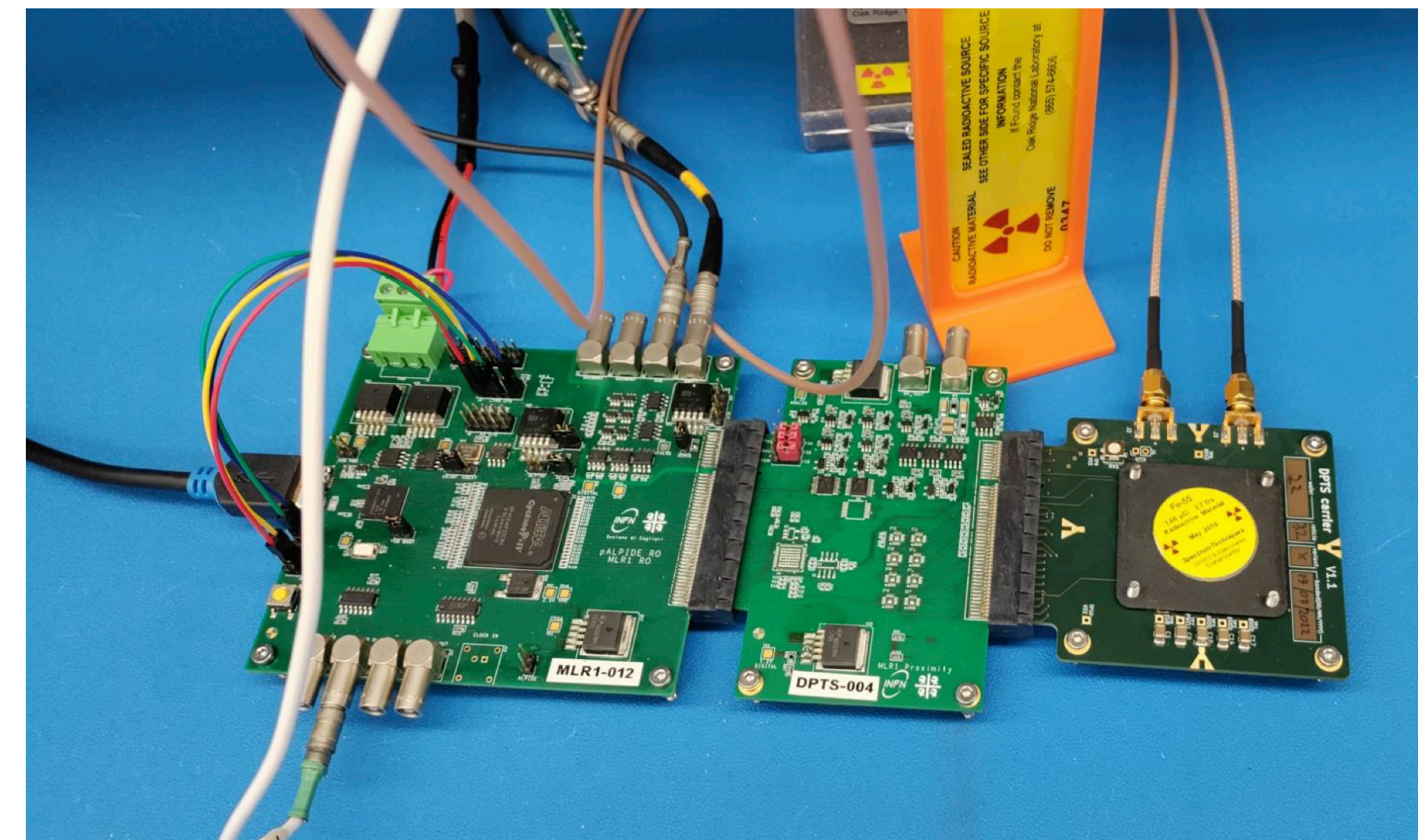
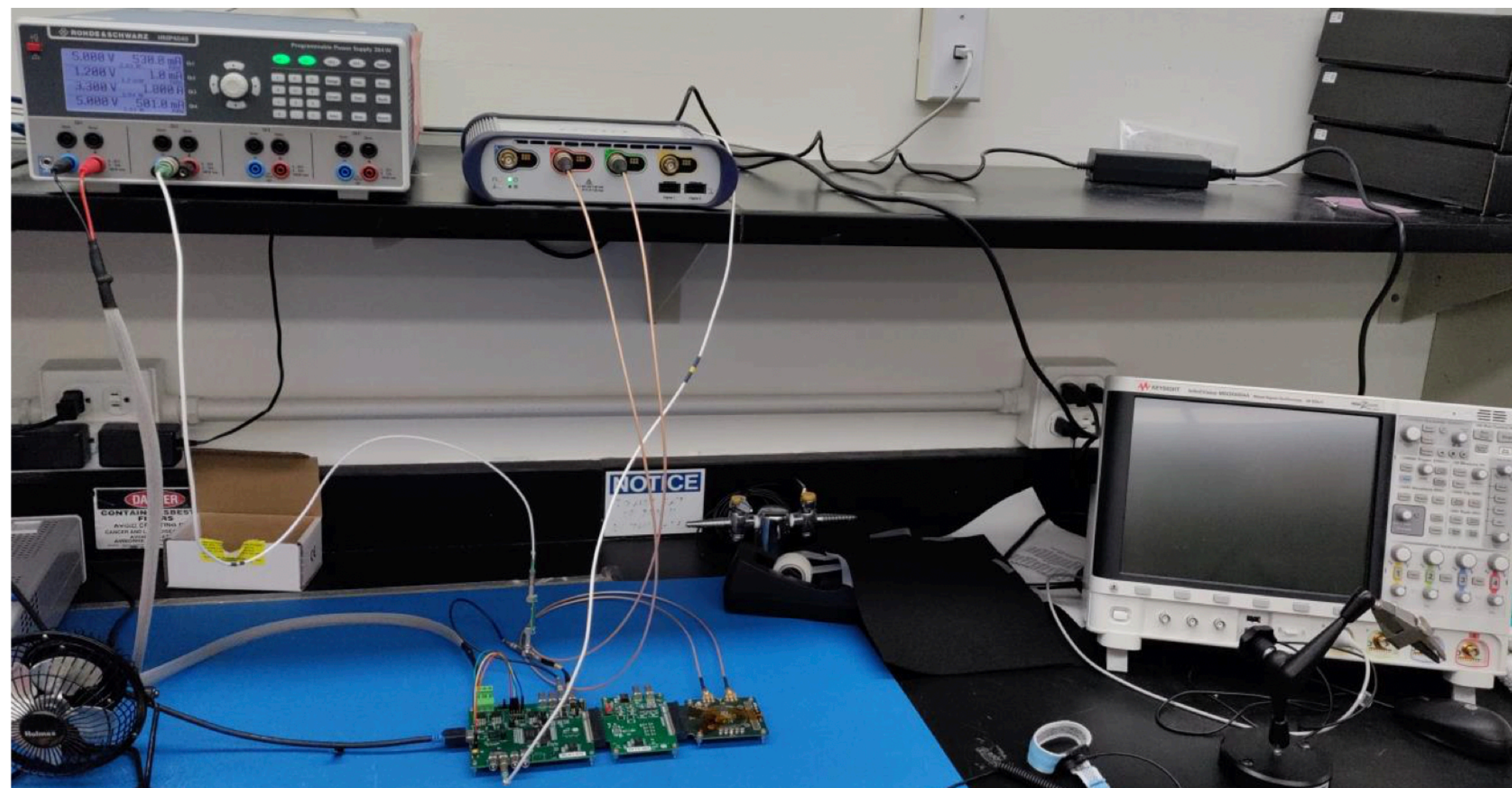


- INFN carrying out APTS and DPTS characterization, including curved geometry structures; trained ORNL and LBNL staff in DPTS characterization,



ePIC SVT — Sensor Characterization

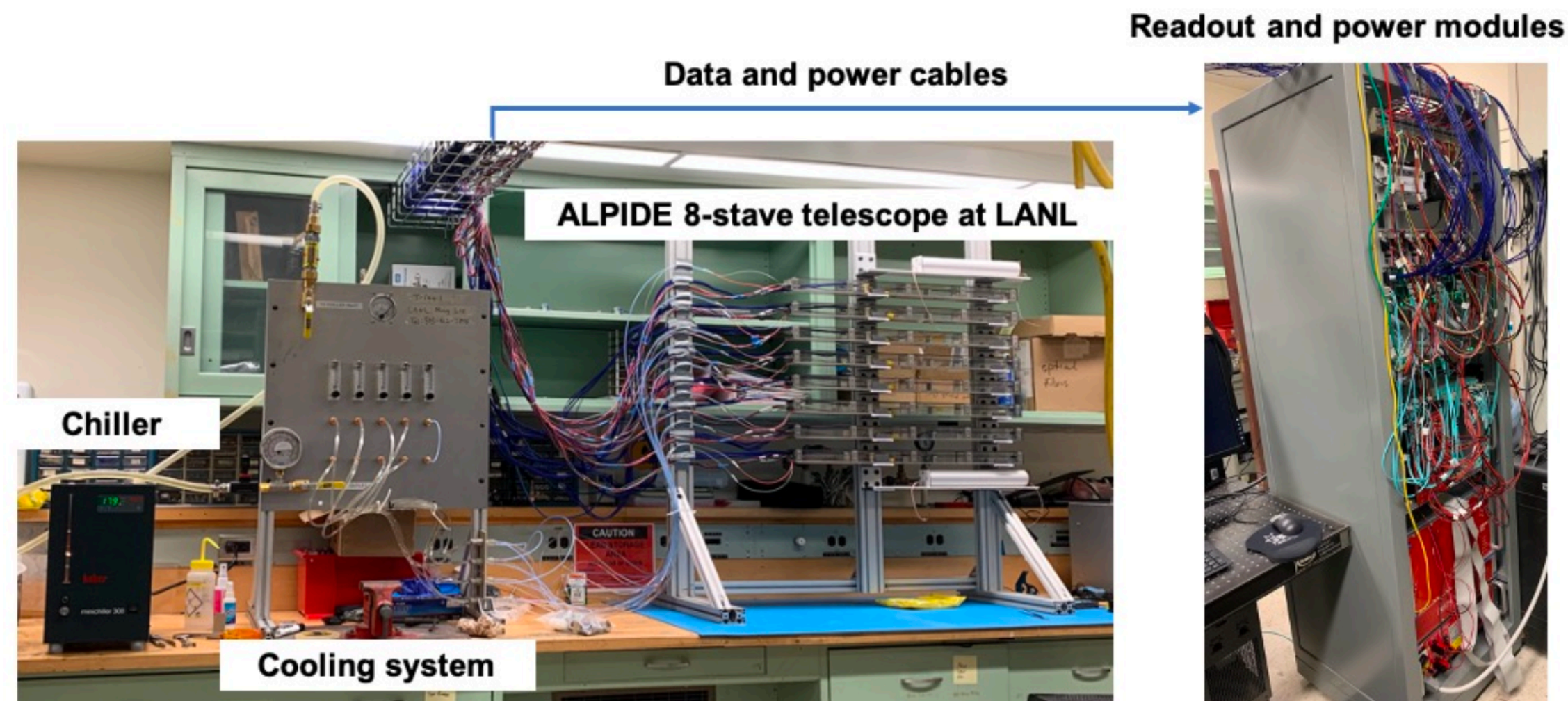
- INFN groups, UK groups, ORNL, LBNL, and MIT are involved in characterization of ITS3 submissions,
- ORNL established a DPTS test setup; ongoing effort towards energy calibration with Fe-55 source, CML buffer parameter scan, time-over-threshold studies, pixel-per-pixel variations



- LBNL established a DPTS test setup; multiple studies including ToT; produced and tested 20 DAQ boards to help overcome supply-chain shortages; participated in test-beam effort

ePIC SVT — Sensor Characterization

- MIT is setting up a PIXEL laboratory at CERN and establishing close collaboration with ITS3; participated in ER1 MOSS test beam and analyzing its data
- LANL has set up an 8-stave ALPIDE (ITS2) telescope for precision tracking with test beams and is making it available for new EIC sensor characterization with test beams in late 2023 and 2024,

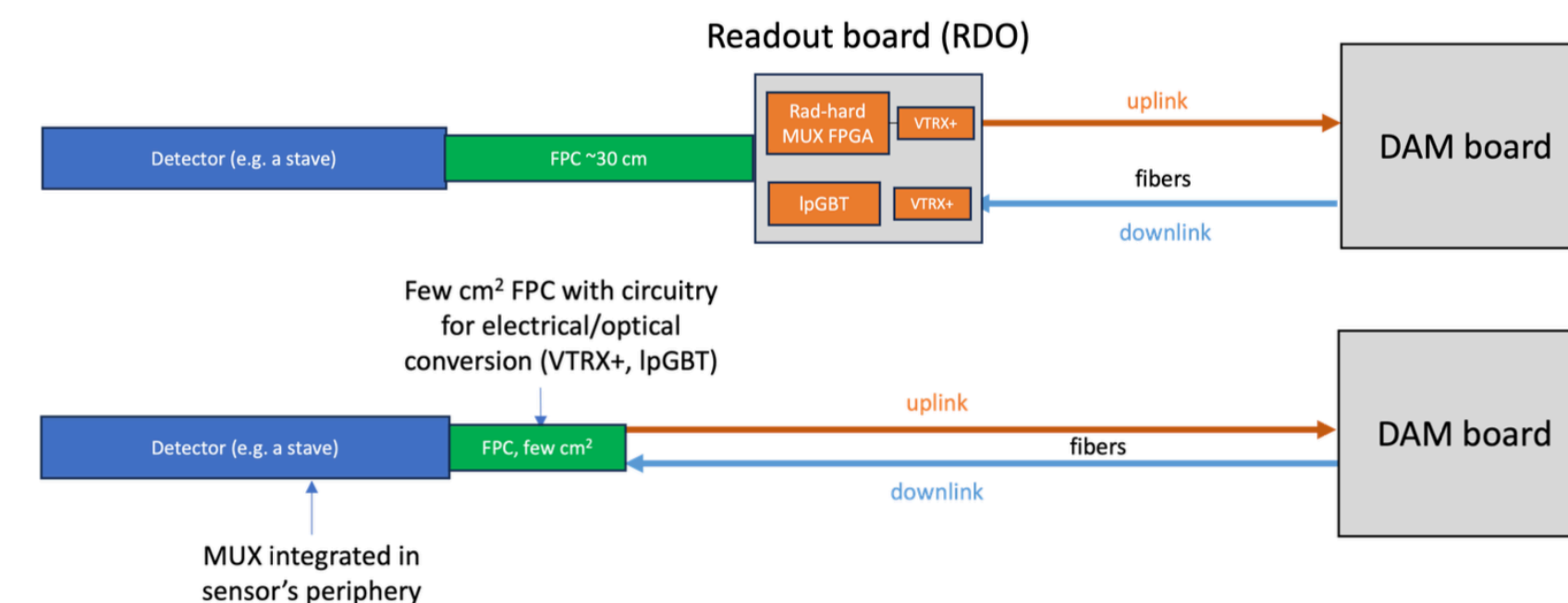


ePIC SVT — Services Reduction

- UK groups and ORNL are involved in Services Reduction
- In a traditional approach, the largest components of services would be the powering system cabling followed by the readout cabling,
- FY23 aims were for a conceptual design of powering and readout schemes for the ePIC SVT and an initial assessment of components to inform selection,
- Powering:
 - Constant-current powering scheme is chosen for the Outer Barrel and Endcap Disks
 - EIC LAS sensors are powered in series,
 - Regulators convert the input current into the (analog and digital) voltage needed by the EIC LAS
 - Regulator architecture: Shunt-LDO
 - Regulator concept developed for the serial powering scheme of the ATLAS and CMS pixel systems at the HL-LHC,
 - Shunt-LDO design is in progress — aim for prototype submissions in early 2024,

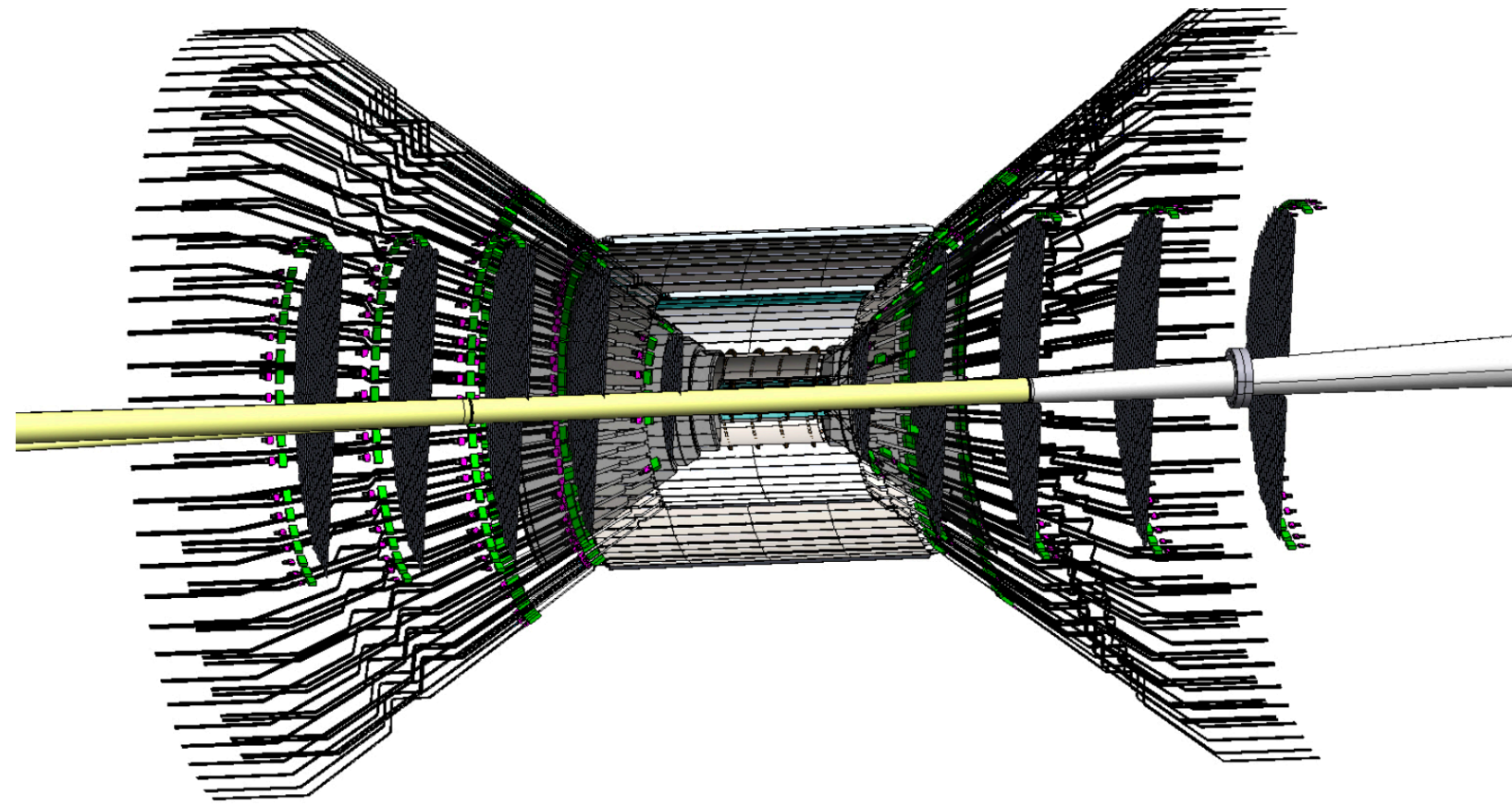
ePIC SVT — Services Reduction

- UK groups and ORNL are involved in Services Reduction
- Readout:
 - Develop a multiplexing strategy for the output links of the EIC LAS and thereby reduce the multiple 10 Gbps links in the ITS3 sensor that will not be required at the EIC in view of the much lower data rates at ePIC,
 - Two options under consideration:
 - External multiplexing using commercial FPGAs
 - Multiplexing integrated on the sensor
- Work with the project to inform service estimates in both areas,
- Q2 timeline of eRD104 project funding has delayed planned ordering for various evaluation boards so that some of the FY23 goals for readout will carry over into FY24.

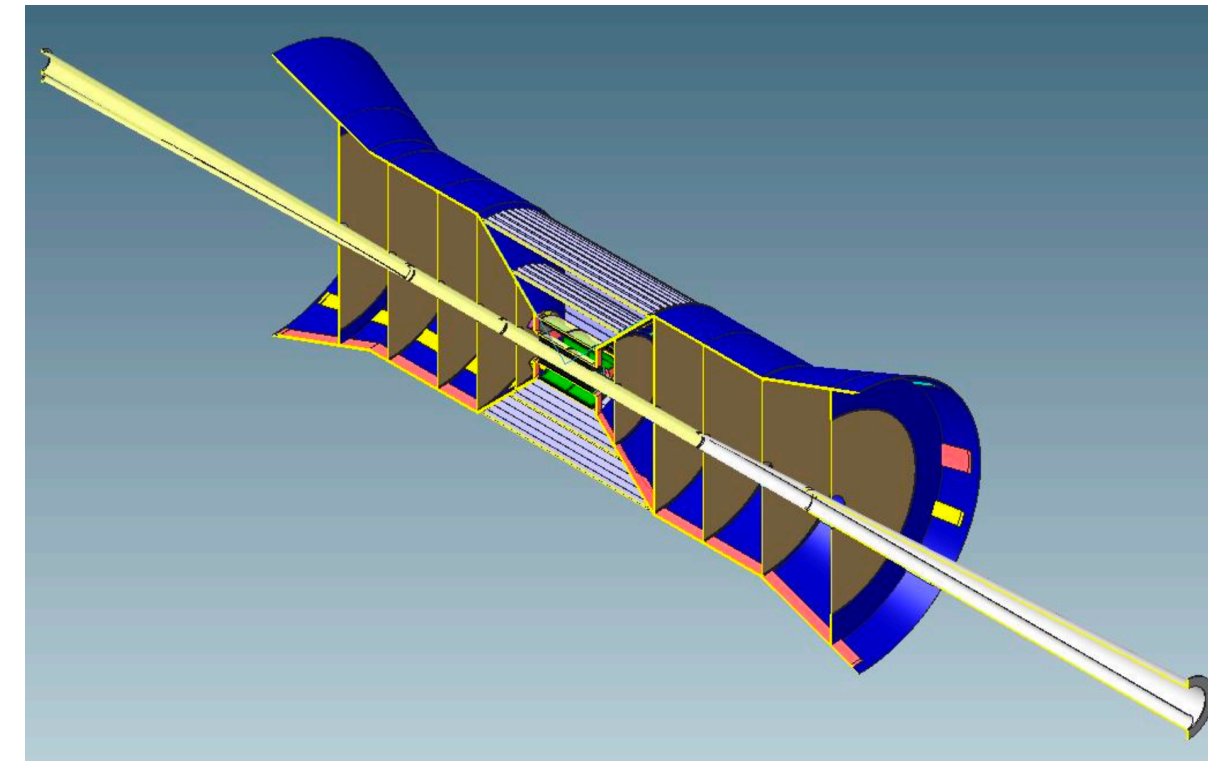


ePIC SVT — Mechanics

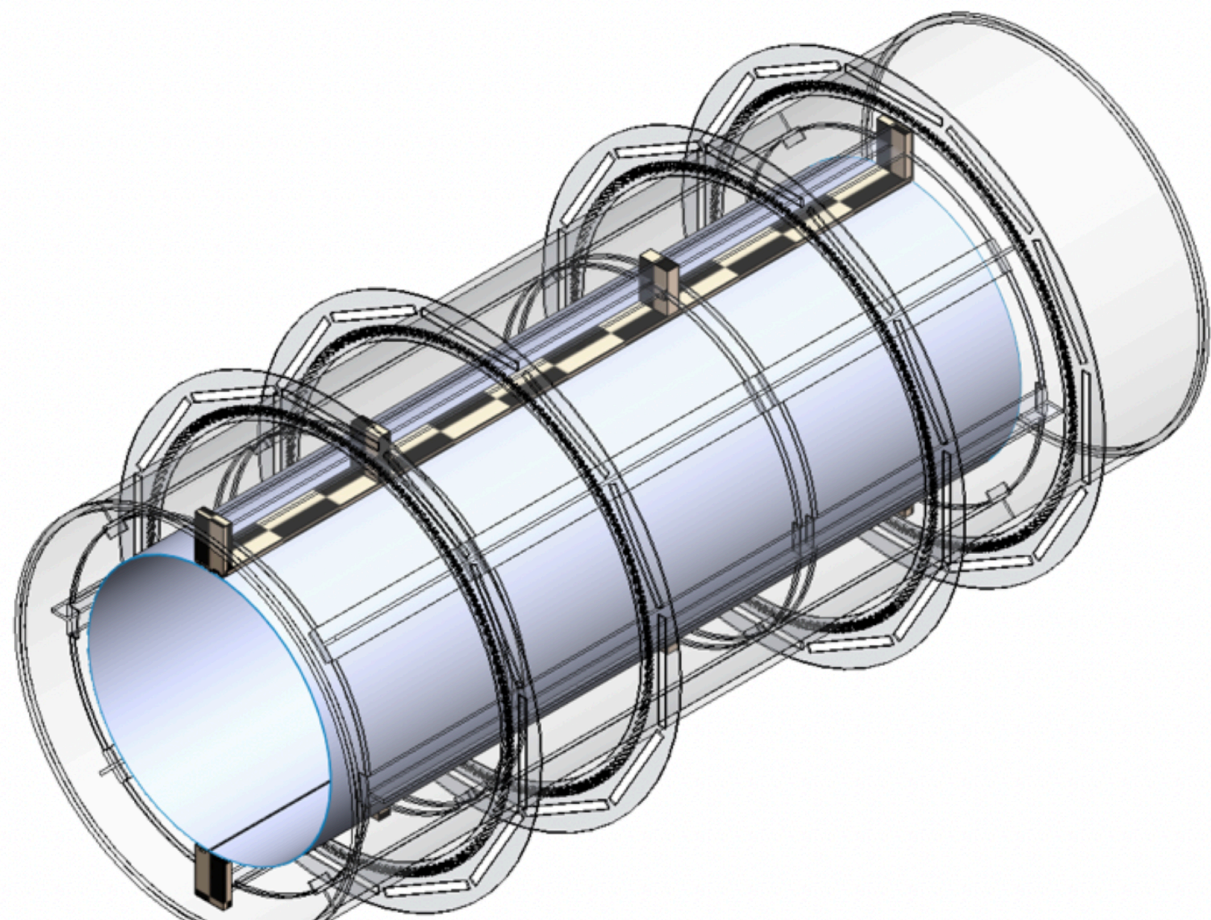
- UK groups, LANL, LBNL, and Purdue are involved in CAD modeling efforts — MIT starting up



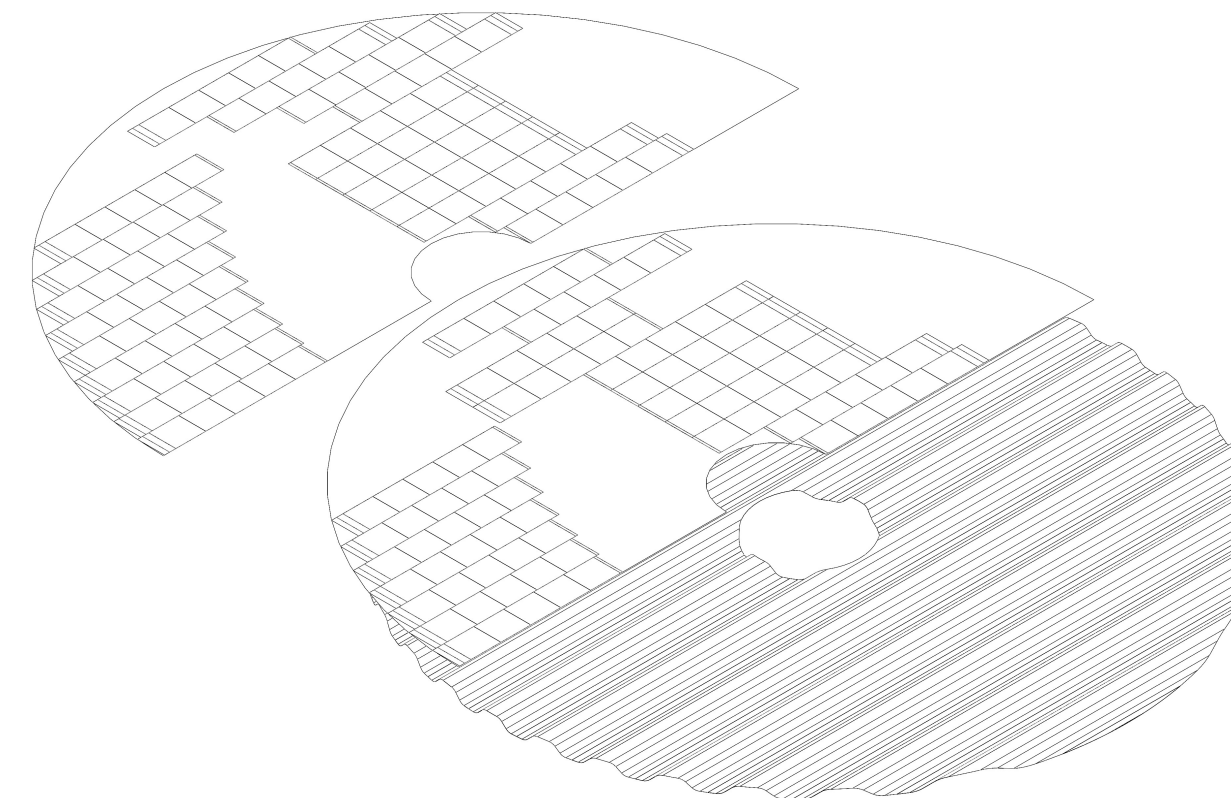
ePIC SVT overall layout - LANL



Emphasis on Outer Barrel layers - UK groups



Sketch for ePIC Global support - Purdue



Disk concept with tiled EIC LAS — LBNL

ePIC SVT — Mechanics

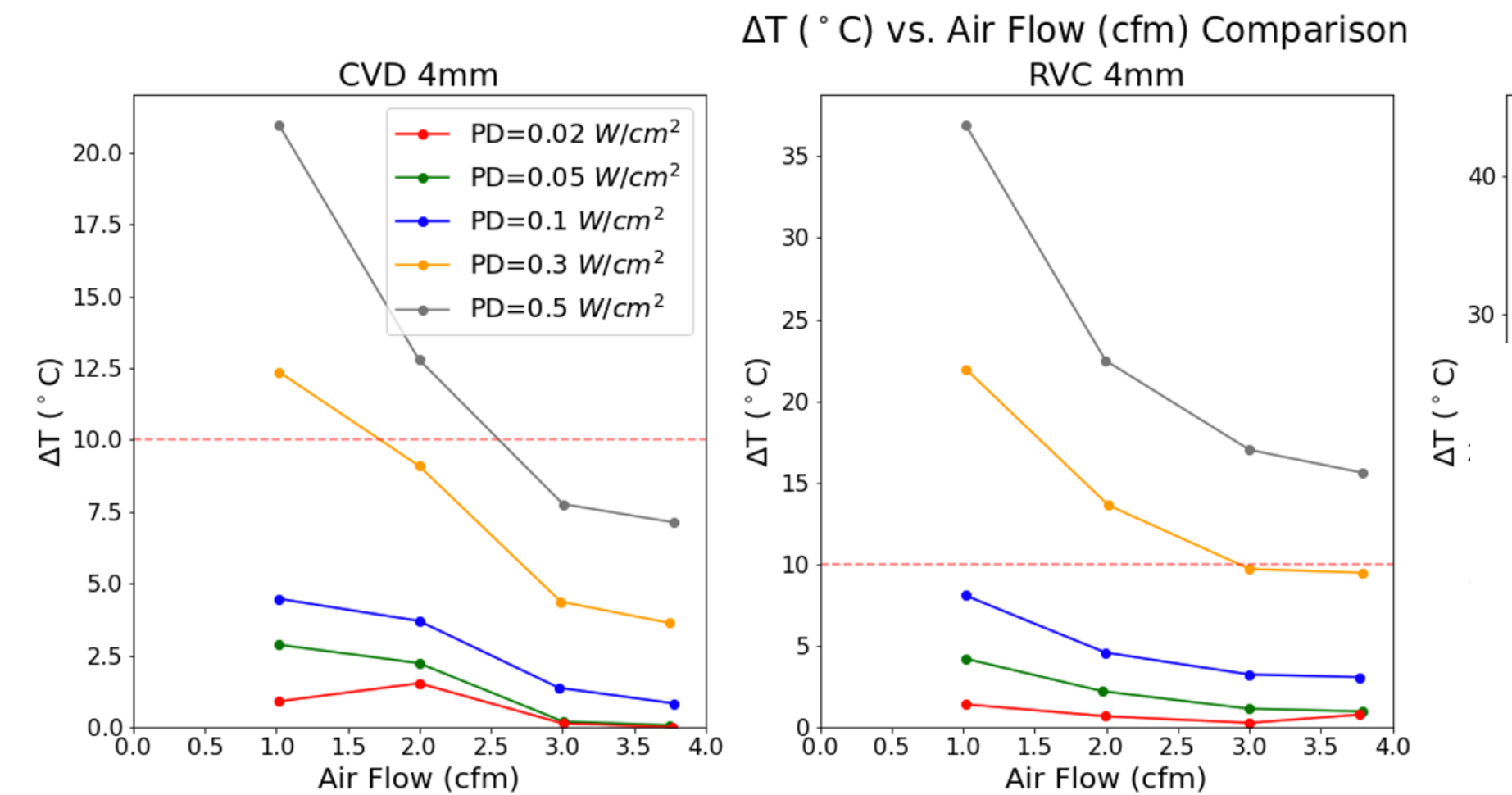
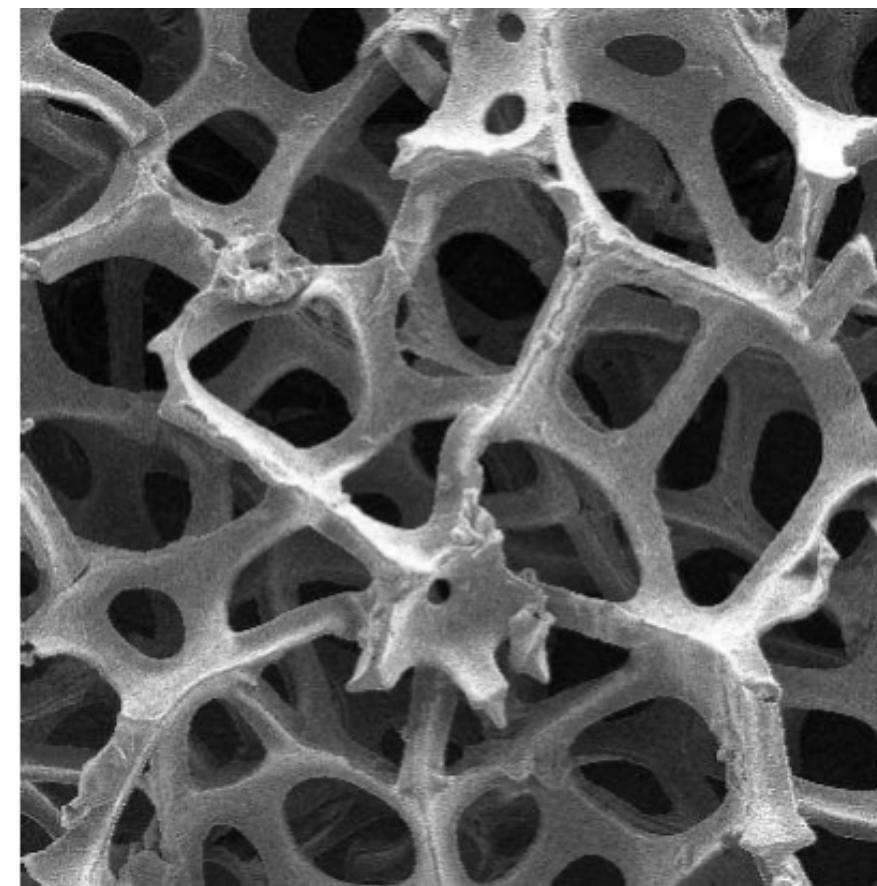
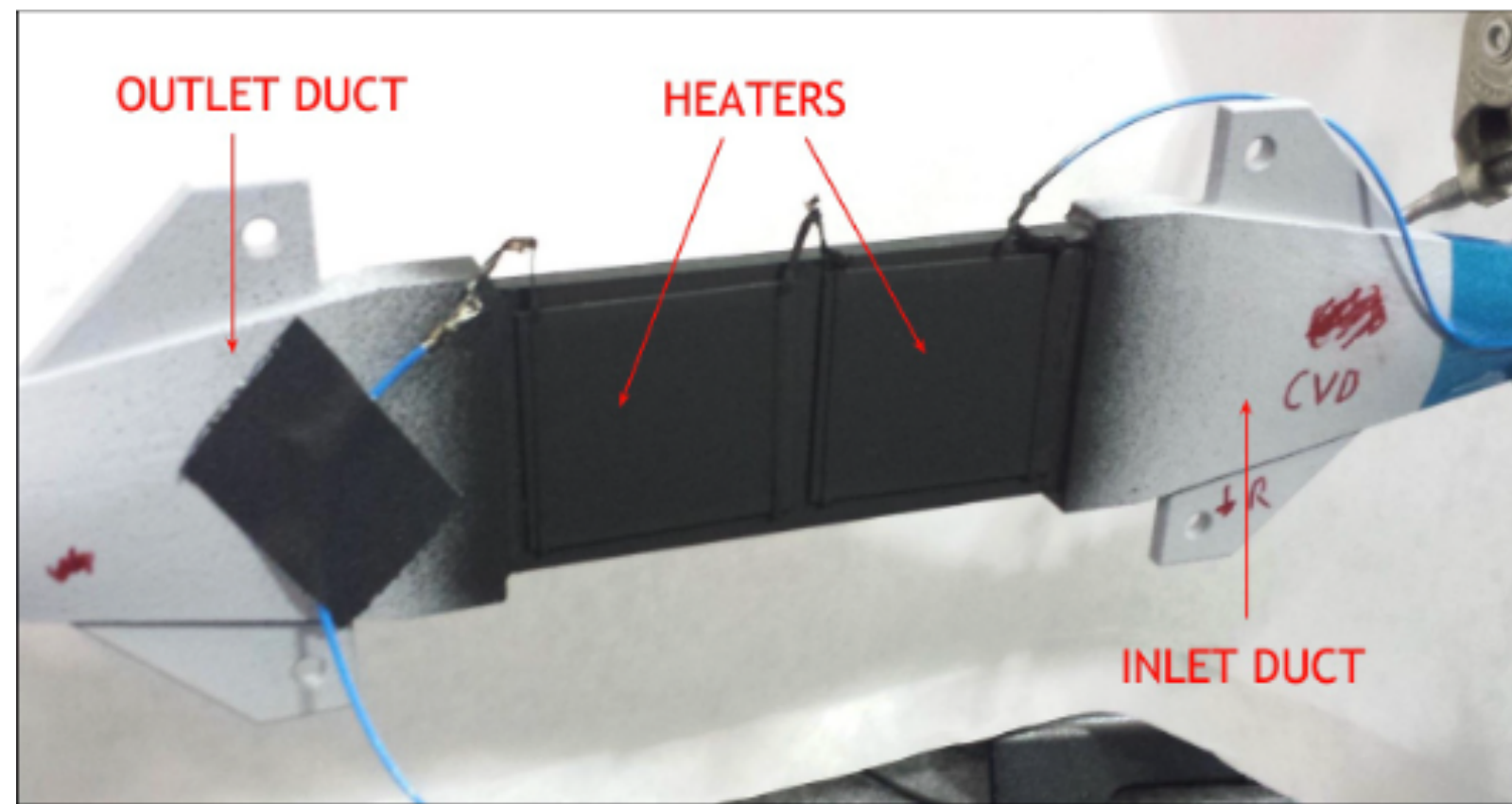
- INFN developed tooling and procedures for handling and bending thin wafer-scale silicon sensors,
- Successfully assembled two curved prototypes, based on blank silicon (no electronics) with the dimensions of the super-ALPIDE (ITS2 based) prototype layer



- INFN Pavia will be joining the effort and make their climate chamber available for stability tests.

ePIC SVT — Cooling

- LBNL is performing studies to find out if internal air cooling is a viable option for the ePIC SVT
- Current estimates are that the sensor main periphery will dissipate 1—2 W/cm² and the pixel matrix ~10 mW/cm²



- ePIC SVT specific structures and heating elements in progress



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ePIC SVT R&D — eRD104

- Contact person: Laura Gonella (University of Birmingham)
- UK groups propose continued collaboration on **services reduction for powering**:
 - Engineering Review of Serial Powering schemes
 - Electrical Testing of shunt-LDO regulators, mock-up SP powering schemes, shunt-LDO performance evaluation
 - Radiation testing (X-rays, electrons, hadrons) of regulators
 - Aluminum flex circuits
- Contributions are predominantly in-kind on a best effort basis; PED request for effort not (yet) supported by UK grant
- ORNL focuses on **readout services reduction** and proposes:
 - Characterization of the radiation tolerant FPGA utilizing the Microchip PolarFire evaluation board,
 - Characterization of the IpGBT environment as a means for electrical / optical conversion utilizing the CERN VLDB+ evaluation kit,
 - Characterization of the Samtec optical FireFly components utilizing a Samtec evaluation board, interfaced to the PolarFire evaluation board,
 - Design and implementation of the multiplexing firmware on both the PolarFire evaluation board as well as the FELIX board as the back-end DAM board
 - Design and fabrication of a test system as well as FPCs for the characterization of the ER-1 NIKHEF serializer chip
 - Radiation testing of fault tolerance of FPGA evaluation board multiplexing with fiber optic transmission at a test beam facility

ePIC SVT R&D — eRD104

- MIT has recently joined the ePIC SVT effort and proposes contributions with postdoc effort stationed at CERN on the readout chain to transition to fiber links close to the sensor, thereby reducing the readout services load. This work will be pursued in collaboration with ORNL.

Table 1: Institutions involved and institutional contacts

Topic	Institute	Institutional contact
Powering system	Birmingham	Laura Gonella
	Oxford	B. Todd Huffman
	RAL	Fergus Wilson
Readout System	ORNL	Jo Schambach
	MIT	Gian Michele Innocenti

Table 2: R&D funding request in k\$ and breakdown by institution.

Institute	EE	ME	PD	M&S	travel	total FY24
ORNL	44.5	15.0		15.0	7.0	81.5
MIT			21.0			21.0
Total	44.5	15.0	21.0	15.0	7.0	102.5

- The need for R&D is likely to continue beyond FY24 into FY25 in view of the still rapidly evolving sensor design.

ePIC SVT R&D — eRD111

- Contact person: Nicole Apadula (Lawrence Berkeley National Laboratory)
- UK groups are proposing:
 - Development of FPC concepts for the inner barrel and exploration of wire bonding and interconnection
 - Study of FPC and module possibilities based on the number of RSU variations for the Outer Barrel. Implications of the study will be used for disk FPC and module design
- Contributions are predominantly in-kind on a best effort basis; project R&D request for effort not (yet) supported by UK grant
- INFN groups are proposing:
 - Climate chamber tests of long term mechanical stability of wafer-scale size sensors at inner barrel bending radii
- Purdue is proposing investigating if cooling options being considered for other detectors can be carried over to the ePIC SVT and explore options for low-mass two-phase CO₂. Careful attention will be paid to material budget.

ePIC SVT R&D — eRD111

- Contact person: Nicole Apadula (Lawrence Berkeley National Laboratory)

Topic	institute involved	institute contact
modules & interconnections	INFN institutes UK institutes	Domenico Elia Georg Viehhauser
barrel & discs	INFN institutes LANL LBNL MIT Purdue UK institutes	Domenico Elia Walter Sondheim Nicole Apadula Gian Michele Innocenti Andy Jung Georg Viehhauser
mechanics, cooling, & integration	LANL LBNL MIT Purdue UK institutes	Walter Sondheim Nicole Apadula Gian Michele Innocenti Andy Jung Georg Viehhauser

Institute	Request (\$k)
INFN institutes	45
Purdue	25
UK institutes	40
Total	110

- Proposed R&D efforts focus on reducing project risk only. Further efforts are needed to bring the ePIC SVT to construction readiness and will be part of a separate PED request.

ePIC SVT R&D — eRD113

- Contact person: Grzegorz Deptuch (Brookhaven National Laboratory)
- Note: The eRD113 proposal currently contains both proposed R&D efforts and PED efforts.
- **Sensor design**
 - The UK groups are proposing:
 - Design and coordination of further development of the DFM standard cell library for the ITS3 ER2 submission
 - Shunt LDO implementation and circuit simulation
 - Simulation and verification of the serial powering scheme using the Shunt LDO
 - Prototyping of serial powering using the Shunt LDO
 - The contributions will be in-kind and on a best-effort basis
 - BNL proposes (in short):
 - Contributions to the DFM standard cells library
 - Continued development of a small-footprint ADC for Vital Functions Monitoring
 - Development of Long-Distance-on-Chip Ultra-Low-Voltage Signaling data transmission
 - New R&D for a Negative Voltage Bias Generator / Regulator compatible with LAS serial powering
 - New R&D for Time Division Multiple Access interface connects for aggregation of high-speed links for data transfer off the MAPS sensors
 - New R&D for TMDA multiplexer design to congregate LAS data to efficiently fill the lpGBT (up-)links
 - LBNL can take on additional design contributions to the DFM standard cells library

ePIC SVT R&D — eRD113

- Contact person: Grzegorz Deptuch (Brookhaven National Laboratory)
- Note: The eRD113 proposal currently contains both proposed R&D efforts and PED efforts.
- **Sensor characterization**
 - INFN proposes:
 - EIC specific optimization of the MLR1 test structure configuration
 - Stitched sensor characterization
 - UK groups:
 - Propose continued characterization of devices fabricated on MLR1 and ER1
 - Seek to contribute to the texting of ER1 MOSS or baby-MOSS sensors (in discussion with ITS3 WP3)
 - The UK contributions will be in-kind and on a best-effort basis
 - ORNL proposes:
 - Characterization and calibration of sensors
 - Proof of principle laser stimulation of sensors
 - Gantry tooling development for sensor and flex circuit handling and assembly

ePIC SVT R&D — eRD113

- Contact person: Grzegorz Deptuch (Brookhaven National Laboratory)
- Note: The eRD113 proposal currently contains both proposed R&D efforts and PED efforts.
- **Sensor characterization**
 - LBNL proposes:
 - Continued characterization effort of sensors
 - Modeling efforts to reduce risk associated with tiling, uncertainties from yields and power specifically for the ePIC SVT
 - LANL proposes:
 - Participation in ITS3 prototype sensor beam tests
 - Contributing to EIC-LAS back-end readout integration in collaboration
 - Irradiation tests for ITS3 sensors using the LANSCE facility at LANL
 - MIT is equipping a pixel lab at CERN and proposes:
 - Characterization effort of ER2 sensors “on the bench” at CERN once these sensors become available,
 - Characterization with test beams of the ER2 sensor and of the ePIC
 - Software integration and DAQ tool development for ER2

ePIC SVT R&D — eRD113

- Contact person: Grzegorz Deptuch (Brookhaven National Laboratory)
- Note: The eRD113 proposal currently contains both proposed R&D efforts and PED efforts.

Topic	Institution	Institutional contact	Institution	PD Staff	Design Eng.	Electrical Eng.	Tech.
Sensor Development	RAL	Iain Sedgwick					
	BNL	Grzegorz Deptuch	UK Institutes				
	LBNL	Carl Grace	INFN Institutes	0.35			
Sensor Characterization	INFN	Rosario Turrisi	BNL		2.3	0.5	0.2
	UK institutes	Laura Gonella	LBNL	0.5	0.2		
	LBNL	Yuan Mei	ORNL		0.05		0.05
	ORNL	Jo Schambach	LANL			0.5	
	LANL	Xuan Li	MIT				
	MIT (new in FY24)	Gian Michele Innocenti		0.7			

Institution	effort	travel	M&S	Total
UK Institutes				in kind
INFN	30		15	45
BNL	1,500	15	90	1,605
LBNL	180			180
ORNL	40		35	75
LANL	250	15	10	275
MIT	100			100
Total	2,100	30	150	2,280

- The need for R&D on sensor design and characterization is likely to continue beyond FY24.

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- Progress on many aspects of the ePIC SVT detector
- ePIC SVT Detector Subsystem Collaboration has grown
- EIC / ePIC — CERN/ALICE agreement to share sensor is key
- Finalization of the ITS3 ER2 design in the next few months will fix crucial parameters for the ePIC SVT development
- Aim to advance designs to converge towards final design choices and scale up prototypes in preparation for the TDR

EIC-related Generic Detector R&D

Per Thomas Ullrich: “Should you also have submitted a generic R&D proposal please indicate this on your slides”

The SVT does *not* rely on the Generic EIC-related R&D Program, c.f. https://www.jlab.org/research/eic_rd_prgm. However, several members of the ePIC SVT DSC are part of submitted proposals to that program:

- Yuan Mei (LBNL) — Industrial aluminum flexible circuit manufacturing
- Nicole Apadula (LBNL), Nicholas Schmidt (ORNL), Giacomo Contin (INFN) — Kapton embedded Monolithic Active Pixel Sensor R&D
- Xuan Li (LANL) — A Fast Timing MAPS Detector for the EIC
- Soumyajit Mandal (BNL) — Photonics-based Readout and Power Delivery by Light for Large-Area MAPS
- Dominik Gorni (BNL) — Large-Area MAPS Combining High Spatial and Temporal Resolution