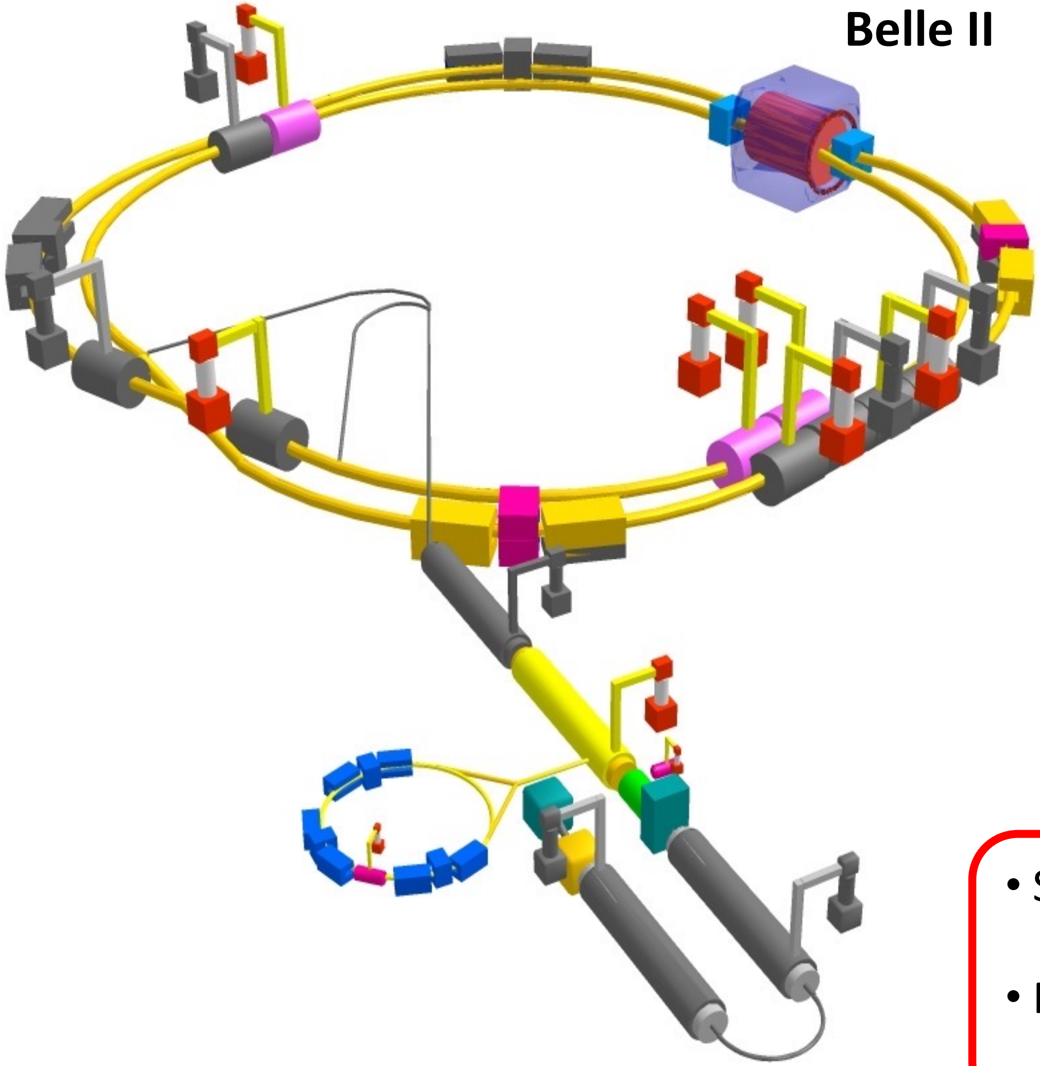
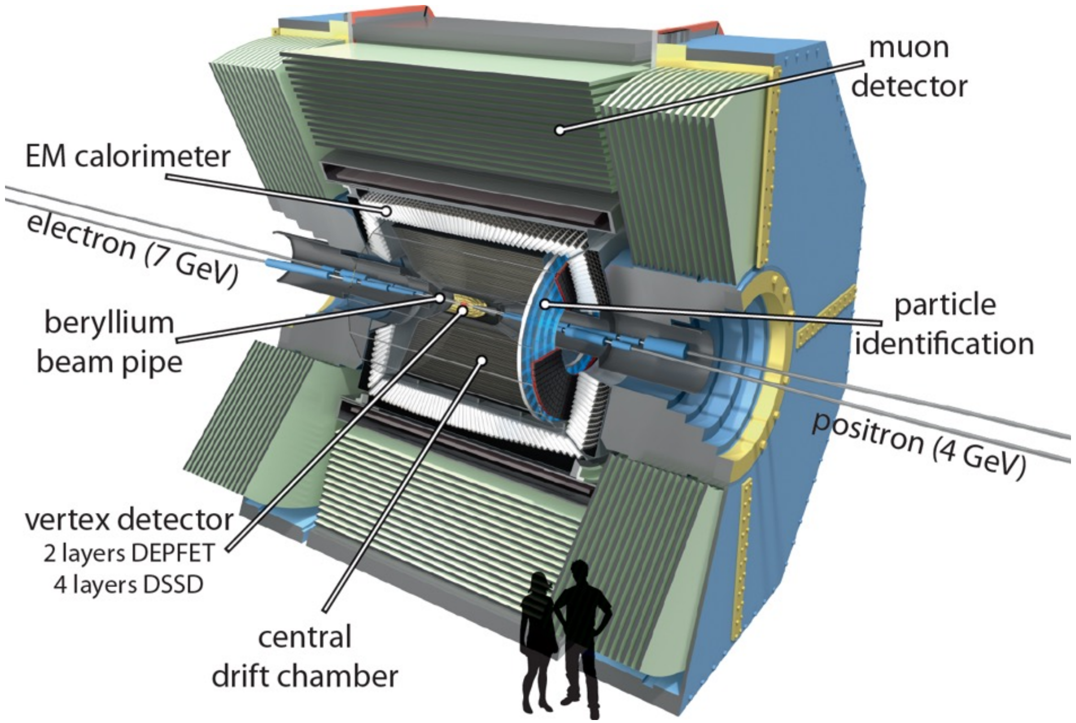
The DMAPS Upgrade of the Belle II Vertex Detector

C. Marinas, IFIC (CSIC-UV)

cmarinas@ific.uv.es

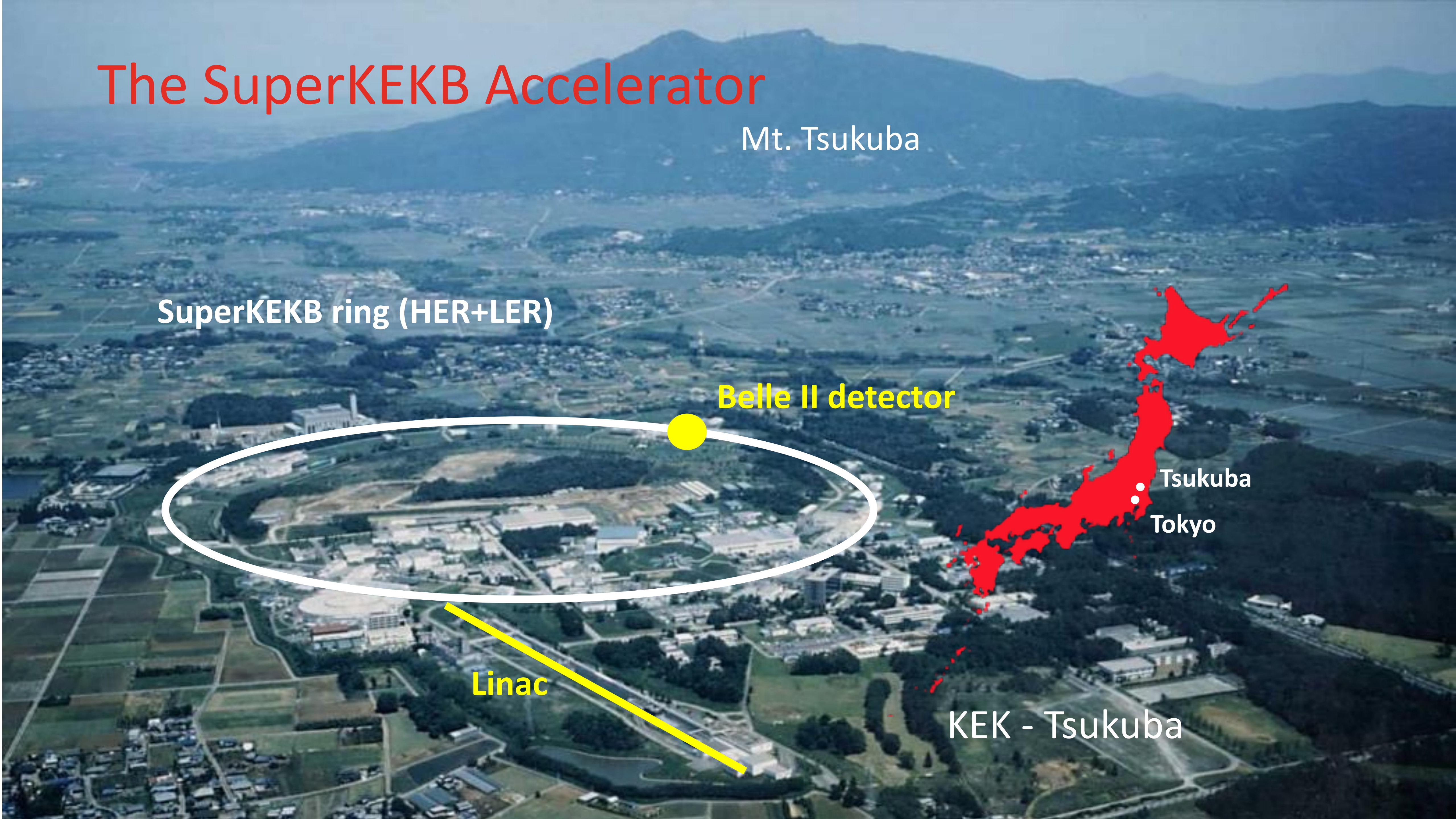
SuperKEKB and the Belle II Experiment



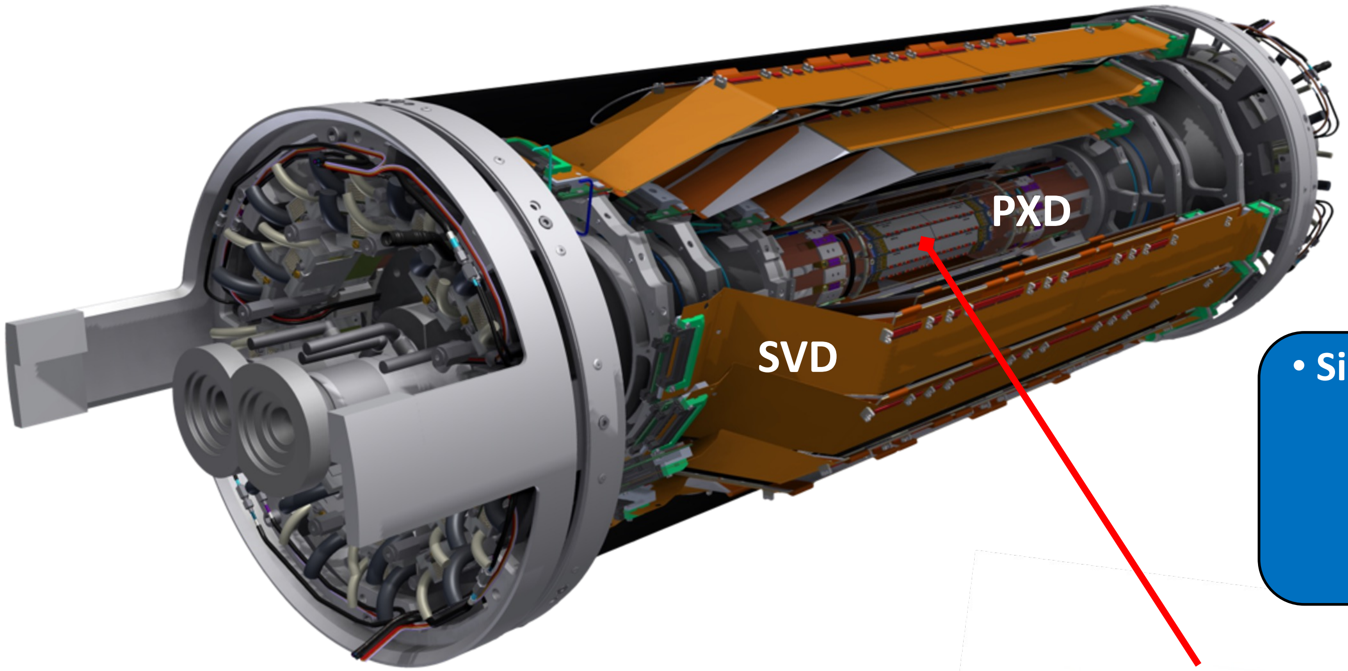


- SuperKEKB: Asymmetric energy e^+e^- collider
  $E_{cm} = m(\Upsilon(4S)) = 10.58$ GeV
- Peak luminosity: $\mathcal{L} = 6 \cdot 10^{35}$ cm^{-2} s^{-1} (x30 than KEKB)
  Beam size reduction. Higher current (x2 higher).

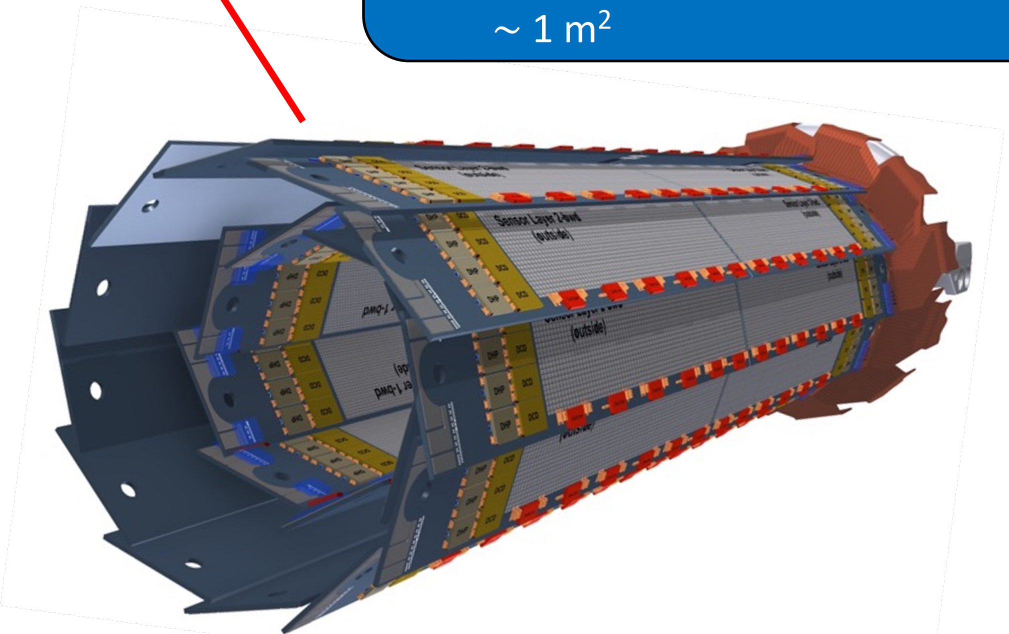
The SuperKEKB Accelerator



Belle II Vertex Detector

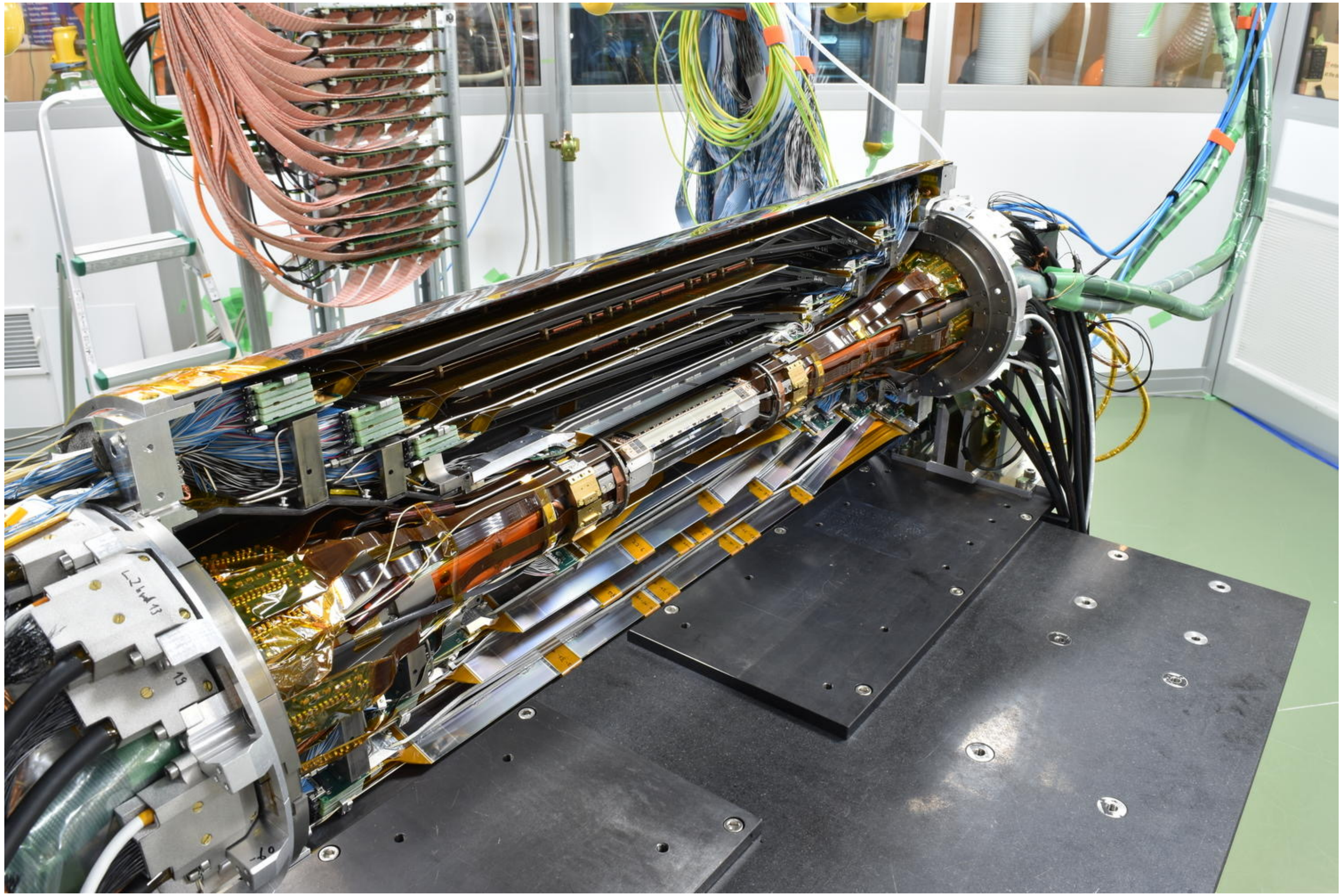


- **Silicon Vertex Detector (SVD)**
  4 layers of DSSD
  r = 3.9 cm, 8.0 cm, 10.5 cm, 13.5 cm
  L = 60 cm
  $\sim 1\ m^2$



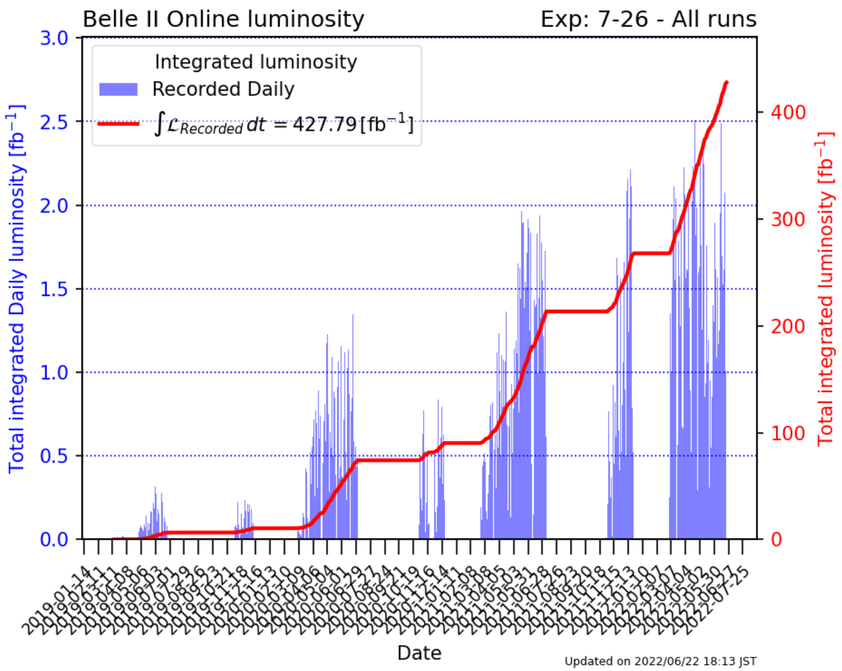
- **Pixel Detector (PXD)**
  2 layers of DEPFET pixels
  r = 1.4 cm, 2.2 cm
  L = 12 cm
  $\sim 0.027\ m^2$

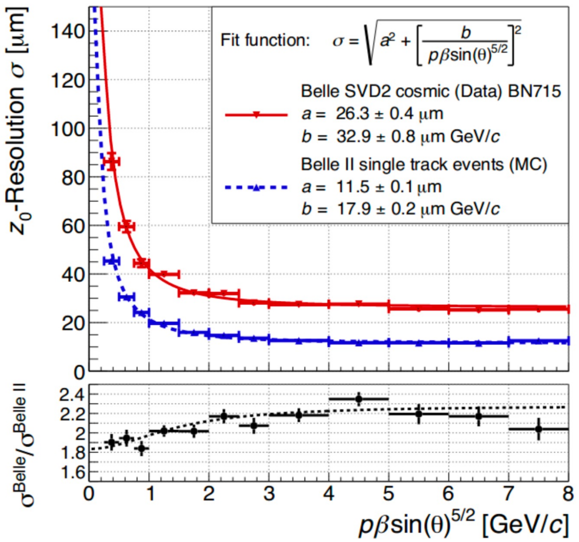
Belle II VXD during Run 1



Partially instrumented PXD

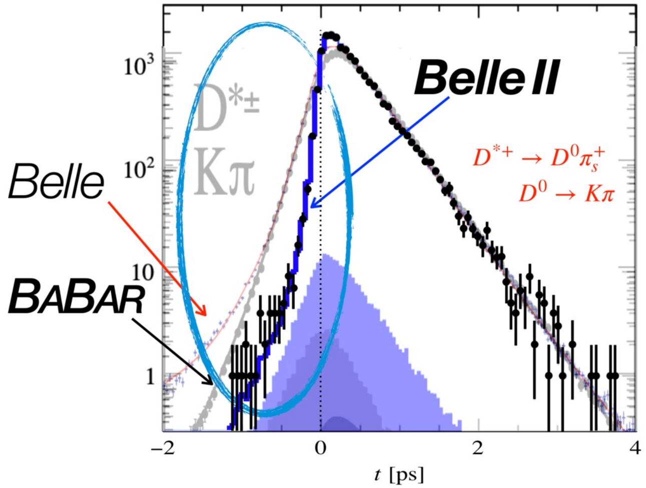
End Run 1 Status and Performance Benchmarks





Excellent tracking performance (2x better single vertex resolution wrt Belle)

World's best D lifetime measurement with only 72 fb^{-1}

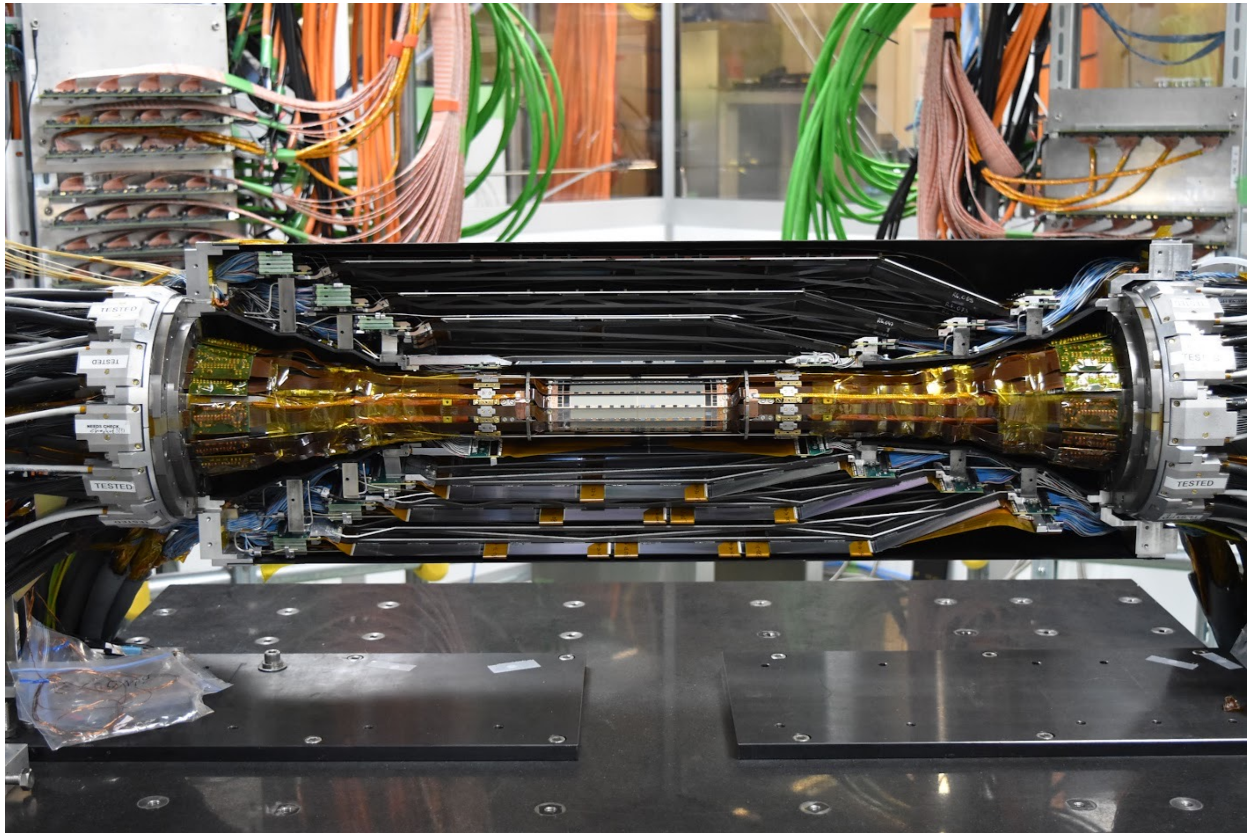


Decay time resolution x2 better than Belle and BaBar

- L_{peak} = 4.7x10^{34} $cm^{-2}s^{-1}$ (x2 KEKB)
- $L_{integrated}$ = 430 fb^{-1} (~BaBar)
- Data taking efficiency ~90%
- Precision measurements

Important test of Belle II tracking performance
→ VXD reconstruction, track finding and vertex fitting

VXD Detector Upgrade – LS1 (2022/2023)



- Detector upgrades:

- Installation of complete pixel detector

- Machine upgrades:

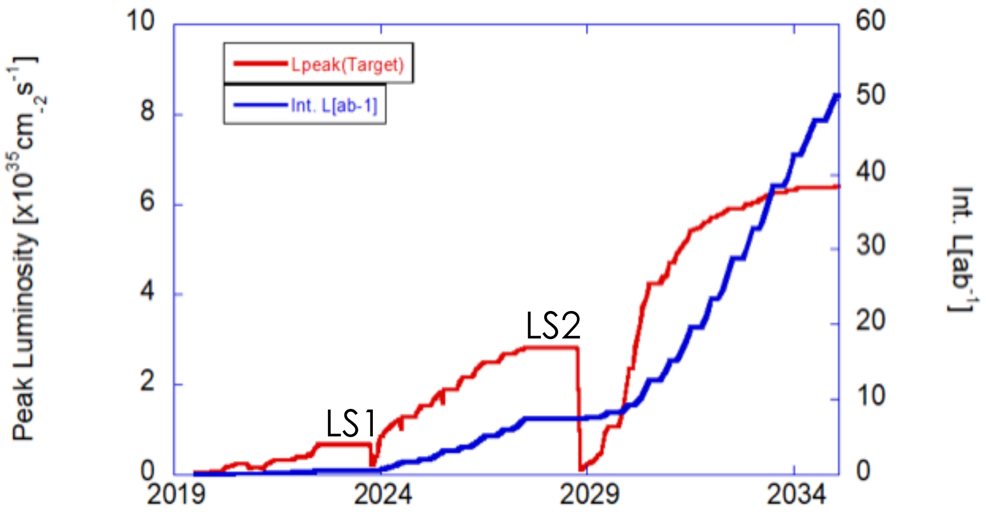
- New more resilient collimators

- Additional background shielding

→ Run 2 ongoing. Target for 2024: 10^{35} $cm^{-2}s^{-1}$

Belle II Upgrade Program

SuperKEKB **peak** & **integrated** luminosity vs time



LS1 : Actual detector consolidation
LS2 : Possible IR and detector upgrades

Path to the future:

1) Improve machine performance and stability
Beam blowup, lifetime, injection power, beam losses

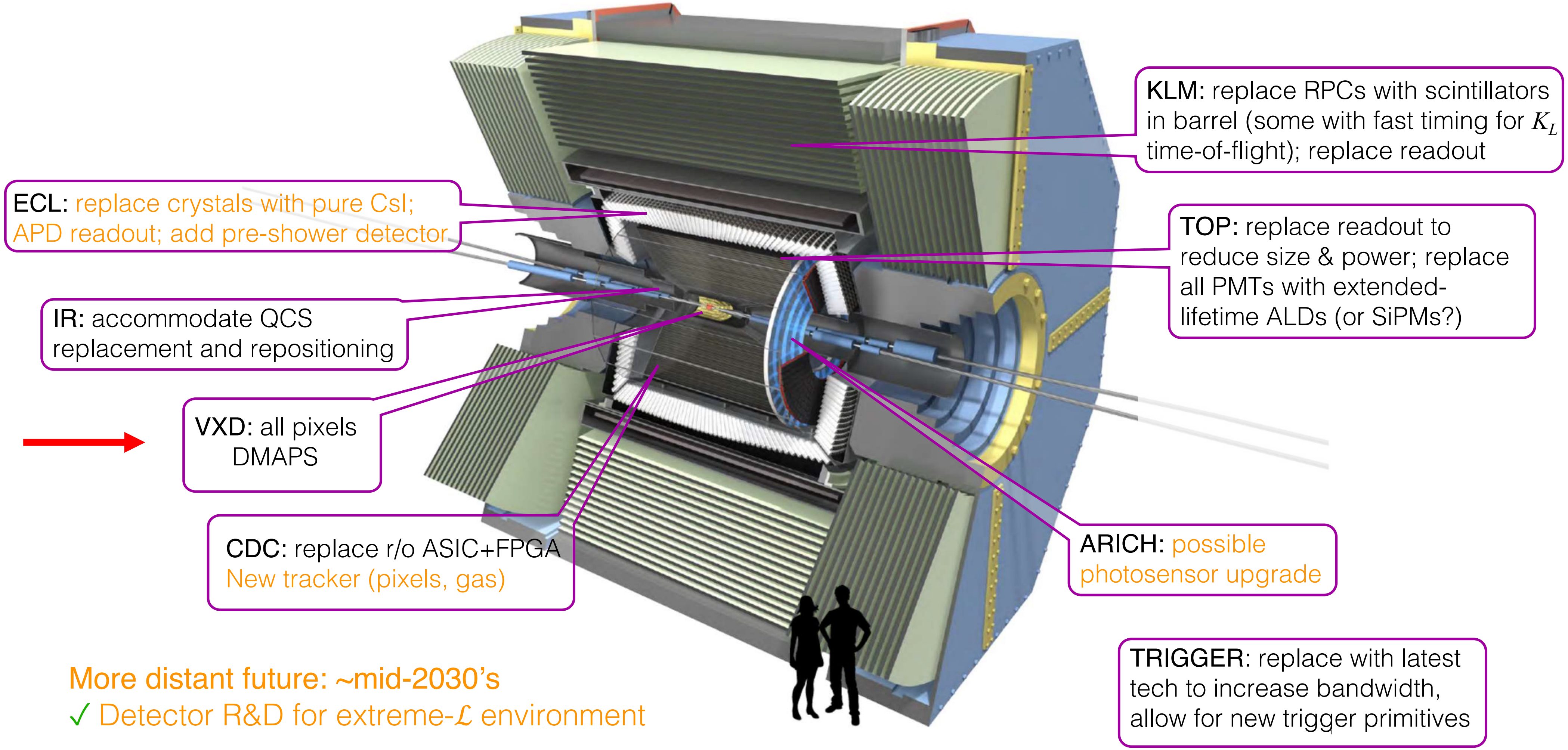
2) Reduce detector backgrounds
Single beam, injection and luminosity backgrounds

3) LS1 Detector consolidation toward $2x10^{35}$ $cm^{-2}s^{-1}$
Installation of more robust components

4) LS2 Detector upgrade toward $6x10^{35}$ $cm^{-2}s^{-1}$
Including possibly a redesign of the interaction region

→ More performant detector and robust against machine-induced backgrounds

Belle II Upgrades – LS2 and Beyond



More distant future: ~mid-2030's

✓ Detector R&D for extreme-$\mathcal{L}$ environment

Requirements for VXD Upgrade

Upgrade motivation:

- Cope with larger background activity
- Improve momentum and impact parameter resolution in low p_T region
- Simplify tracking chain with all layers involved
- Operation without special modes nor data reduction

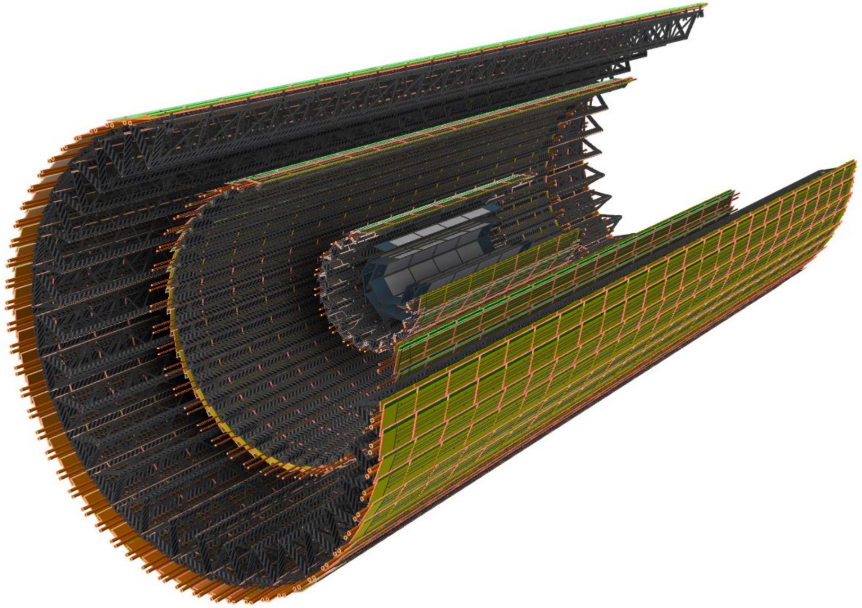
Key sensor specifications:
- Pixel pitch 30-40 µm
- Integration time $\lesssim$100 ns
- Power dissipation $\lesssim 200\ \mathrm{mW/cm^2}$

Improve physics reach per ab^{-1}

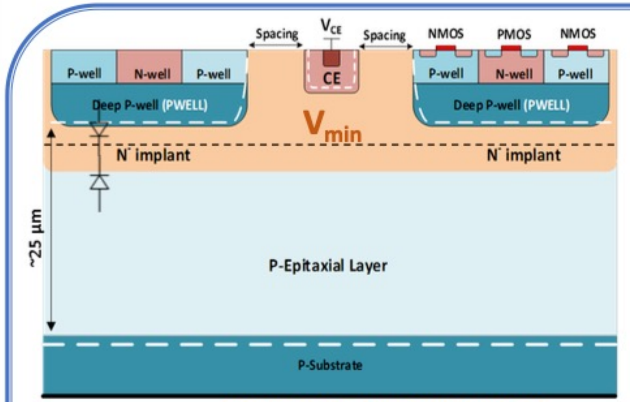
Radius range	14 – 135 mm
Tracking & Vertexing performance	
Single point resolution	< 15 µm
Material budget	0.2% X_0 / 0.7% X_0 inner- / outer- layer
Robustness against high radiation environment (innermost layer)	
Hit rate	~ 120 MHz/cm²
Total ionizing dose	~ 10 Mrad/year
NIEL fluence	~ 5e13 n_{eq}/cm²/year

Belle II Upgrade: VTX - DMAPS

- 5 straight layers barrel, using CMOS pixel sensors
- Low material : 0.2% X_0 (L1+L2) - 0.5% (L3) - 0.8% X_0 (L4+L5)
- Moderate pixel pitch ~ 30 μm^2
- Time precision 50-100 ns
  - Option for track-triggering with a fast low-space-granularity
- iVTX: innermost 2 layers, self-supported, air cooled
- oVTX: 3 outer layers, CF structure, water cooled
- Overall service reduction and operation simplification



TJ-Monopix Family



W. Snoeys et al. https://doi.org/10.1016/j.nima.2017.07.046

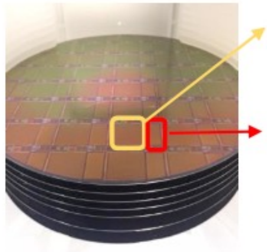
$$C_d \leq 3fF$$

$$P \approx \frac{S}{N} \approx \frac{Q}{C_d}$$

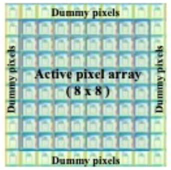
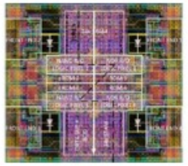
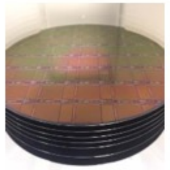
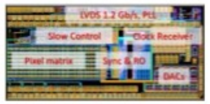
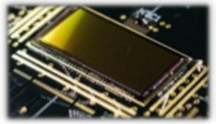
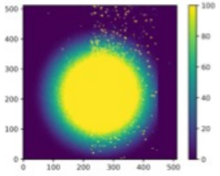
DMAPS in TJ 180 nm: Concept

- Small sensor capacitance (Cd)
  - Key for low power/low noise
- Radiation tolerance challenges
  - Modified process
  - Small pixel size
- Design challenges
  - Compact, low power FE
  - Compact, efficient R/O

Large scale demonstrator chip development

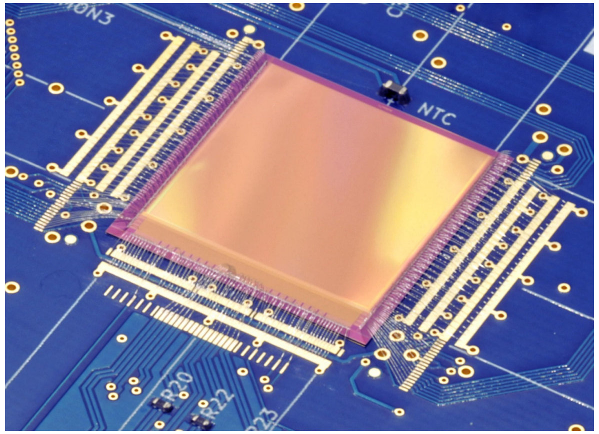


- MALTA
  - Asynchronous readout
- TJ-Monopix1
  - Synchronous column-drain R/O
- Process modification enhancements, Cz substrate ⟹ improved efficiency
- TJ-Monopix2: Improved full-scale DMAPS

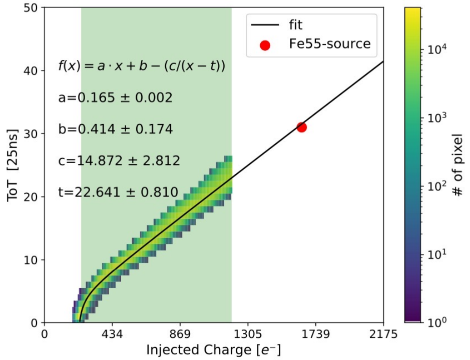
TJ-Investigator characterization	*TJ-Monopix1* & MALTA Design	*TJ-Monopix1* & MALTA Submission	Mini-MALTA sub. with process fixes	*TJ-Monopix1* resub. process fixes & Cz	*TJ-Monopix2* & *MALTA2* Design	*TJ-Monopix2* & MALTA2 Submission	*TJ-Monopix2* Characteriza tion	*"OBELIX"* Design
								Full scale System-ready: LDO, CDR, memory etc.
Q2 2016	Q4/2016	Q3/2017	Q3/2018	Q2/2019	Q2/2019	Q3/2020	Present	~~Future plans~~ Present

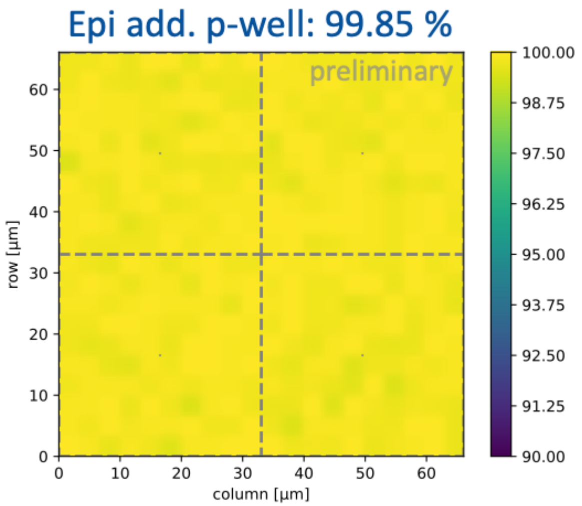
TJ-Monopix2 Characterization

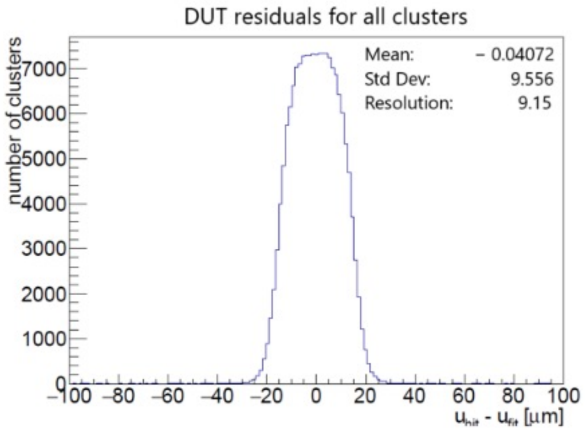
- TJ-Monopix2 as forerunner of OBELIX
  - 33x33 µm^2 pitch, 25 ns integration, 2x2 cm^2 matrix
  - 7 bit ToT information, 3 bit in-pixel threshold tuning
  - Various sensing volume thickness (CZ-bulk, epi-30 µm)



- Detailed characterisation
  - In-laboratory
    - Threshold / noise
    - ToT calibration
  - In-beam (DESY, 5 GeV electrons)
    - Efficiency ~99%
    - Position resolution ~9 µm







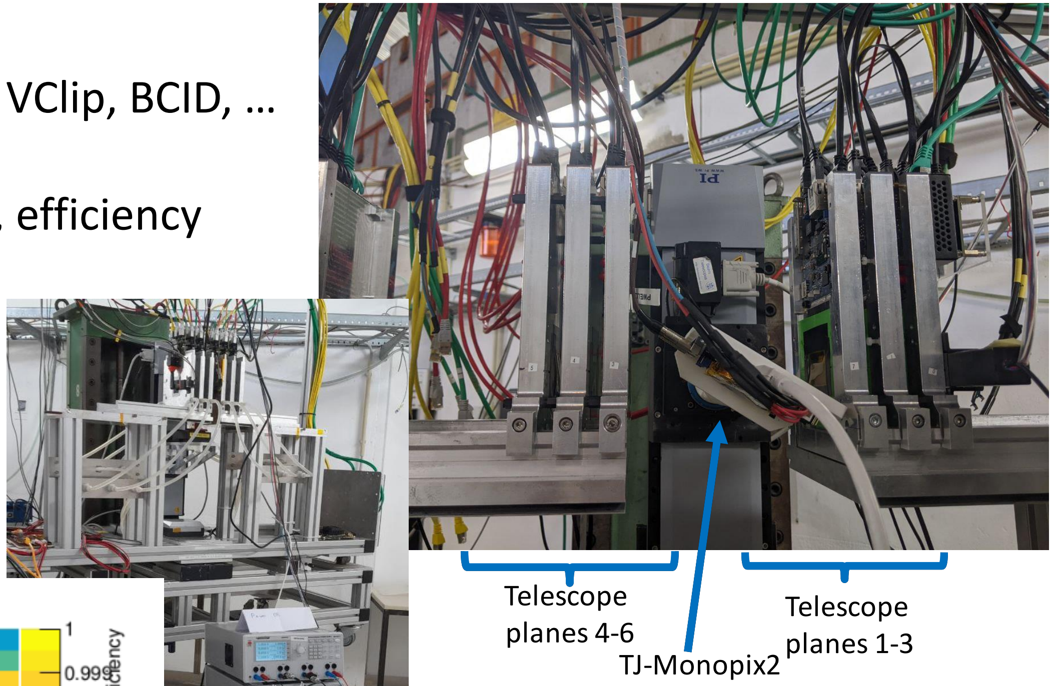
Irradiated TJ-Monopix2 Test Beam

Serial	Irradiation	Substrate
W02R05	None	30 µm EPI
W02R09	Neutrons 1×10^{14}	30 µm EPI
W05R16	Protons 5×10^{14}	30 µm EPI
W08R19	None	30 µm EPI
W14R12	None	Cz

Parameter scans:

HV, IBias, PSub, VClip, BCID, …

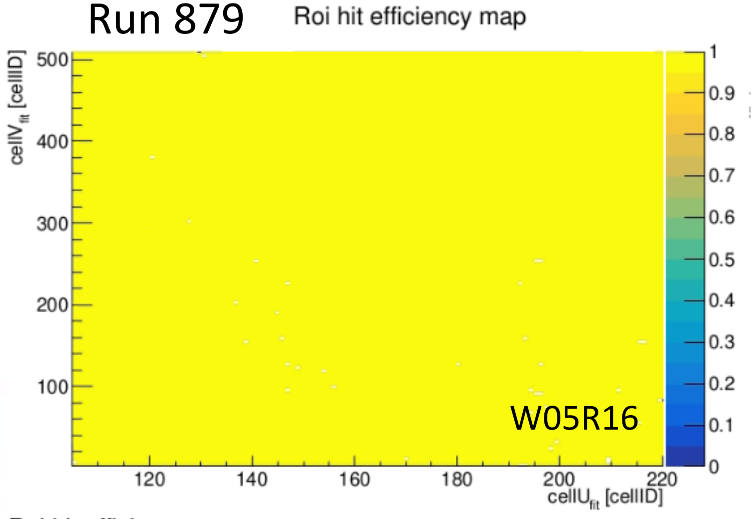
Angular scans, resolution, efficiency

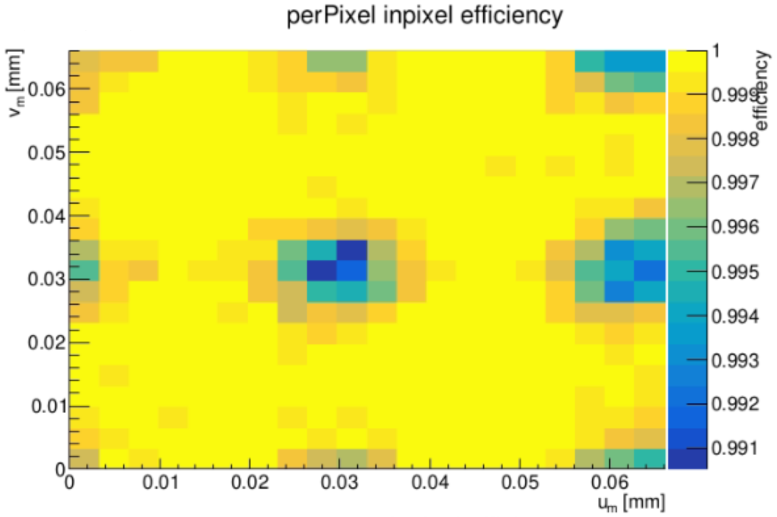


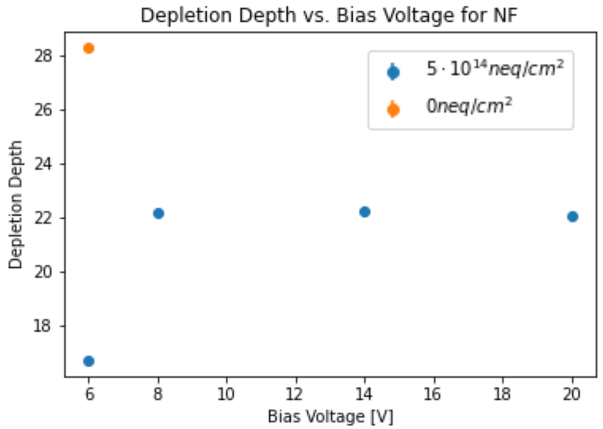
Efficiency >99% for 5×10^{14} n_{eq}/cm^2 (310 e^- threshold)

Cluster position residuals ~9.5 µm

Run 879

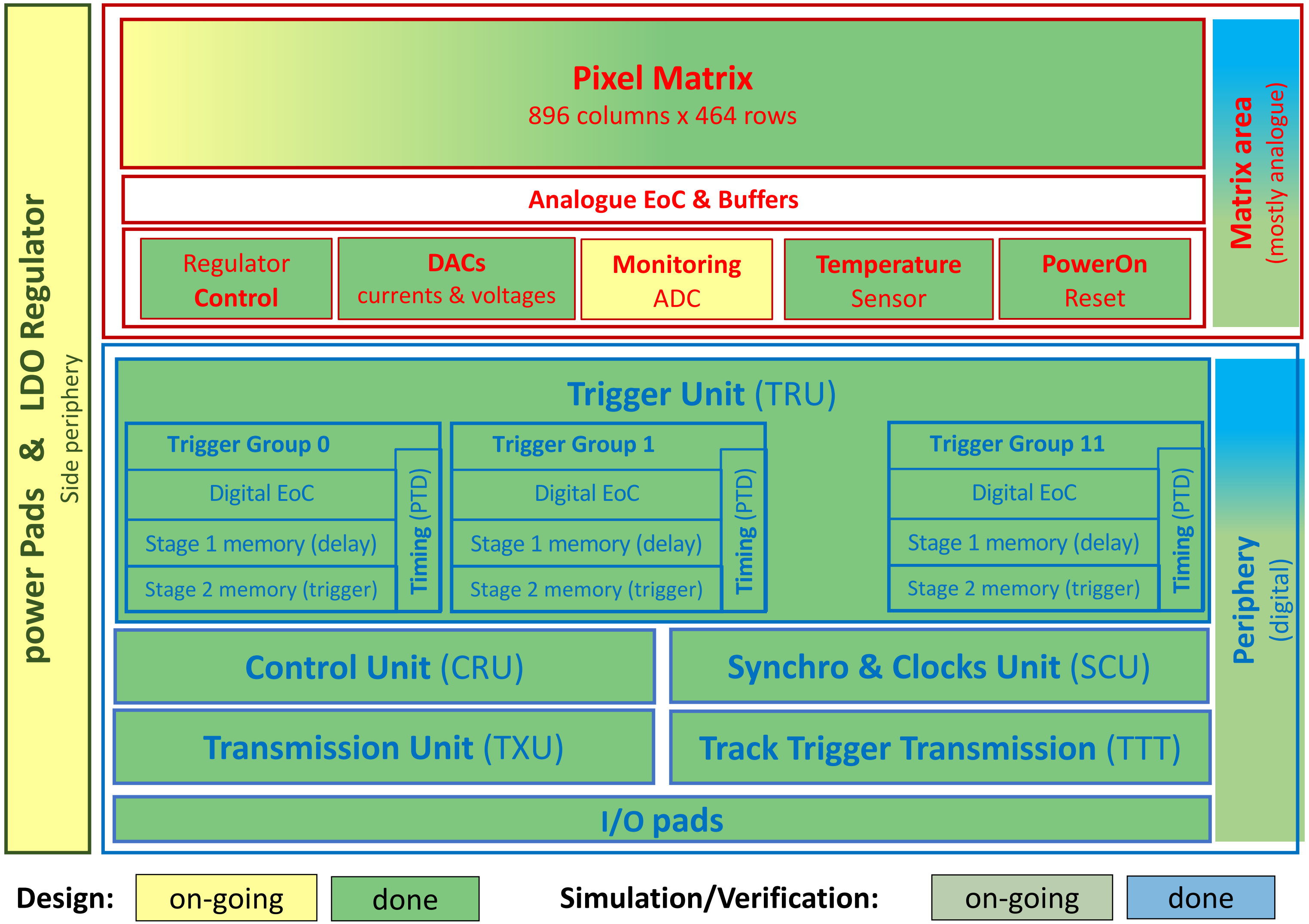






cmarinas@ific.uv.es

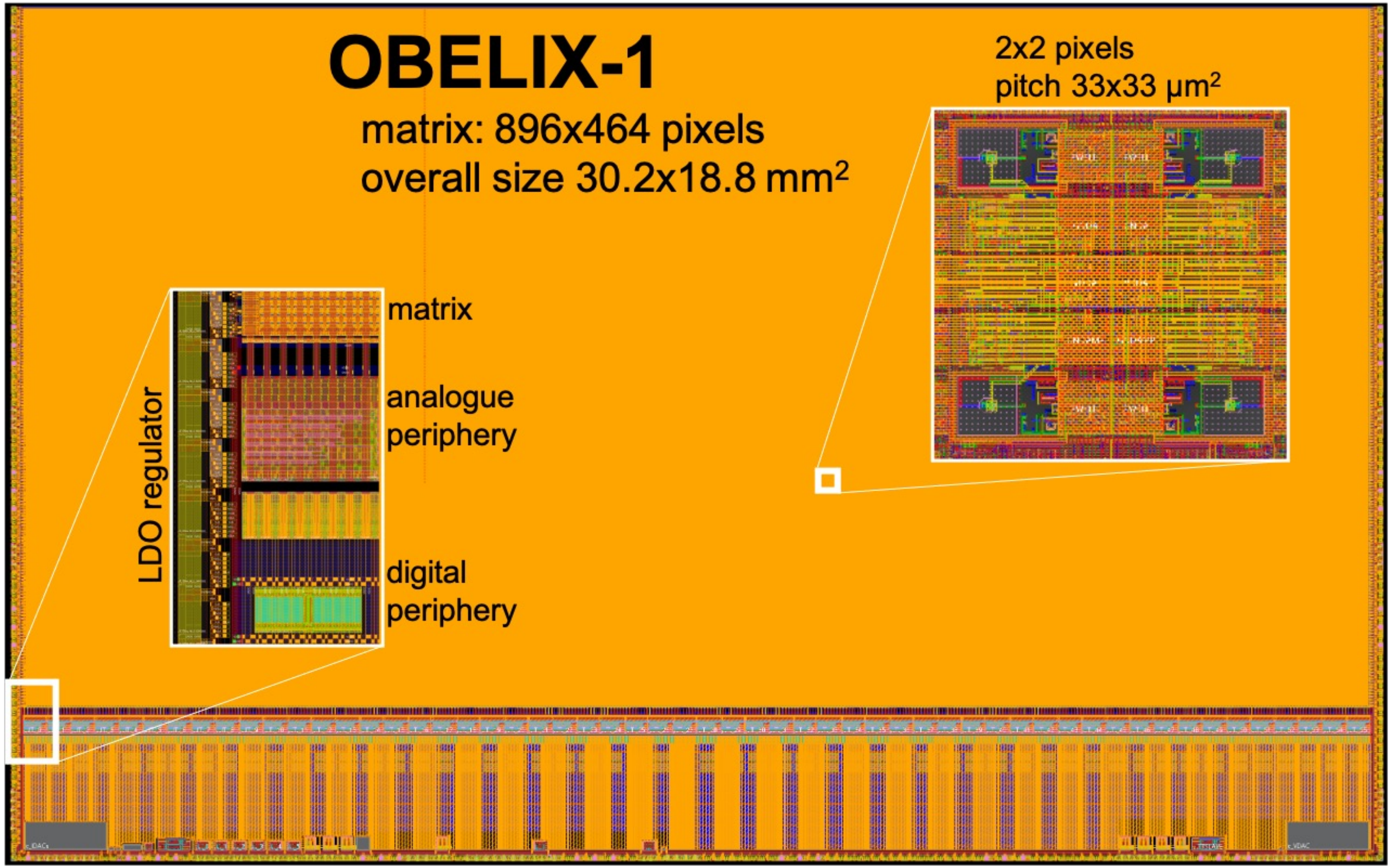
OBELIX – Design Status



- Main functionalities done (but regulator)
  - Pixel options chosen
- Final integration on-going
- Simulation/verification = main activity
- Documentation: started

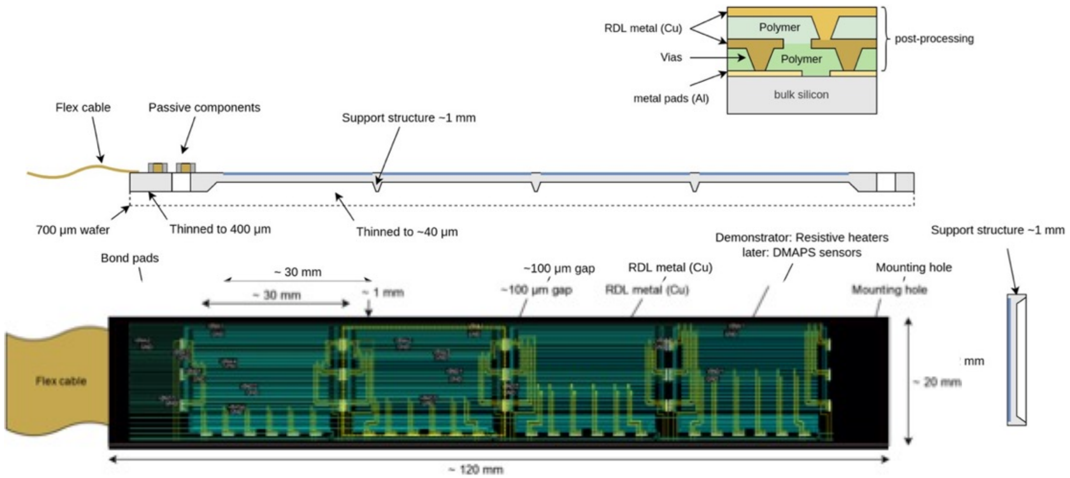
Submission: Q3-2024

OBELIX – Layout



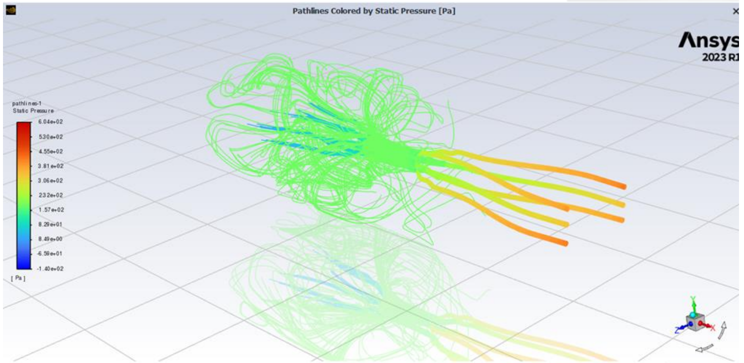
iVTX Inner Layer Concept

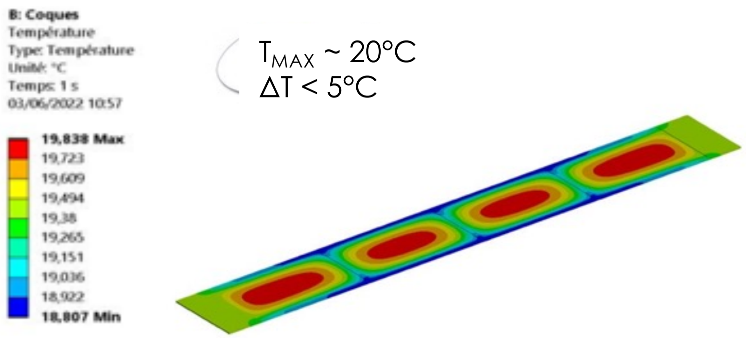
- All-silicon module < 0.15 % X_0
  - 4 contiguous sensors diced as a block from the wafer
  - Redistribution layer for interconnection
  - Heterogeneous thinning for thinness & stiffness



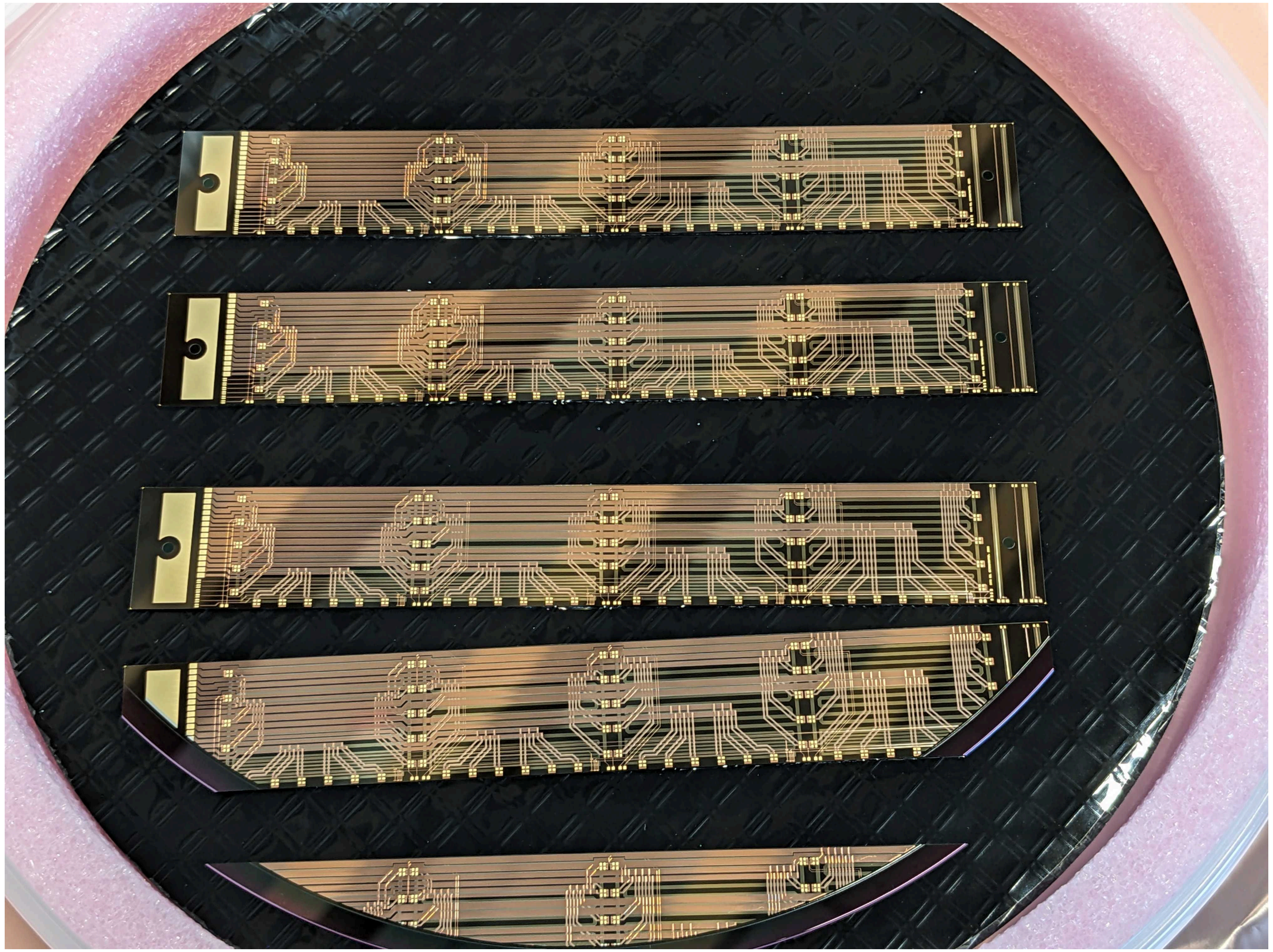
- Prototyping
  - First real-size ladders at IZM-Berlin with dummy Si
    - True iVTX geometry available

- Simulation on cooling
  - Dry air cooling 15°C
  - Assume 200 mW/cm^2





iVTX Ladder Demonstrator



- Production finished smoothly:

  FE-I3 and heaters
  300 – 700 um thick

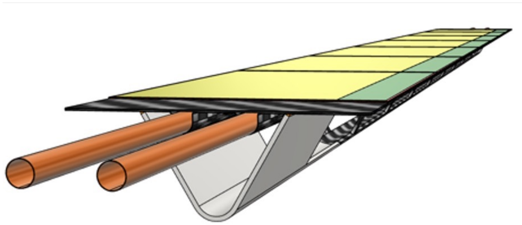
- Characterization started:

  First quality inspection with needles shows resistivity is on the expected range.

  Integrity of data lanes will follow

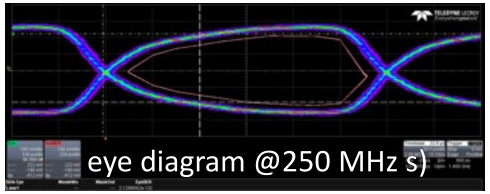
oVTX Outer Layer Concept

- Long ladders
  - Evolving from ALICE-ITS2
    - Carbon-fiber truss support frame
    - Cold-plate with water coolant
    - Long-flex for power & data



- L3-4, radius 4-9 cm, length < 50 cm
  - Single sensor row, ~0.5 % X_0
- L5, radius 14 cm, length 70 cm
  - Double sensor rows , ~0.8 % X_0

- Prototypes for L5 under test
  - Deformation & vibration
    - Max sagitta ~500 µm
    - First resonance f=250 Hz
  - Signal propagation
  - Cooling at T_{room} ~24°C
    - Leakless water flow at T_{in} = 10°C
    - Heaters dissipating 200 mW/cm^2
    - 22°C < $T_{sensors}$ < 26°C



cmarinas@ific.uv.es

Summary: LS2 Upgrade Plans

- *Vertex detector*: Plans to replace VXD with a fully pixelated CMOS detector (VTX)
  - TJ-Monopix2 performance, including irradiated devices, matches expectations
    → Solid steppingstone towards OBELIX, to be submitted in Q3 2024
  - Preparing complete ladder demonstrators, including its test stands

    → Detector layer concept validations incorporated on the CDR
  - Preparing the next big step: **TDR**

THANK YOU

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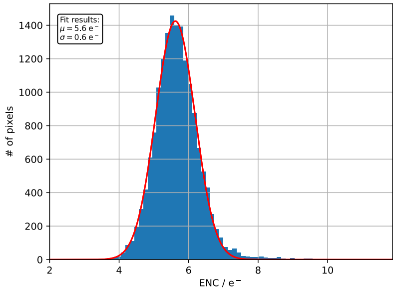
Plan de Recuperación, Transformación y Resiliencia
CSIC
Consejo Superior de Investigaciones Científicas

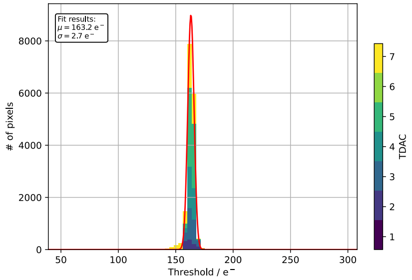
TJ-Monopix2 Characterization

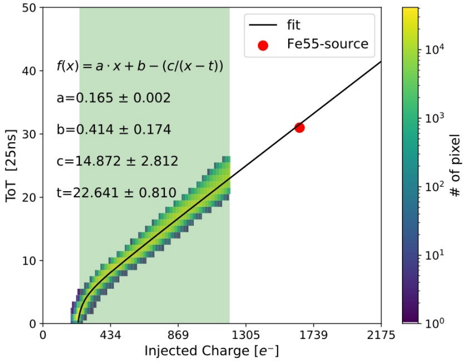
For all FE flavors and all pixels:

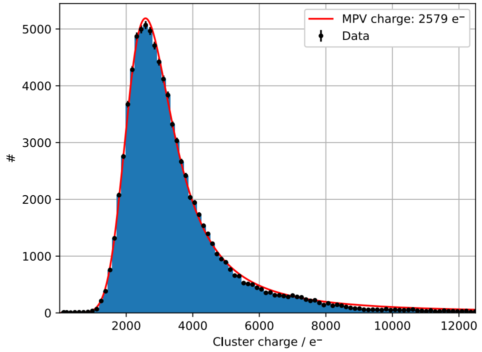
Noise, threshold and threshold dispersion

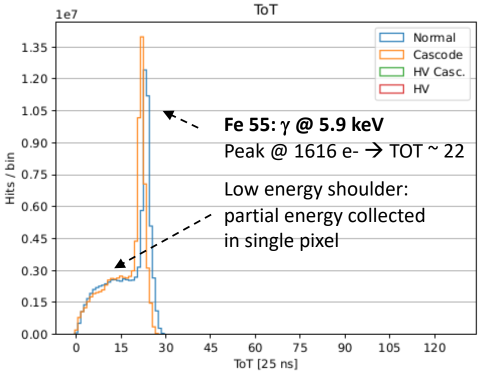
ToT calibration curve (internal injection and sources)











Consistently achieving <300 e⁻ threshold levels in all samples

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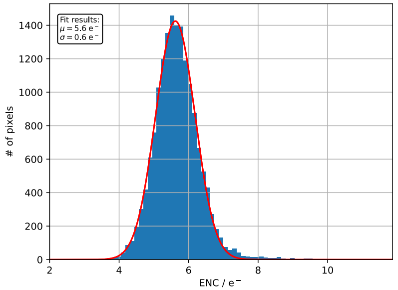
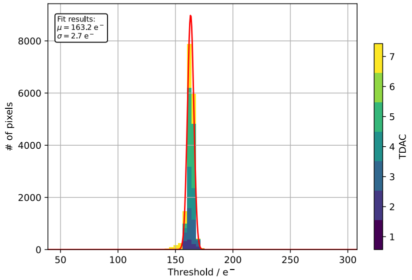
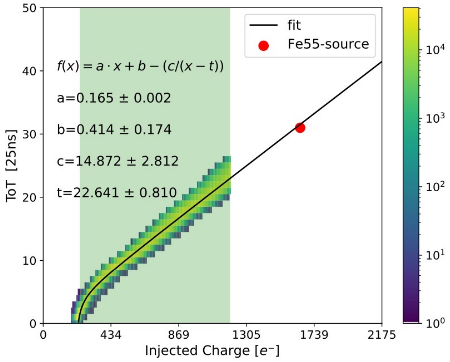
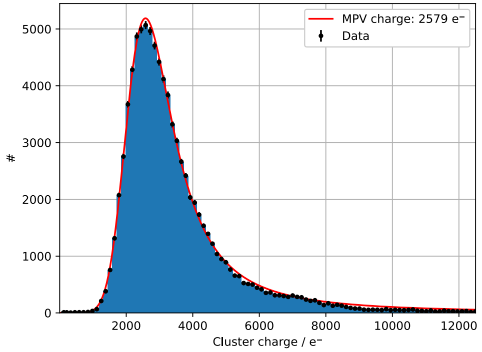
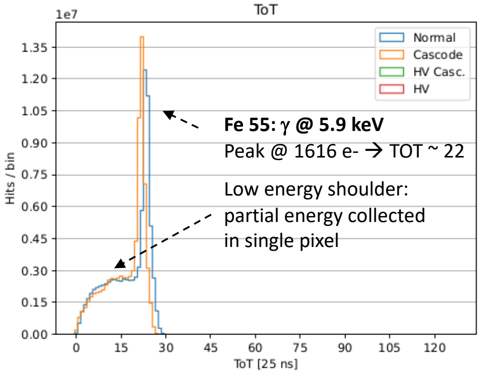
ToT calibration curve (internal injection and sources)











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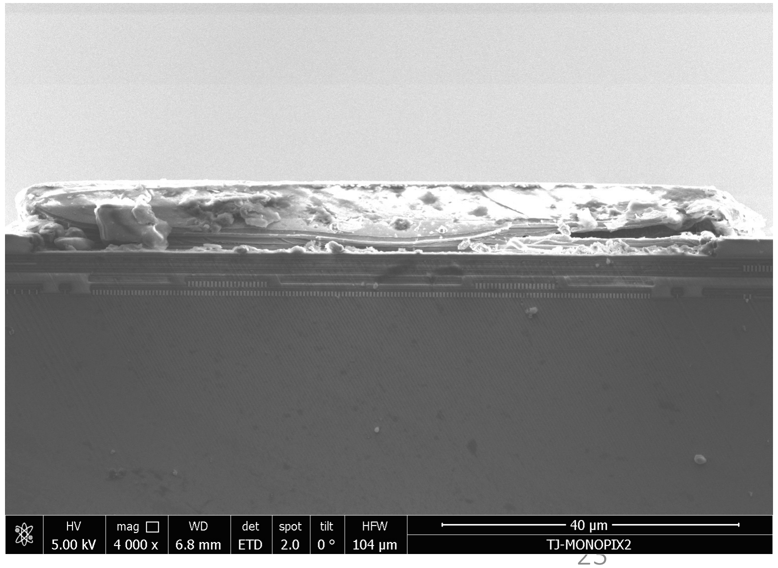
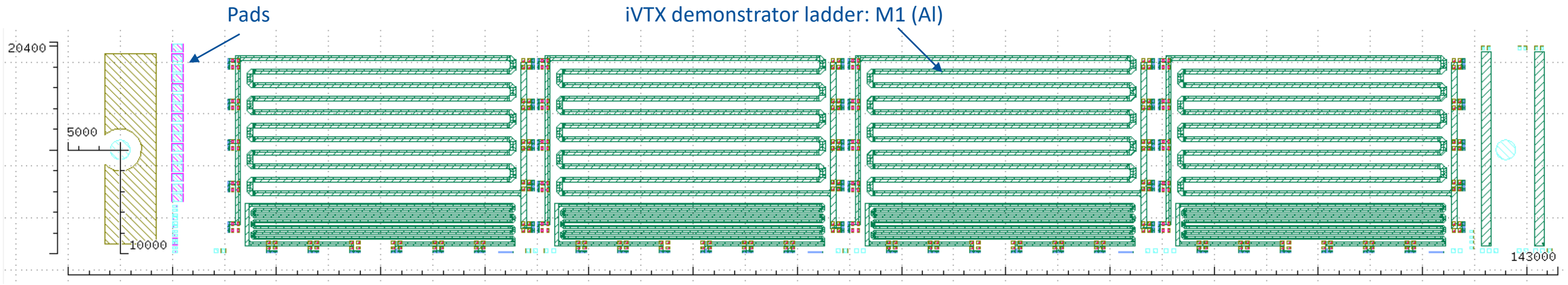
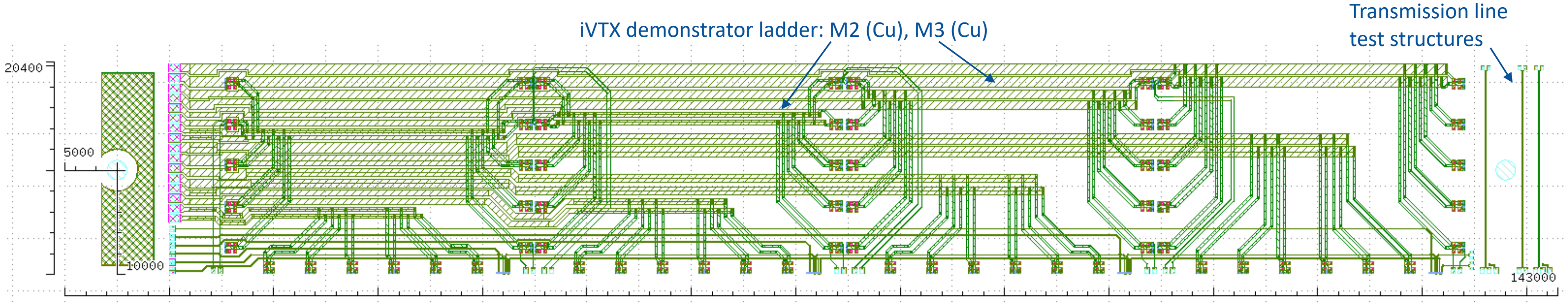


Bonding issues while preparing new samples:
→ Currently ~ 50% success rate

Several samples neutron irradiated up to $5x10^{14}$ n_{eq}/cm^2 available → Characterization ongoing

iVTX Ladder Demonstrator



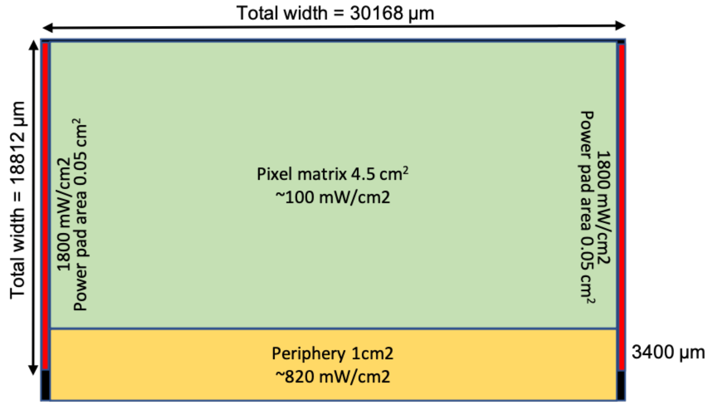


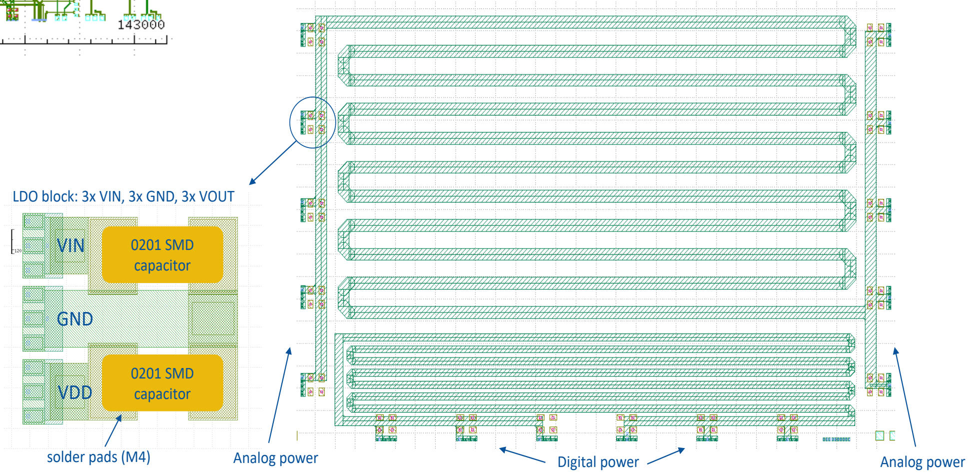
Metal system:

- Resistive heaters: 1.5 um Al (M1)
- 2 RDL metal layers: 3 um Cu (M2, M3)
- Top metal finish: NiAu (M4)
  Wirebonding, SMD soldering

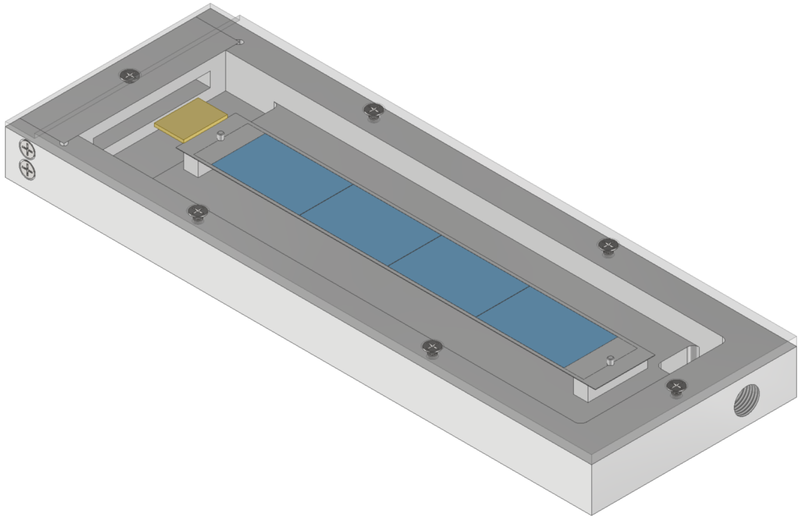
Final ladder dimension: 143 x 20.4 mm^2
Dummy heaters: 30 x 20 mm^2
Prepared for 1.7 mm mounting hole

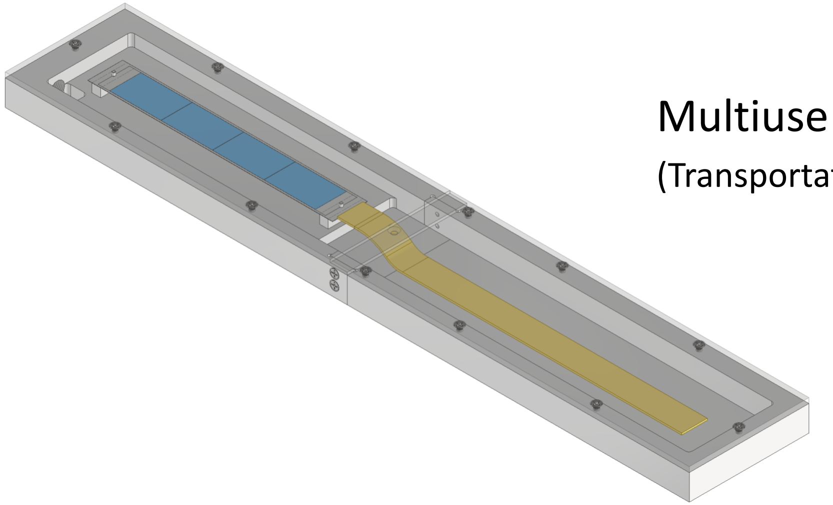
Characterization electrical, mechanical and thermal performances of iVTX ladders





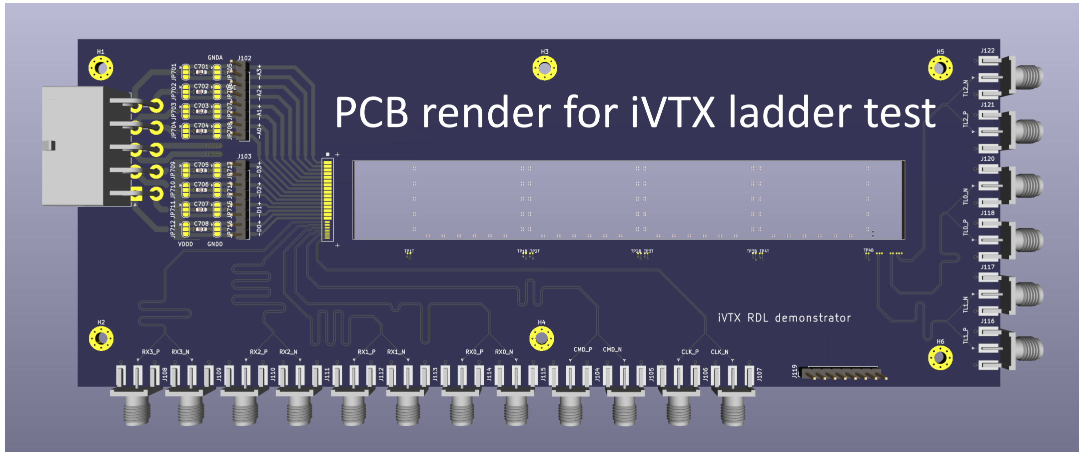
iVTX Ladder Tests





Multiuse Ladder Box Concepts

(Transportation, bonding, tests)

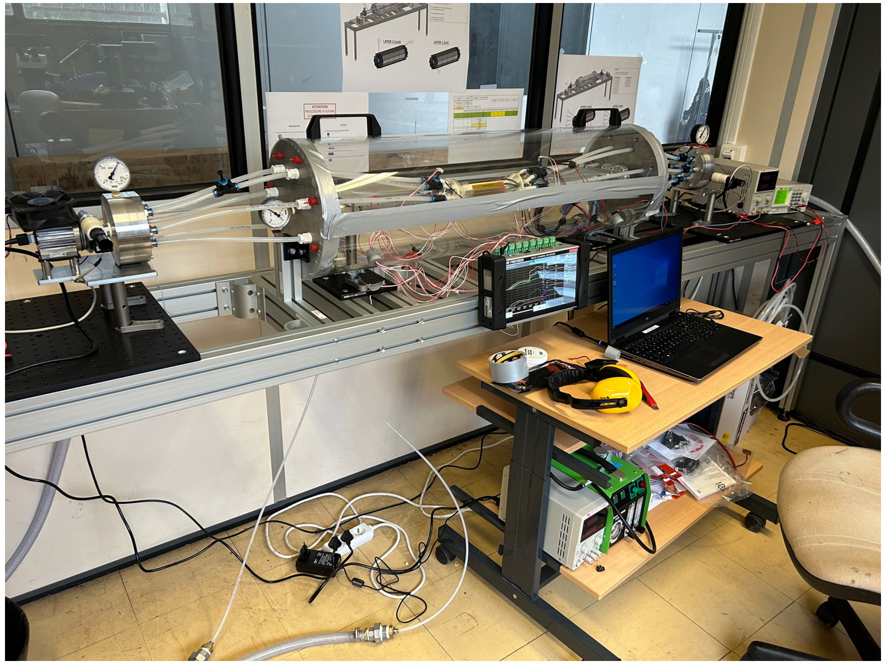


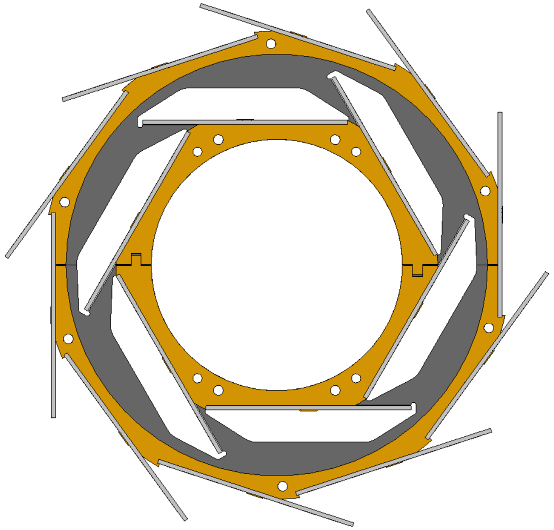
Configurable power routing and test points for I*R drop measurements

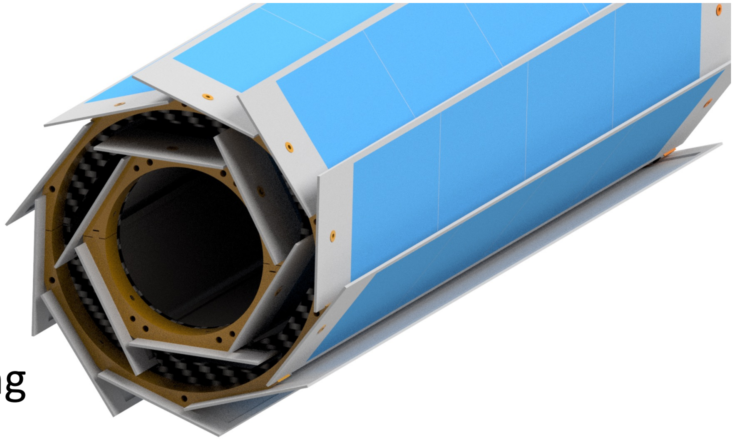
SMA connection for data lanes and and TDR measurements

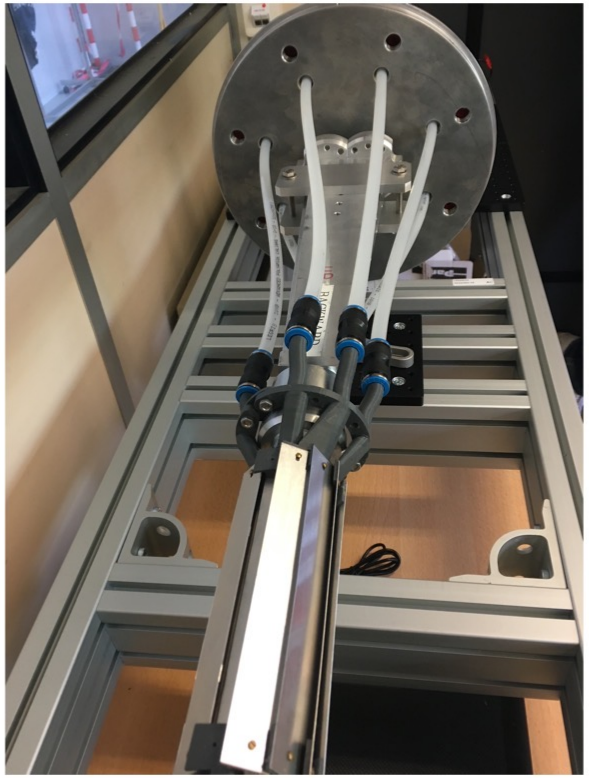
Also preparing a PCB mockup of the ladder to practice soldering etc

iVTX Integration and Cooling









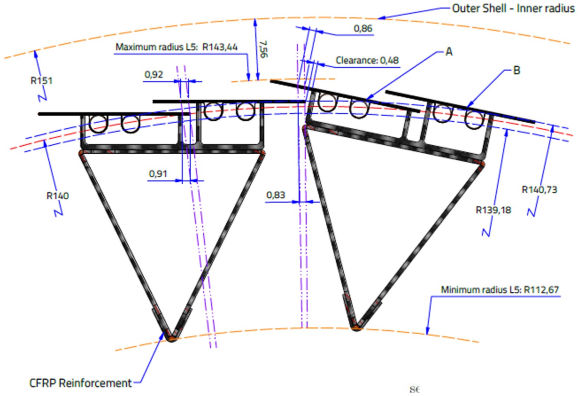
iVTX wind tunnel to study flow configurations

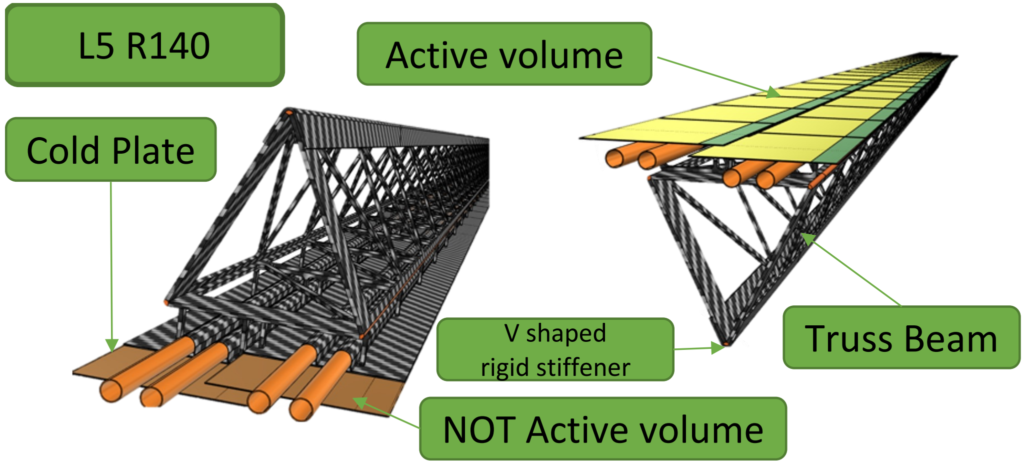
Air cooling feasibility still under study

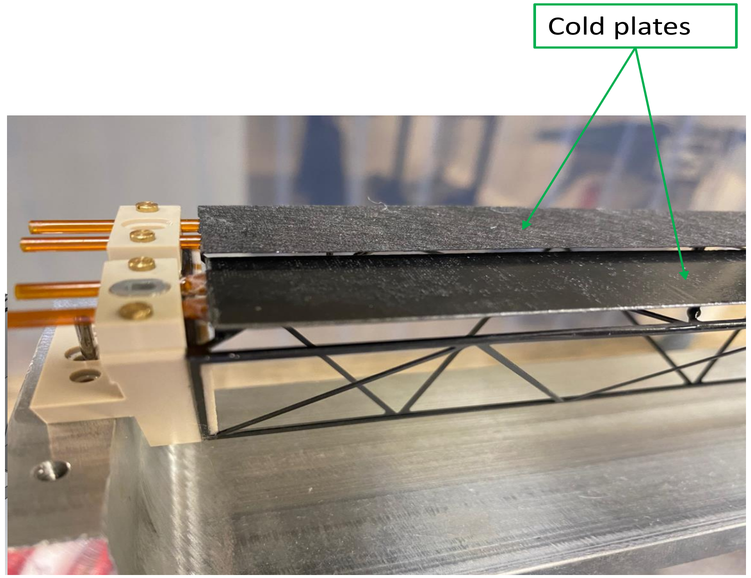
First ideas on ladder mounting and service routing

oVTX Stave Integration

Realistic CAD model, including overlaps







Studying thermomechanical properties with realistic models

Designing effort on production jigs and assembly procedures

Ladder concept compatible with X/X0 expectations (0.4-0.8%)

Layer 3 R69 Radiation length summary 2 flex from FW and BW side (6 + 6 chips) - 12 chips

COMPONENT	X/X0 (%)
Support Structure	0,087%
Cold Plate	0,064%
Pipes & Coolant	0,048%
Glue	0,022%
Flex (FW + BW)	0,150%
Chips	0,066%
Grand Total	0,438%

Layer 4 R89 Radiation length summary 2 flex FW and BW side (8 + 8 chips) - 16 chips

COMPONENT	X/X0 (%)
Support Structure	0,086%
Cold Plate	0,069%
Pipes & Coolant	0,048%
Glue	0,021%
Flex FW + BW	0,161%
Chips	0,067%
Grand Total	0,454%

Layer 5 R140 Radiation length summary 2 flex FW and BW side (12 + 12 chips) - 24 chips

COMPONENT	X/X0 (%)
Support Structure	0,169%
Cold Plate	0,093%
Pipes & Coolant	0,153%
Glue	0,127%
Flex FW + BW	0,186%
Chips	0,069%
Grand Total	0,796%

cmarinas@ific.uv.es