Upgrading Belle II with Depleted CMOS MAPS

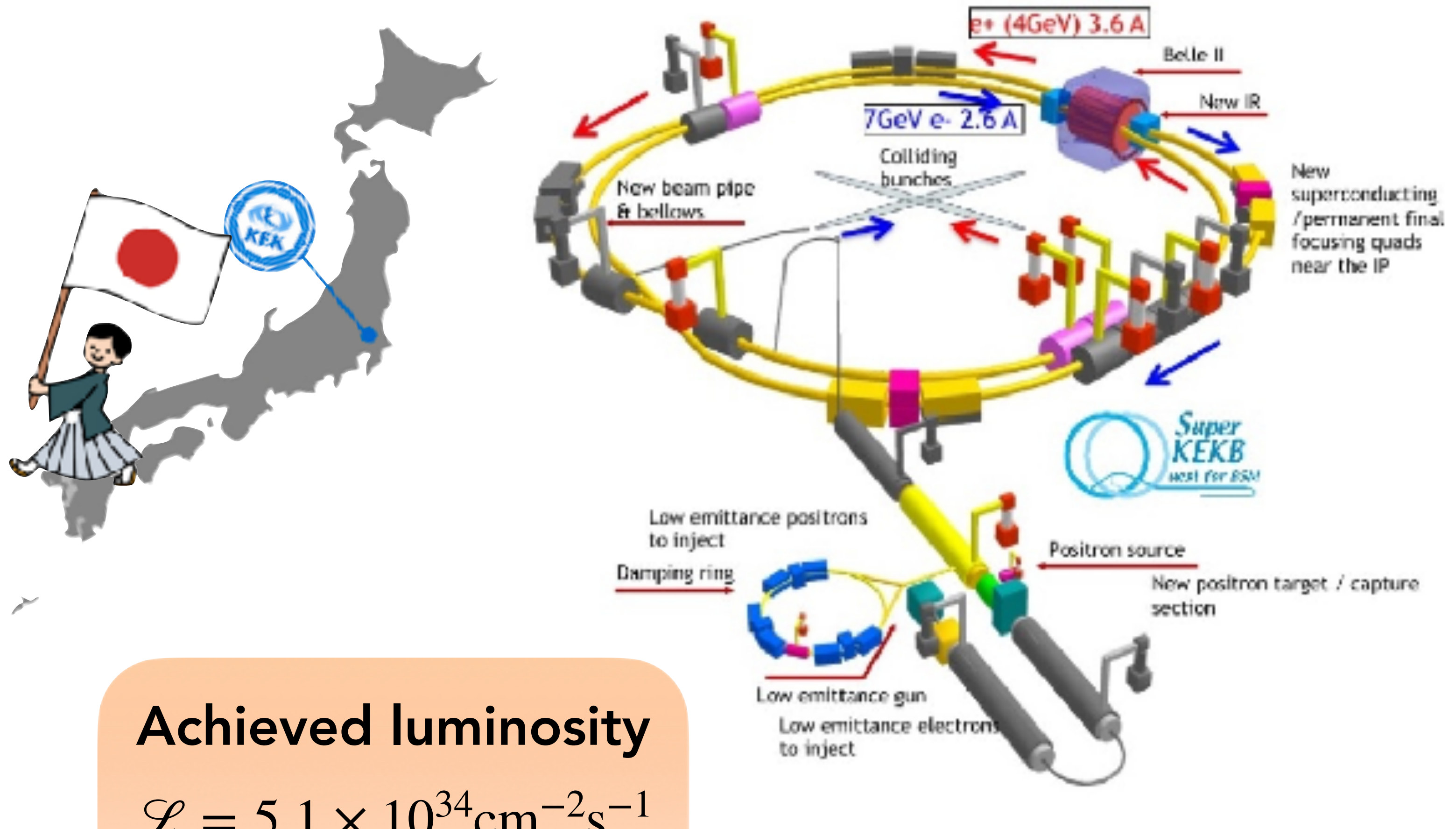
The OBELIX innovation

Alice Gabrielli on behalf of Belle II VTX collaboration

IFD 2025 - INFN workshop on Future Detectors
Sestri Levante, March 19th 2025

Belle II experiment and upgrade motivations

- Belle II searches for new physics beyond standard model at luminosity frontier.
- SuperKEKB e^+e^- collider in Japan → **aims at reaching higher peak luminosity but with challenging background conditions** for the current detector
- **At the target luminosity, the vertex detector VXD may reach its operational limits**



Achieved luminosity

$\mathscr{L} = 5.1 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\int \mathscr{L} dt = 530\,\mathrm{fb}^{-1}$

Target luminosity

$\mathscr{L} = 6 \times 10^{35} \mathrm{cm}^{-2}\mathrm{s}^{-1}$

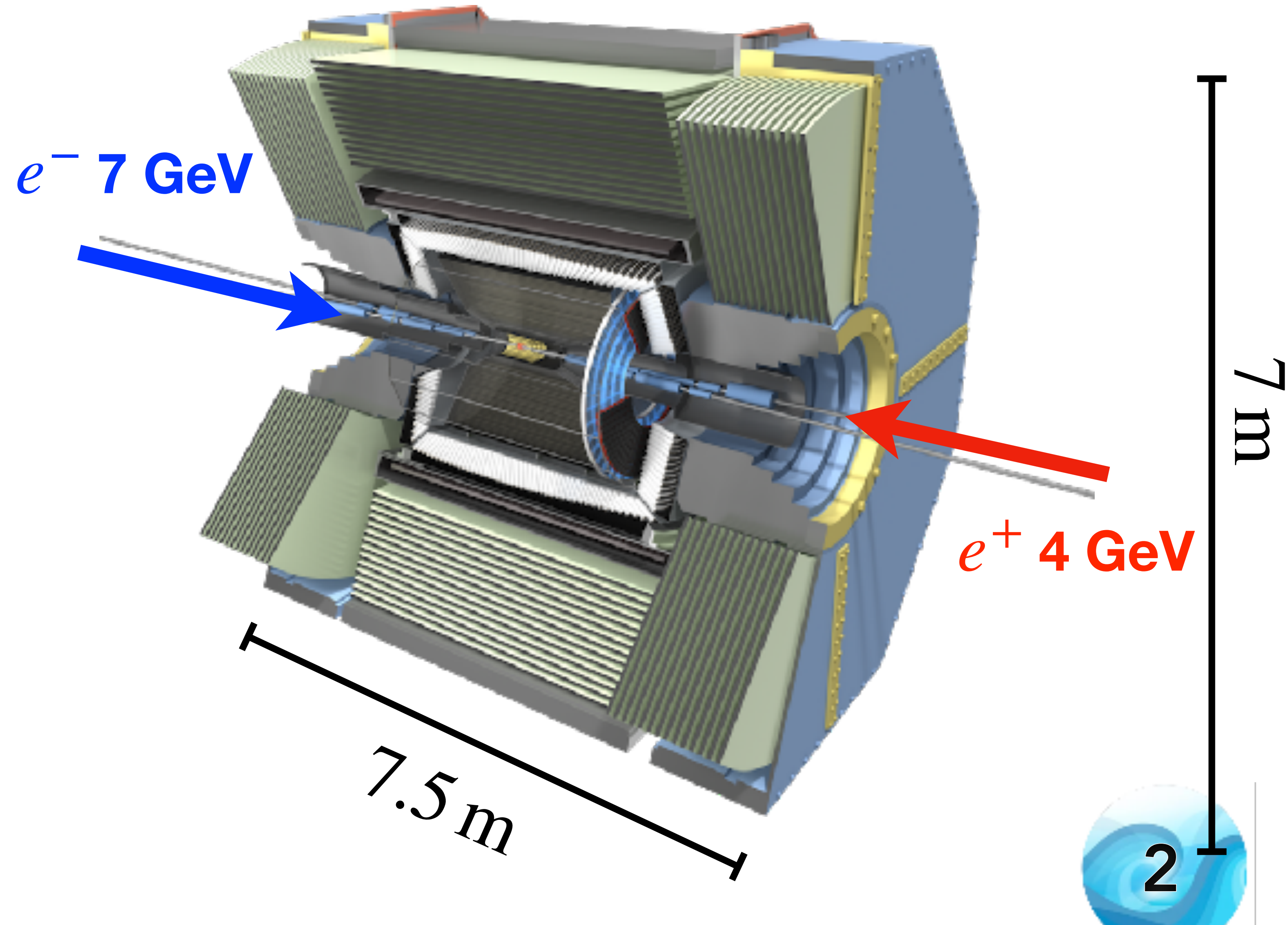
$\int \mathscr{L} dt = 50\,\mathrm{ab}^{-1}$

⇒ Need to improve tracking performance and robustness against background

Upgrade requirements:

- Hit rate up to 120 MHz/cm^2
- Fast time stamping 50-100ns
- Resolution <15μm → pitch of 30-40μm
- Aiming power dissipation ≤200mW/cm^2
- Operation simplicity and reduced services
- Radiation levels: TID~100 Mrad, NIEL~5 $\times$ 10^{14} neq/cm^2

Depleted Monolitich Active Pixel Sensors (DMAPS)



The new VTX and OBELIX

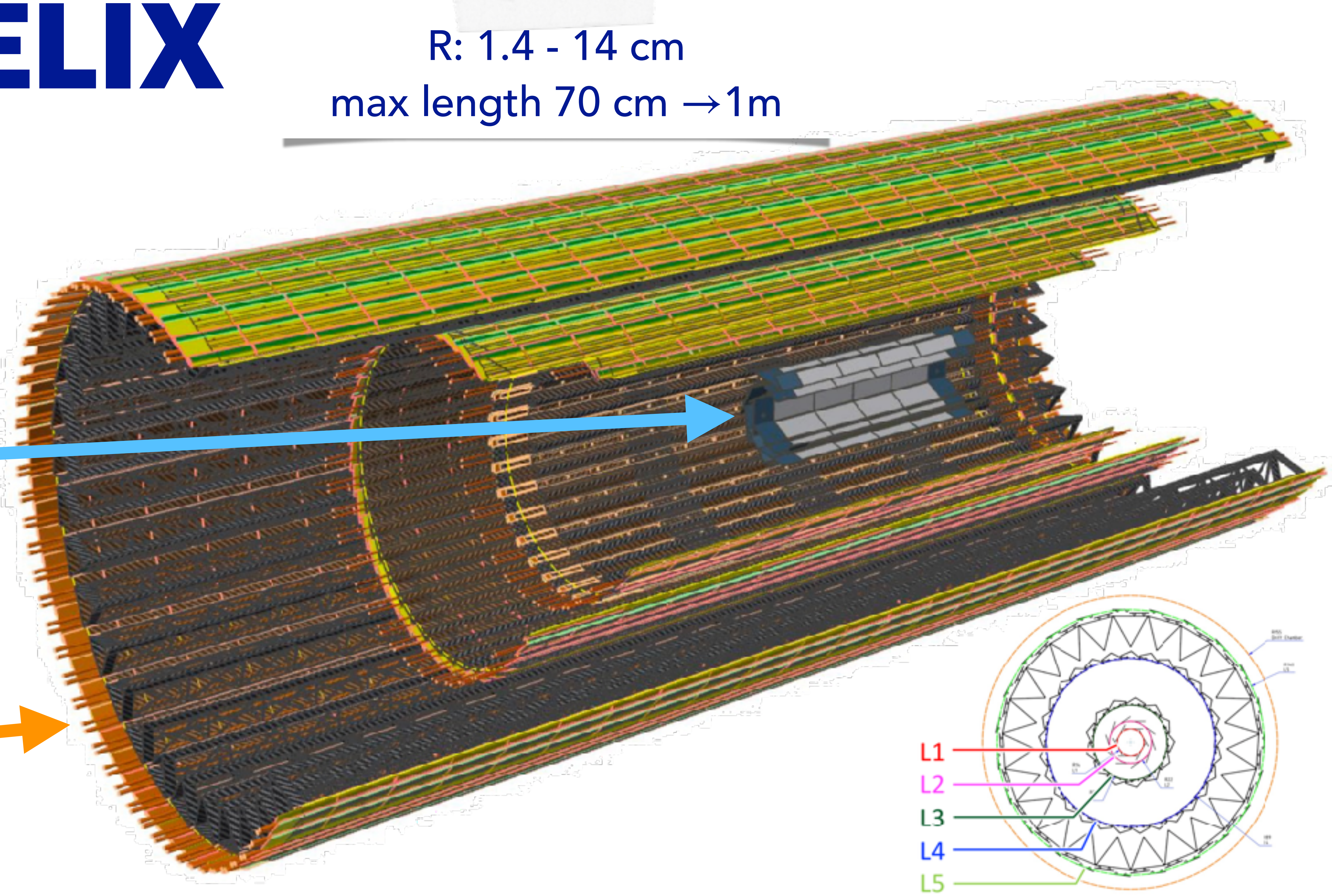
- **Baseline VTX layout with 5 straight layers with DMAPS pixel sensors**

iVTX (L1 & L2): all-silicon, self-supported, air/water cooled
→ 0.2-0.3 % X_0/layer

oVTX (L3 to L5): carbon fiber frame, water cooled
→ 0.3 - 0.8% X_0/layer

→ Total material budget reduced to 2.4% X_0 w.r.t. 3.5% X_0 of VXD

⇒Identical pixel sensor on all layers:
Optimized BELle II pIXel (OBELIX) chip



	L1	L2	L3	L4	L5	Unit
Radius	14.1	22.1	39.1	89.5	140.0	mm
# Ladders	6	10	17	40	31	
# Sensors	4	4	7	16	2 × 24	per ladder
Expected hitrate*	19.6	7.5	5.1	1.2	0.7	MHz/cm^2
Material budget	0.2	0.2	0.3	0.5	0.8	% X_0

**Large uncertainty on BG extrapolation/possible changes in IR region*

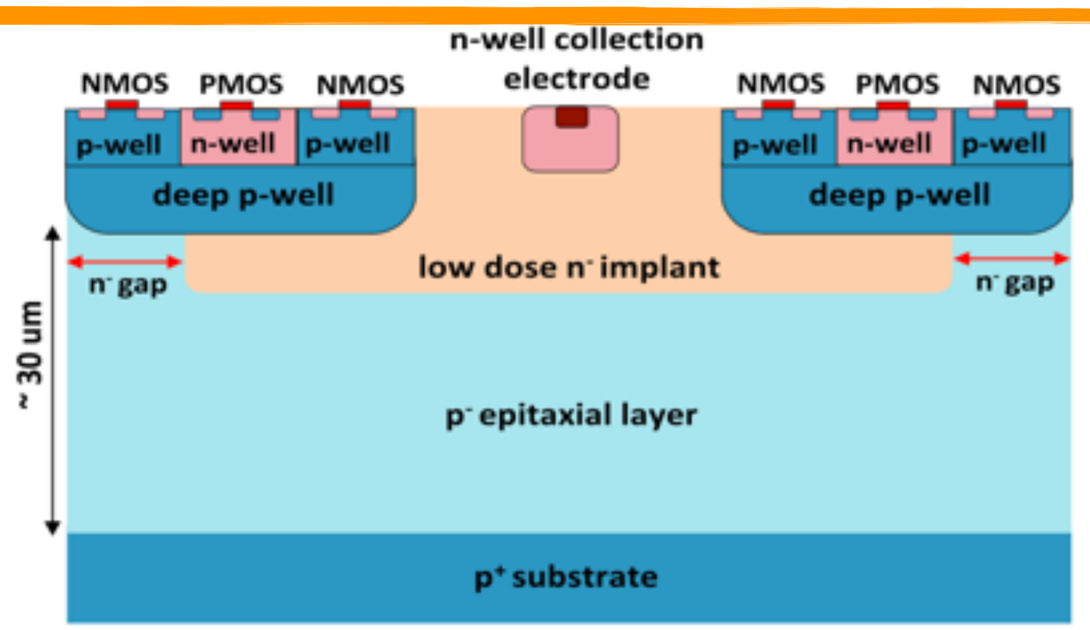
- Vertex detector (VTX) upgrade is under evaluation for LS2 (~2032)

OBELIX innovation

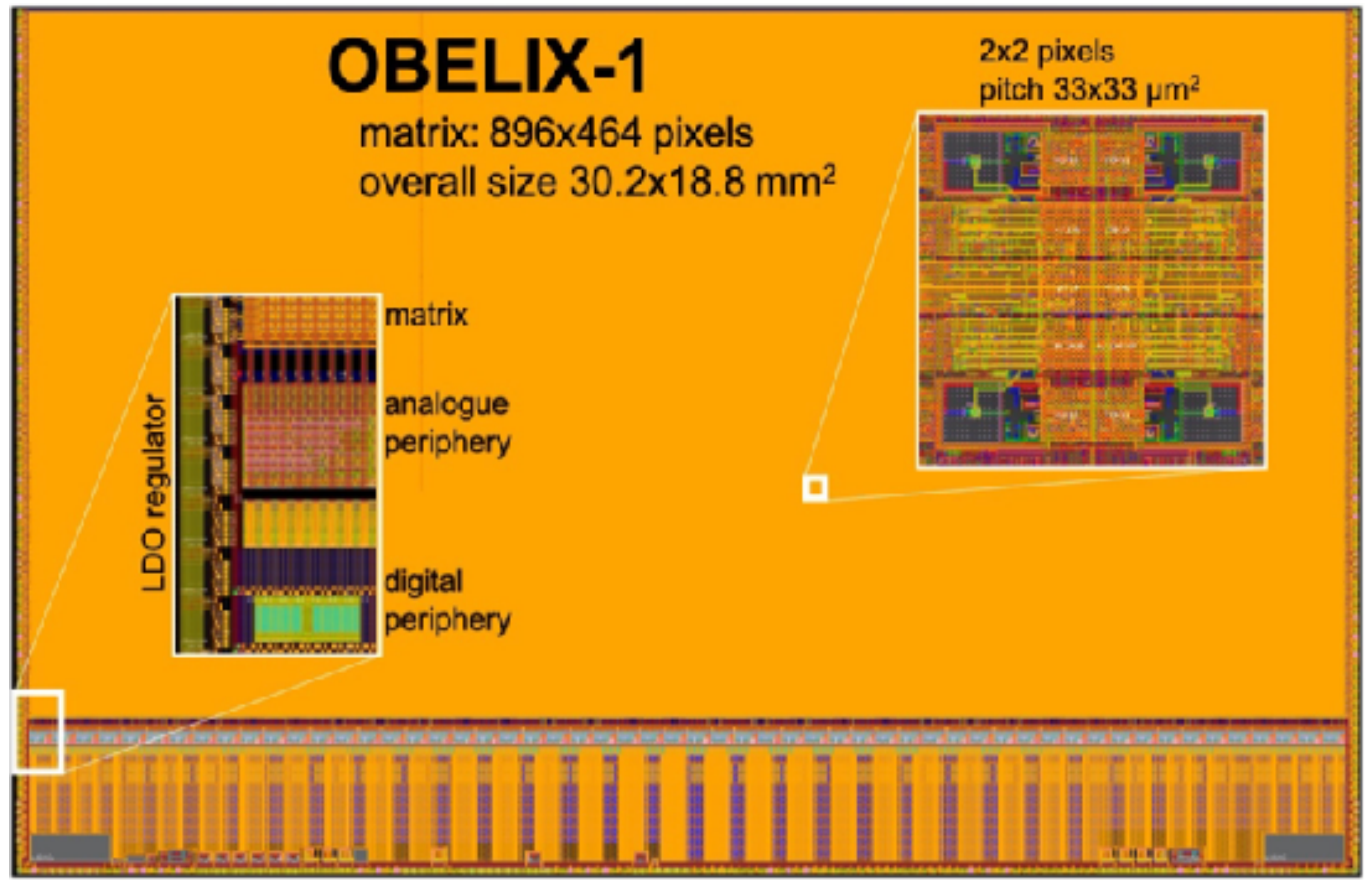
OBELIX specifications

Pitch	33 μm
Signal ToT	7 bits
Time stamping	50 to 100 ns
Fine time * stamping	~5 ns for hit rate <10 MHz/cm²
Hit rate max for 100% eff.	120 MHz/cm²
Trigger handling	30 kHZ with 10 μs delay
Trigger * output	~10 ns resolution with low granularity
Power (with hit rate)	200 to 300 mW/cm² (1 to 120 MHz /cm²)
Bandwidth	1 output 320 MHz

** optional features*



DMAPS
Tower Semiconductor
180 nm CMOS
modified process



Matrix inherit from TJ-Monopix2, size adjusted

⇒ Values obtained from post-layout simulations

OBELIX sensor design

Analog:

- Column drain architecture from TJ-Monopix2
- Monitoring ADC
- Temperature sensors

Power pads:

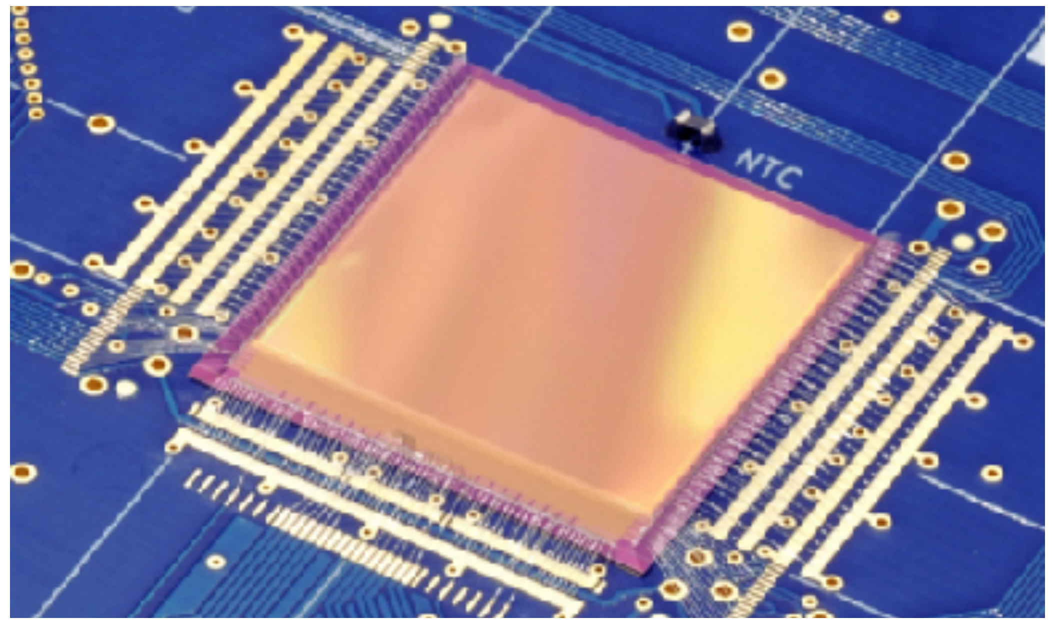
- On-chip LDOs voltage regulators

Digital periphery:

- Two new modules adapted for Belle II trigger:
  - ⇒ TRU: Pixel readout, trigger processing
  - ⇒ TTT: Fast transmission in parallel

- OBELIX design with new digital periphery with trigger logic for Belle II and optional features to allow Track Trigger capability and finer time-stamping for outer layer hits (low rate)
- First full scale prototype OBELIX-1sensor ready submission in summer 2025

TJ-Monopix2 - The Forerunner of OBELIX



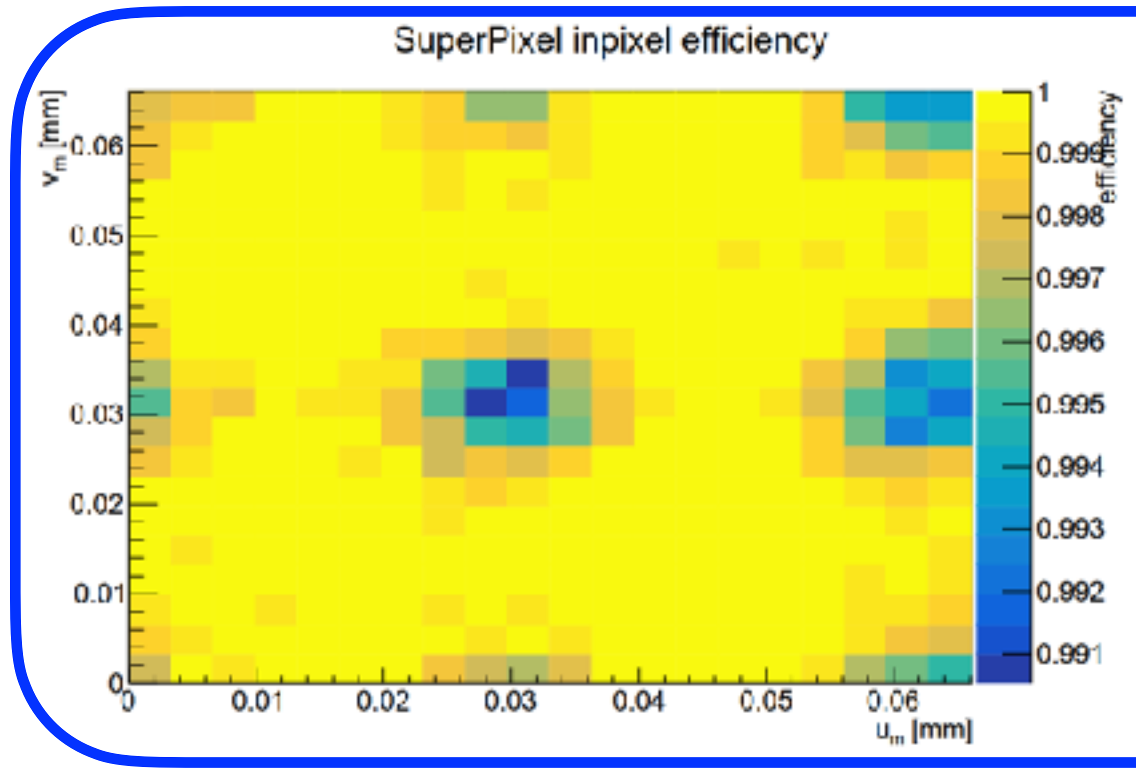
TJ-Monopix2 sensor bonded on a test board

DMAPS Tower Semiconductor 180 nm CMOS process but modified process to improve rad-hardness & faster readout

- 33x33 μm^2 pitch, 25 ns integration, large matrix 512×512 pixels (2×2 cm^2)
- Column drain readout capable to handle >> 120 MHz/cm^2 triggerless
- 7 bit ToT information, 3 bit in-pixel threshold tuning

Characterisation of TJ-Monopix2 for OBELIX

- Lab measurements vs. simulations to validate key performance
- Stable operation down to **THR ~250e^-**, THR dispersion**~17e^-**, noise **~8e^-**



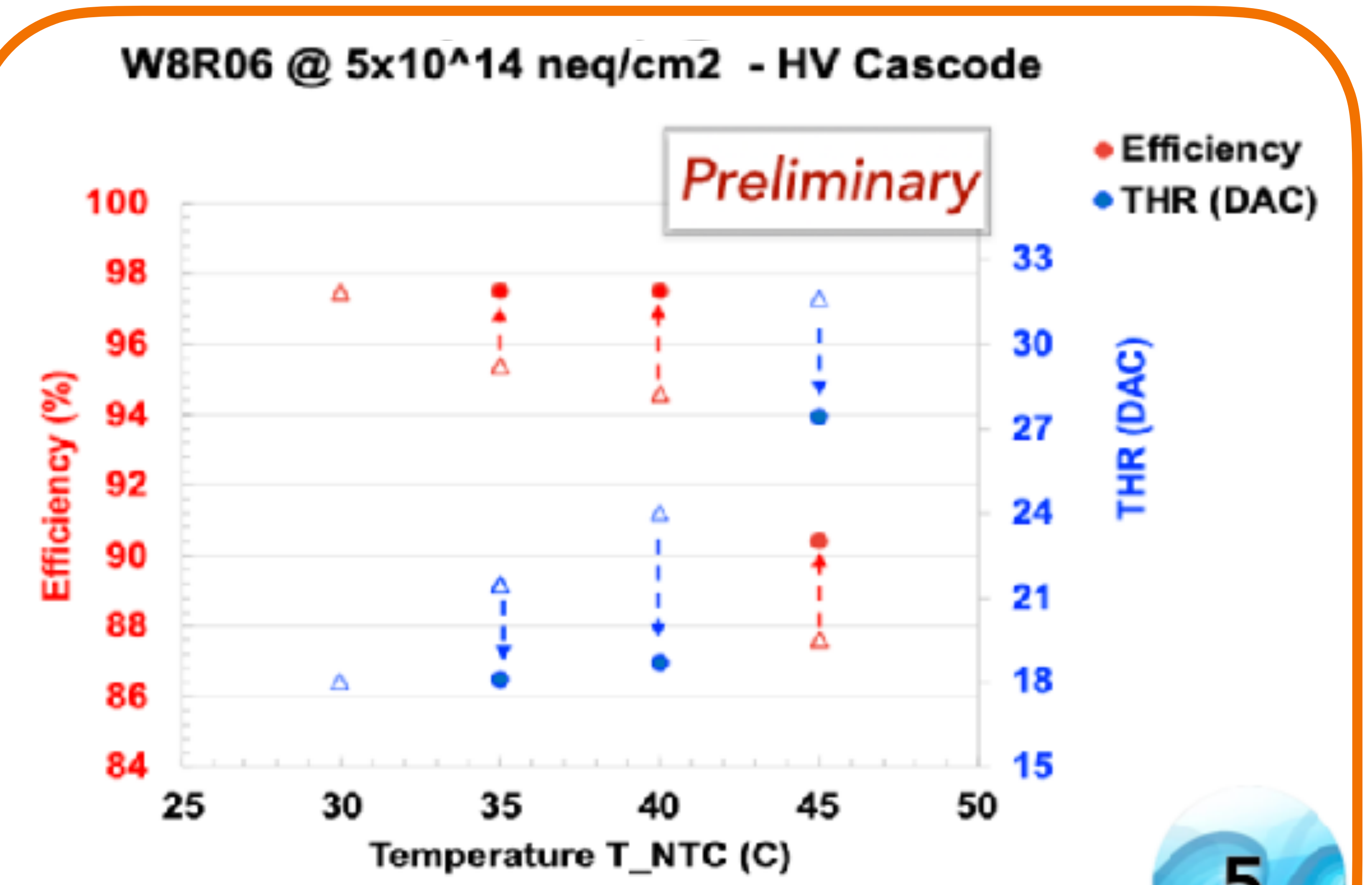
FE amplifier	Coupling	Efficiency [%]
Normal	DC	99.99
Cascode	DC	99.79
Normal	AC	98.11
Cascode	AC	99.13

- Multiple **beam tests @ DESY (3–5 GeV e⁻)** on irradiated & non-irradiated samples:

  TestBeam 2023: High efficiency post-irradiation (NIEL $5 \times 10^{14} n_{eq}/cm^2$, Troom) by increasing bias

  TestBeam 2024: Higher temperature after p-irradiation (NIEL $5 \times 10^{14} n_{eq}/cm^2$) leads to increased THR & noise, causing an efficiency drop

  TestBeam in March 2025 with improved temperature control will verify this behavior



★ chip temperature ~10/15°C higher than NTC temperature

Conclusions & Future Prospects

- **Belle II upgrade**: At **target SuperKEKB luminosity**, the current **VXD may reach its limits**, showing excellent performance but a limited safety margin at high background levels. A **DMAPS-based vertex detector (VTX) upgrade is under evaluation for LS2 (~2032)** to enhance robustness and tracking performance.
- **OBELIX development:** Based on **TJ-Monopix2 matrix** with an optimized digital periphery
- **Performance validation**: Extensive **lab testing & beam tests** confirm key parameters critical for OBELIX
- Next steps: First full-scale OBELIX-1 prototype submission in summer 2025
- **OBELIX is an important step forward in the development of next-generation vertex detectors.**

VTX collaboration

IGFAE, Santiago	*Jilin University*	*IJCLab, Orsay*	*IPHC, Strasbourg*
University of Bergamo	*KIT, Karlsruhe*	*RAL, Oxford*	*University of Tokyo*
IUniversity of Bonn	*IPMU, Kashiwa*	*INFN & University of Pavia*	*KEK, Tsukuba*
University of Dortmund	*Queen Mary University of London*	*INFN & University of Pisa*	*IFIC (CSIC-UV), Valencia*
University of Göttingen	*CPPM, Marseille*	*IFCA (CSIC-UC), Santander*	*HEPHY, Vienna*