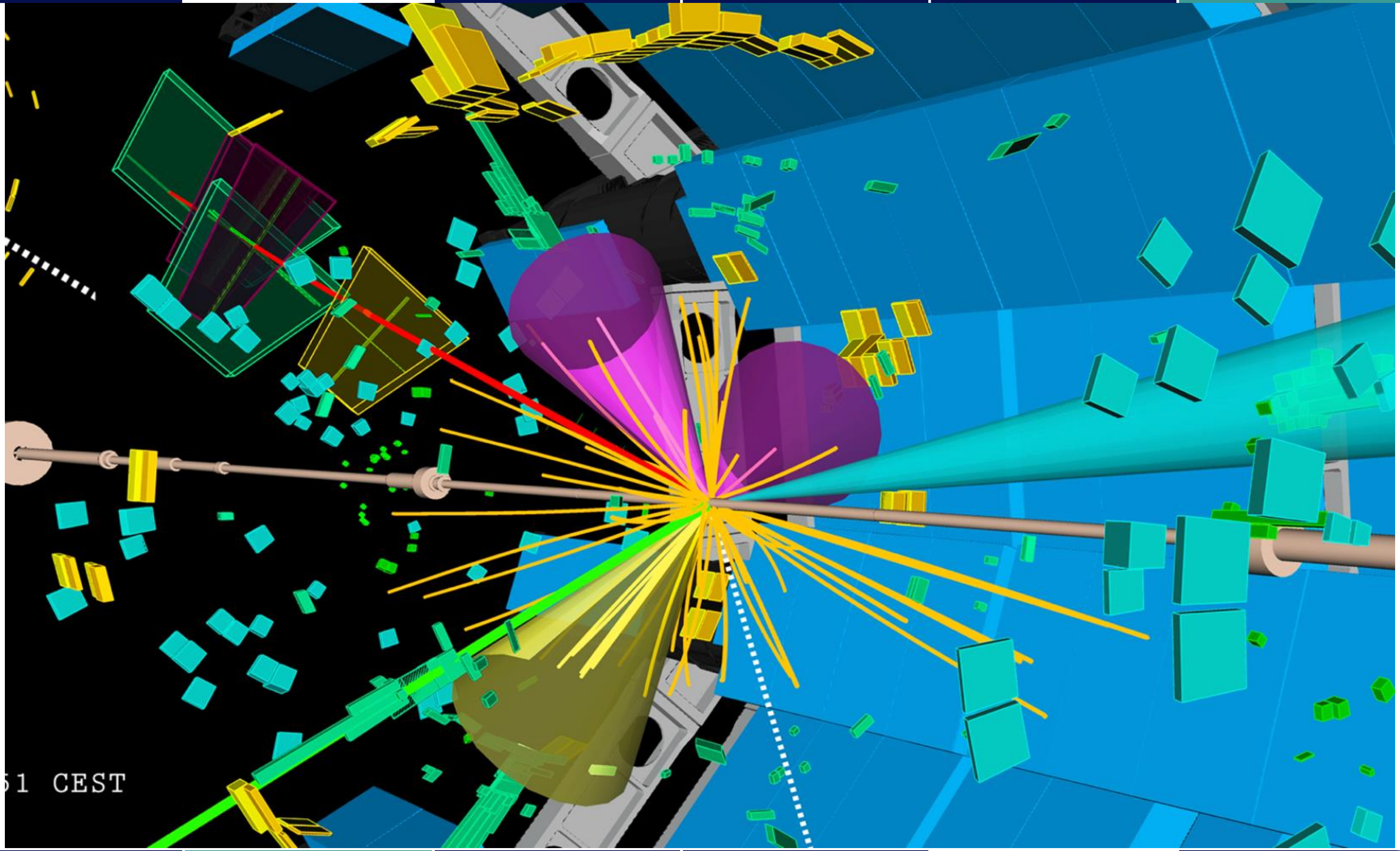


DRD4

F9 activities and role

Photon-detector R&D and particle identification

Rok Pestotnik

F9 retreat, Krvavec, 28-30 Sept 2026

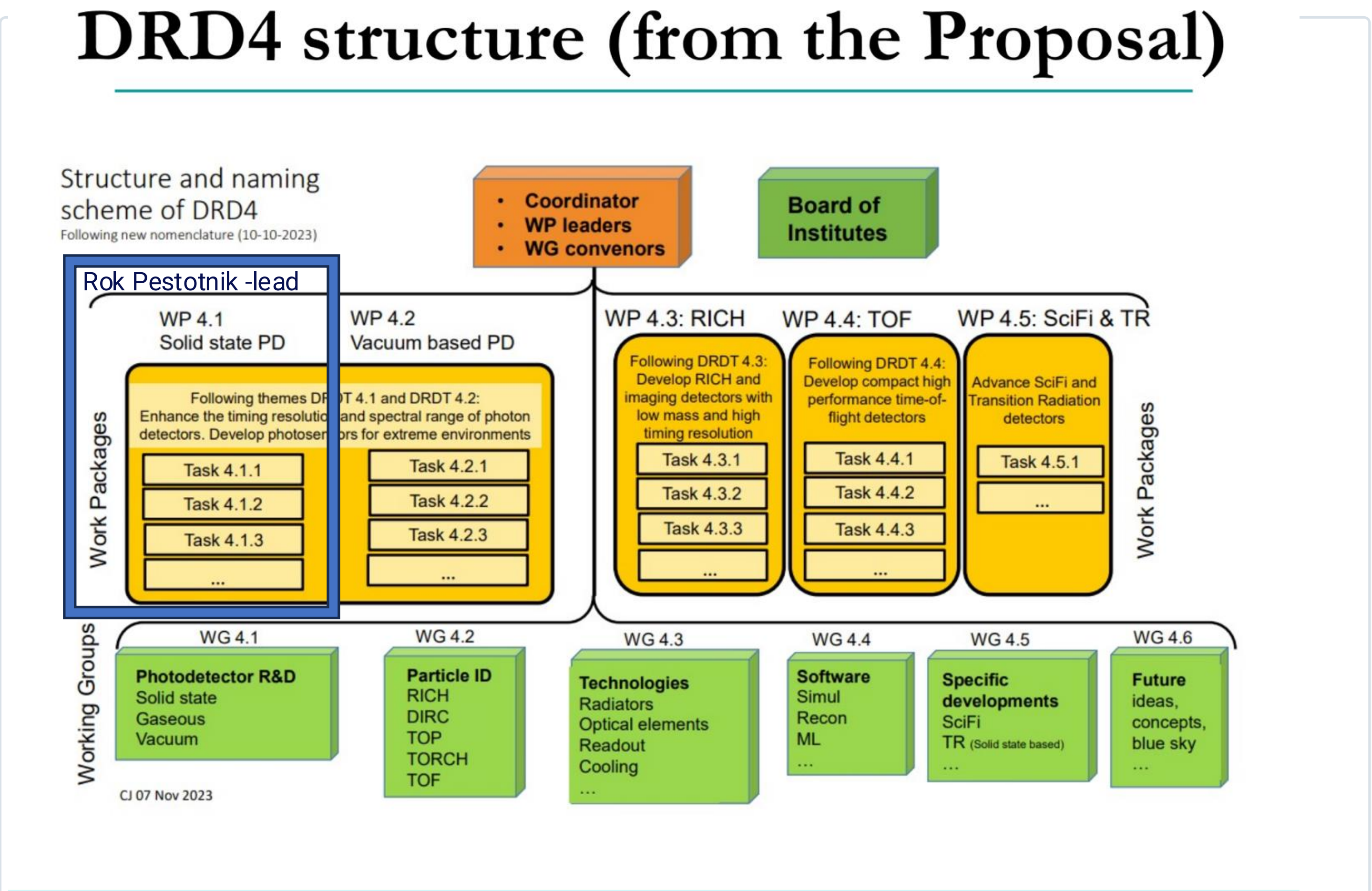
WP1 • WP2 • WP3

DRD4 and the F9 footprint

F9 participates in three of the five project-oriented Work Packages

Institut "Jožef Stefan", Ljubljana, Slovenija

Peter Križan and Christian Joram were mandated by ECFA to prepare the DRD4 launch



DRD4

International detector-R&D collaboration
70 institutions from 20 countries (2026)
5 Work Packages + 6 Working Groups

WP1 Solid-state photodetectors

WP2 Vacuum-based photodetectors

WP3 RICH & imaging detectors

Important for us: link between sensor R&D, sensor-electronics integration and complete PID detector systems.

Irradiation @ TRIGA (WP1) → **Characterization** (WP1) → **R&D CMOS SPAD / SiPM** (WP1) → **ASIC + integration** (WP1) → **Photon detector module** (WP2 / WP3) → **RICH / PID system** (WP3)

WP1 - the core F9 technology programme

Institut "Jožef Stefan", Ljubljana, Slovenija

From radiation damage to integrated single-photon detector systems

Irradiation & radiation hardness

Neutron / proton irradiation, annealing and operation after high fluence.

SiPM characterization

IV, DCR, gain and SPTR over a wide temperature range, including cryogenic operation.

Sensor + chip integration

2.5D / 3D integration, flip-chip, compact packaging, cooling and reduced parasitics.

Digital CMOS SPAD

Rad-hard digital SiPM concepts, fast in-pixel electronics, timing and reconfigurable readout.

WP1: Solid-State Photodetectors

- Task 1 - Demonstrator of BSI SiPM array
  - Development of back-side illuminated SiPM (potential for better PDE and radiation tolerance); development of ultra-granular SiPM that integrates with the electronics by using 2.5D or 3D interconnection techniques
- Task 2 - Demonstrator of CMOS-SPAD monolithic sensor
  - Implementation and characterization of CMOS-SPAD sensors for light detection in high energy physics
- Task 3 - Fast radiation hard SiPMs
  - Standardize procedures for quantification of radiation effects; irradiated SiPMs characterization in wide temperatures range (down to -200 ˚C); study of annealing; enable the use of SiPM in highly irradiated zones
- Task 4 - Timing of SSPD, including readout electronics
  - Study and improve the timing of SiPMs; co-design of a multi-ch. readout ASIC exploiting the timing potential; integration and packaging with integrated cooling; vertical integration of SiPM arrays to FEE (better timing via reduction of interconnections' parasitic inductances and capacitances)

WP1 Leader: Rok Pestotnik (Ljubljana)
Task leaders: Alberto Gola (FBK), Lodovico Ratti (Pavia), Rok Pestotnik, Andreu Sanuy (Barcelona)

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WP1 deliverables directly match the F9 competence chain

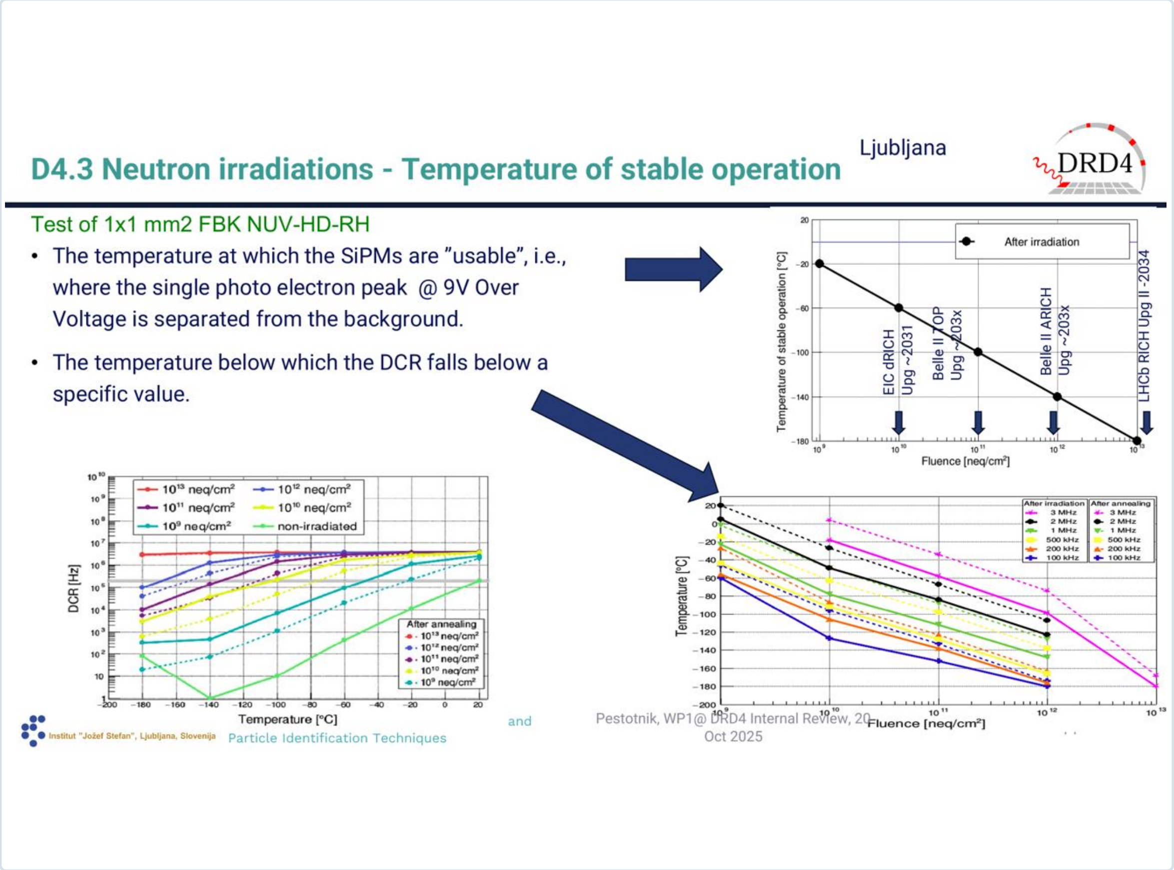
- radiation-hard SiPMs: **Boris Gardinovački**
- CMOS-SPAD monolithic sensors: **Rok Dolenec**
- ultra-fast SiPM + readout electronics: **Andrej Seljak**
- integration into demonstrator systems: **Andrej Seljak**

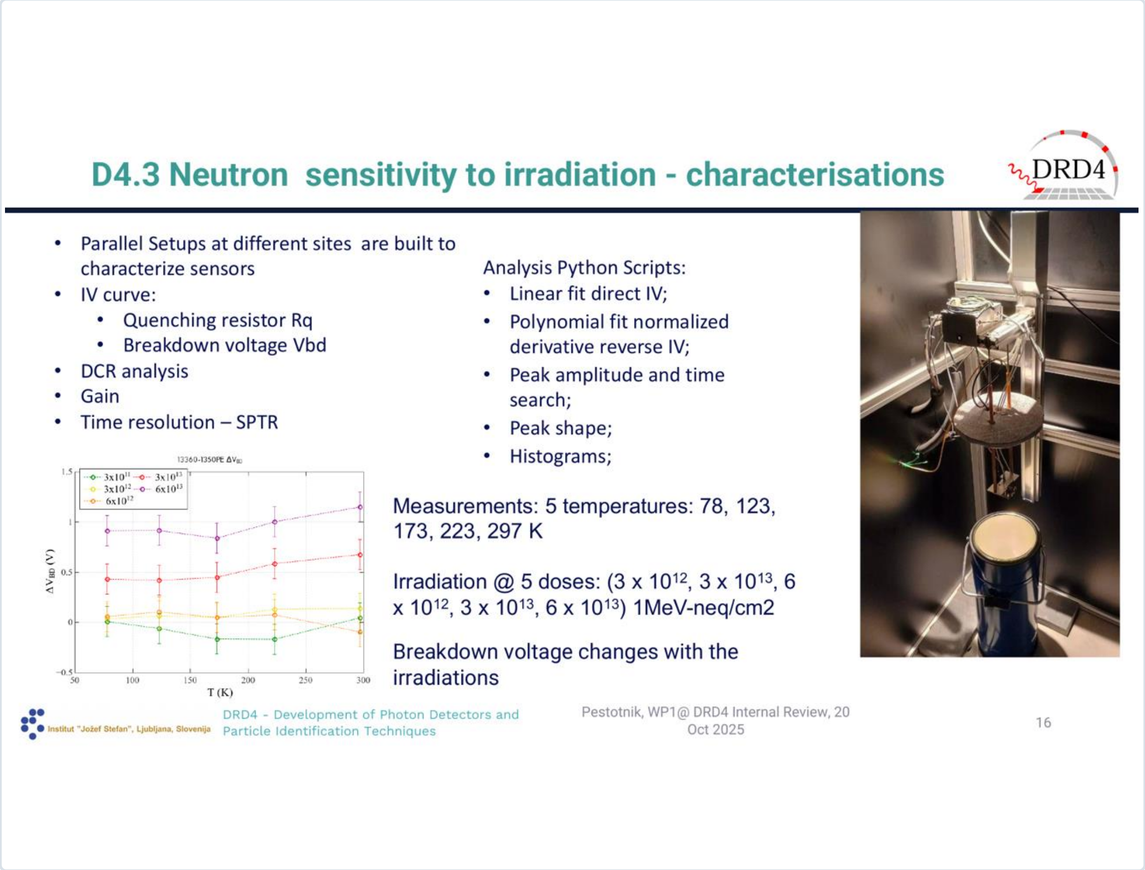
F9 strength: linking all four lines rather than treating them as separate activities.

Irradiation and characterization of SiPMs

Institut "Jožef Stefan", Ljubljana, Slovenija

A major F9 contribution to WP1 radiation-hard photon detectors





F9 workflow irradiation → IV / breakdown voltage → DCR → gain → SPTR → temperature of stable operation → annealing

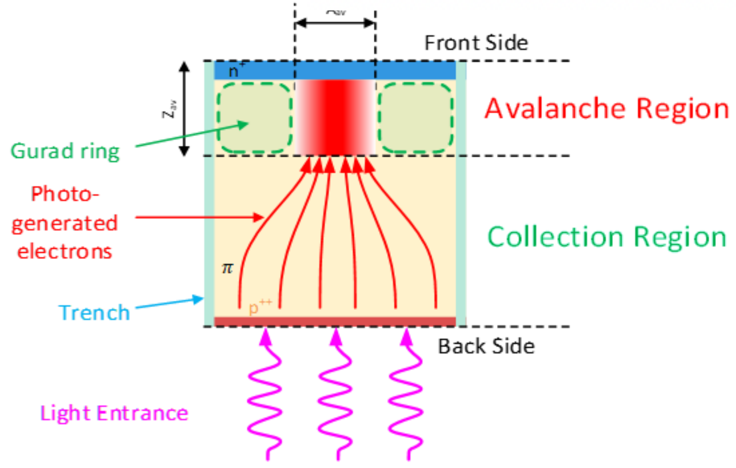
Backside-illuminated, NUV-sensitive SiPM

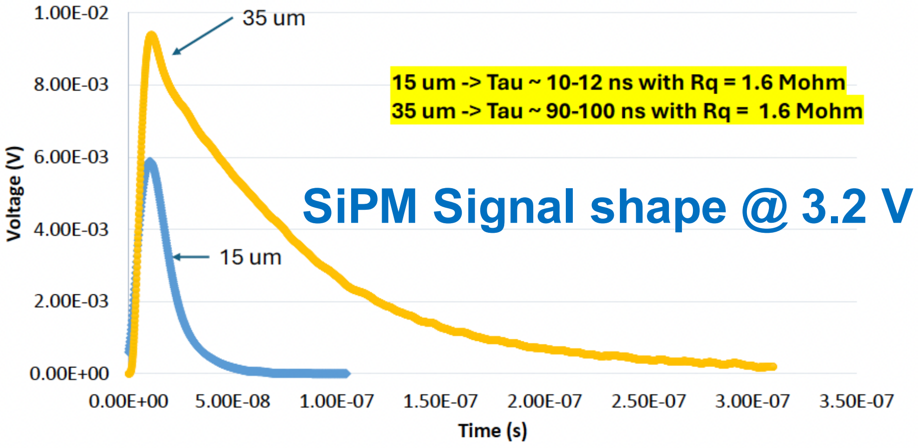
FBK CRS CUSTOM RADIATION SENSORS

Separation between charge collection and multiplication regions

Potential Advantages:
- **100 % FF** with maximum focusing factor of small cell sizes
- No need for vias, smaller SPADS -> High speed and dynamic range
- **Radiation hardness**
- **Uniform entrance window on backside: ideal for an enhanced optical stack for VUV sensitivity**
- Direct coupling of individual pixels to readout chip-> Integrated electronics

Cons:
More difficult to control Cross Talk and After Pulses
Timing performance may be degraded from difference in charge collection path length.

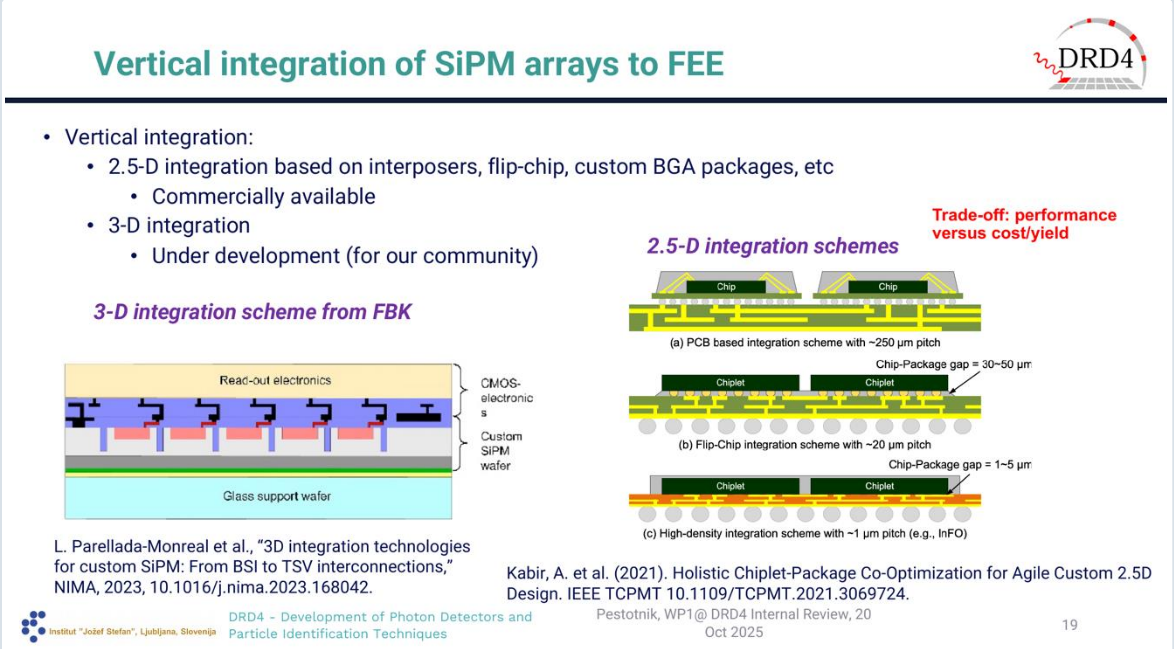




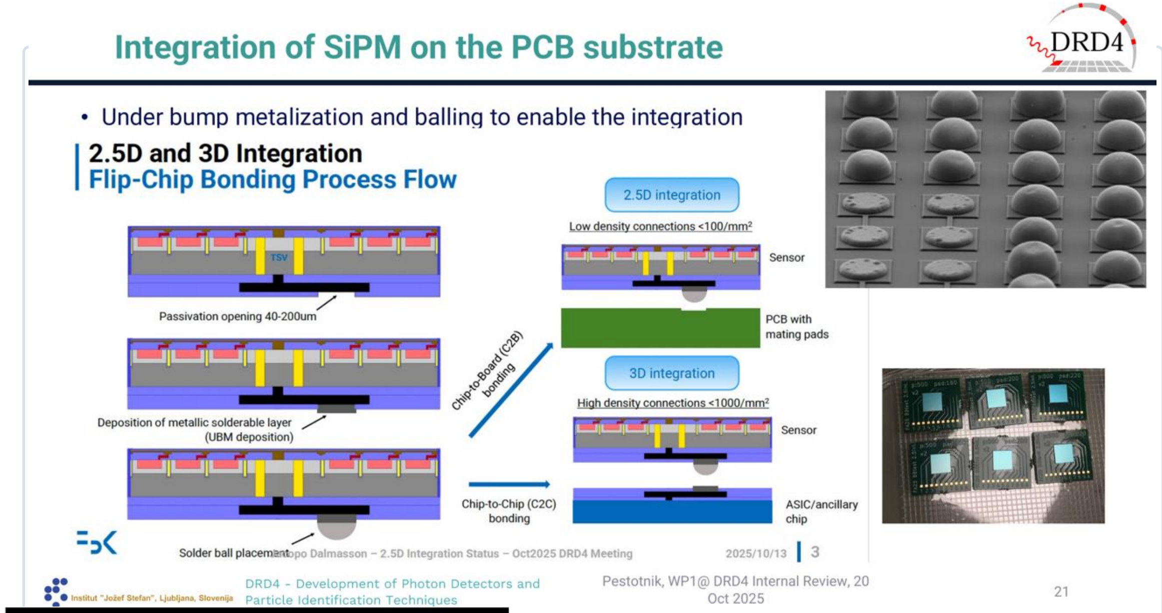
Integration of SiPMs with readout chips

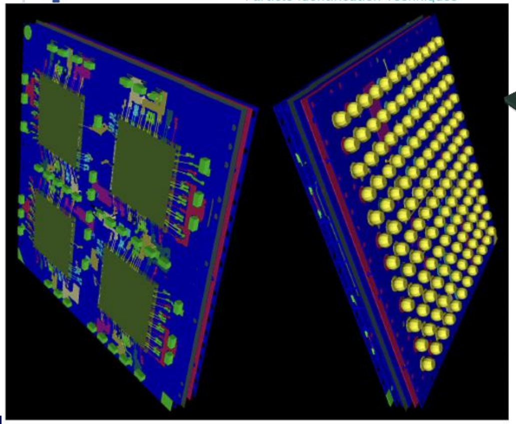
Institut "Jožef Stefan", Ljubljana, Slovenija

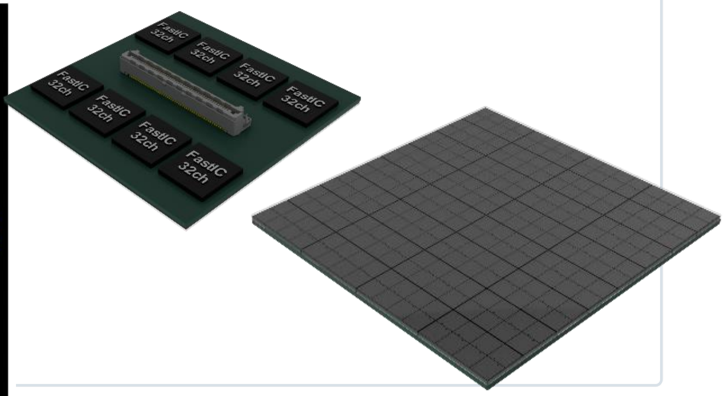
Moving from good sensors to compact, high-performance detector modules



I. FastIC+ BGA (32 channels) - chips integrated in a BGA package 11x11 mm2
- 12x12 pads (144 balls)
- balls of 0.3/0.35mm and pitch of 0.8mm
- 4x FastIC+ (3x3mm) + Passive components (01005 metric) + decoupling capacitors







Key issue: minimize interconnect parasitics while keeping the system manufacturable, coolable and testable.

Digital CMOS SPADs - spadRICH

Radiation-hard digital SiPM concepts for future RICH detectors

WP1: Solid-State Photodetectors

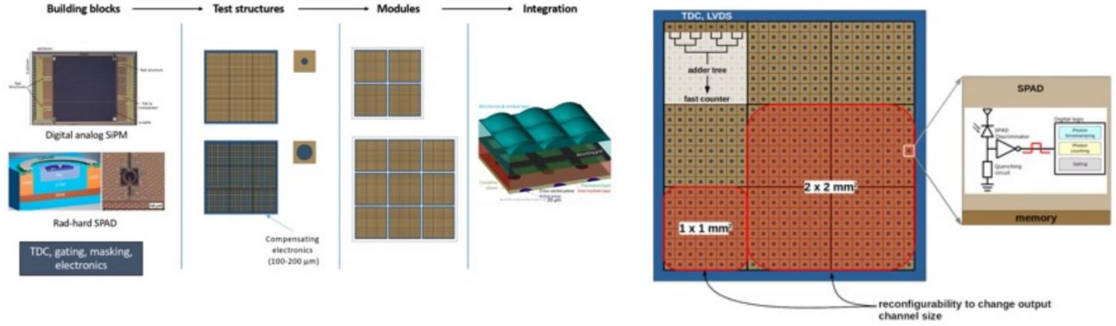
Examples of ongoing activities

CMOS-SPAD light sensors: co-integration of SPADs and electronics, digitised output signals

spadRICH - Radiation-hard digital analog silicon photomultipliers for future upgrades of Ring Imaging Cherenkov detectors

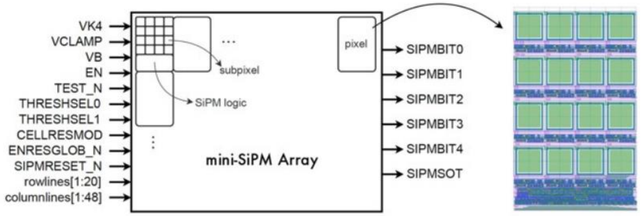
aqualab EPFL

Institut "Jožef Stefan" Ljubljana, Slovenija



ASPIDES -Development of a technology platform for the design, production and commissioning of dSiPMs

INFN Istituto Nazionale di Fisica Nucleare



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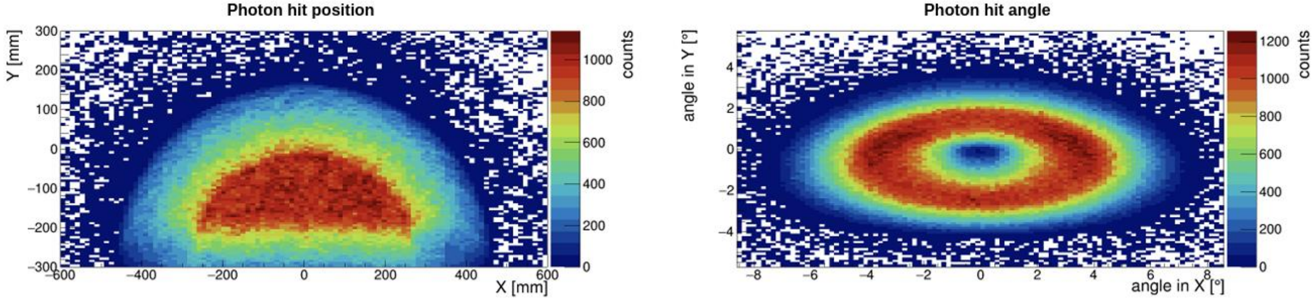
F9 focus

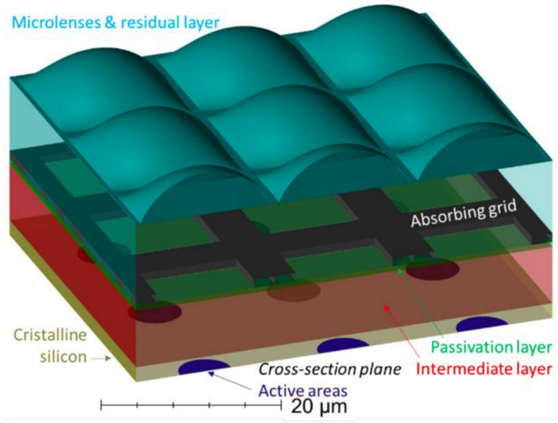
- digital / analog SiPM architecture
- radiation-hard CMOS SPADs
- fast front-end and timing
- microlens / optical concentration
- integrated digital readout
- direct relevance to LHCb RICH and future PID

EPFL + JSI + UL + UM

Microlenses on top of SPADs for RICH applications

- Simulated photon spatial and angular distributions at the upper LHCb RICH1 photodetector plane



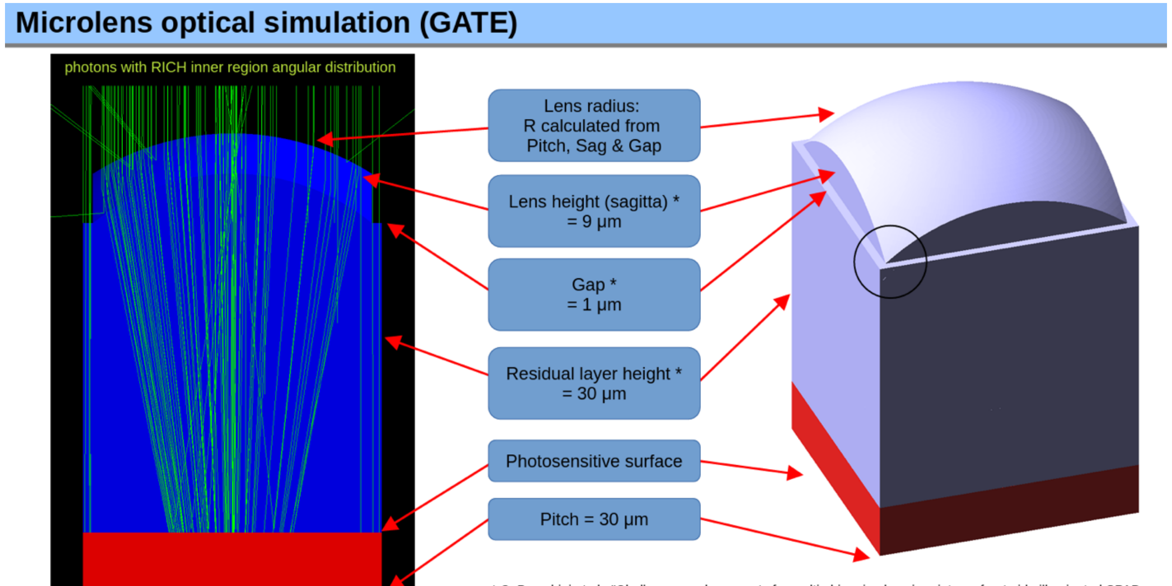


Microlenses can efficiently concentrate
I→ enable smaller SPAD active area

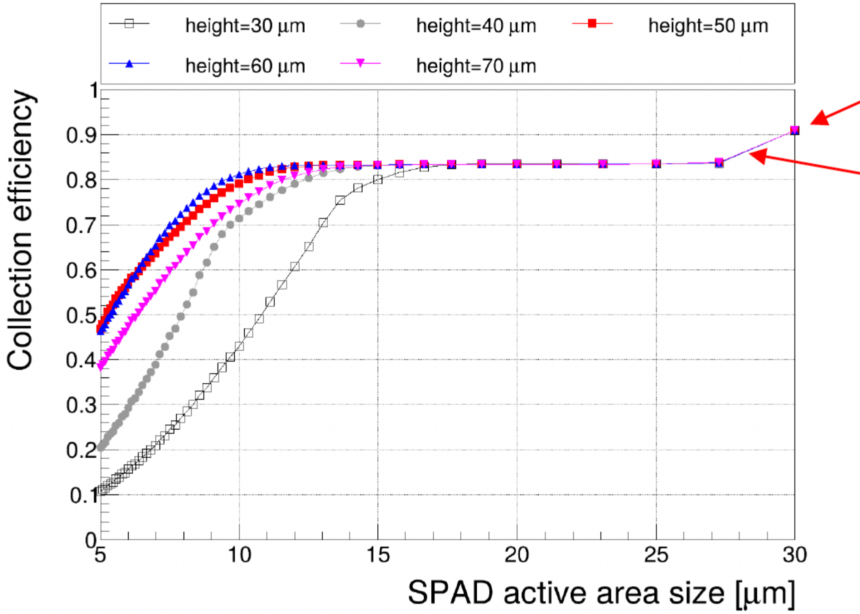
- improved neutron hardness
- space for integrated electronics, guard rings

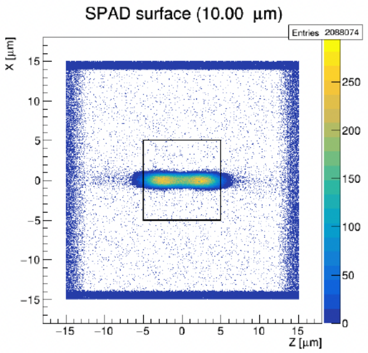
Simulated microlens optics: optical stack of the CMOS process

And SPAD junction depth in silicon not included



* C. Bruschini et al., "Challenges and prospects for multi-chip microlens imprints on front-side illuminated SPAD imagers," Opt. Express 31, 21935-21953 (2023). https://doi.org/10.1364/OE.488177



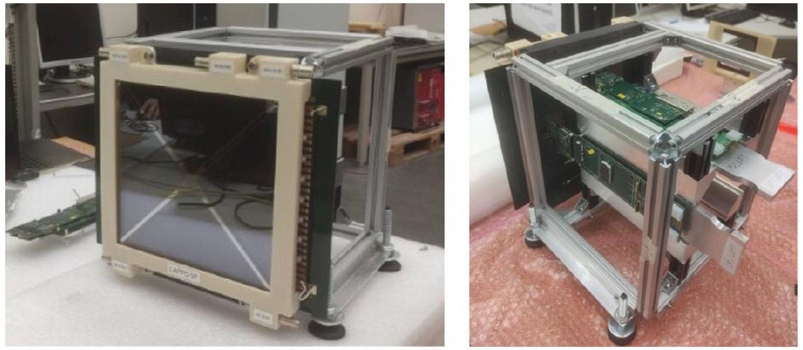


WP2 - vacuum-based photodetectors

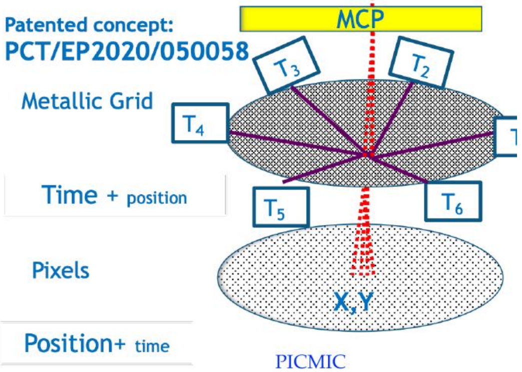
F9 participation links large-area fast photon sensors to Belle II upgrade studies

DRD4 and FCC: photodetectors

- Photon detectors with improved performance: MCP-PMTs
  - Longer lifetime and higher instantaneus rate; Higher photodetection efficiency; Large area; Integration with electronics
- Examples:
  - Large Area Picosecond Photo-Detector (LAPPD)
    - Cover large areas with fast-timing capability (20 cm square); HRPPD (10 cm square) with no support structures in window for higher rates
  - Diamond transmission dynode (MCP alternative): increase lifetime and rate
  - Read-out systems (e.g. PICMIC, Timepix4) to fully exploit excellent intrinsic time and position resolution of MCPs



LAPPD



PICMIC

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Why WP2 matters for F9

Large-area MCP-based photodetectors – fastest response

F9 activity

INCOM LAPPD studies for the Belle II Upgrade, connecting vacuum-photodetector R&D with particle-identification needs.

- **Samo Korpar**
- **Trey Frank Grijalva**
- **Connor Pecar**
- **Rok Pestotnik**

WP2 also develops MCP-PMT lifetime/rate capability, new photocathodes and integrated readout.

WP3 - RICH and other imaging detectors

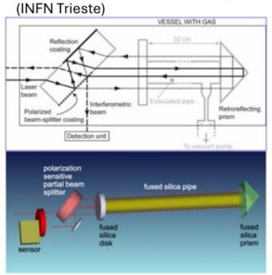
Where sensor R&D becomes a particle-identification system

WP3: RICH and other imaging det.

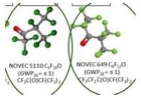
Examples of ongoing activities

- **WP4.3.1:** New Materials Radiators and Components
Study of novel and optimized radiators, including gas alternatives to perfluorocarbons and enhanced aerogel tiles, along with the development of advanced instrumentation and techniques for the characterization, quality assessment, and monitoring of Cherenkov radiators.

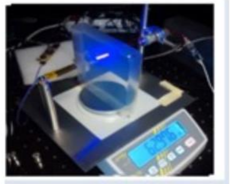
Modified folded Jamin interferometer for gas refractive index monitoring (INFN Trieste)



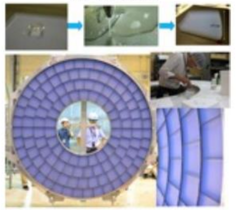
Study of gas alternatives to perfluorocarbons or eco-friendly fluorocarbon gas system



Optimized Aerogel Radiator Tiles



INFN Ferrara

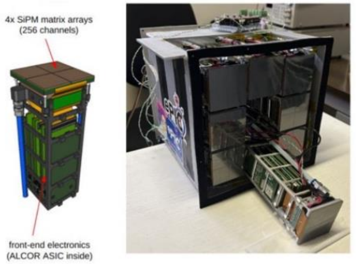


Jozef Stefan Institute

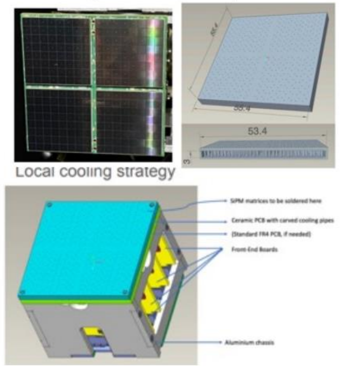
- **WP4.3.2:** Development of new RICH detector concepts for improved performance.
  - Several new concepts and detector designs under consideration including a pressurized RICH with inert gasses like Argon as a possible alternative to fluorocarbon greenhouse gases.

- **WP4.3.3:** Prototype Single-Photon Sensitive Module for Imaging Arrays from sensor to DAQ and self-calibration systems.

EPIC dRICH prototype SiPM module (INFN Bologna)



Prototype SiPM Housing with local cooling (Uni and INFN Genova)



- **Samo Korpar**

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F9 / JSI in WP3

- optimized aerogel radiator tiles
- RICH detector-component studies
- photosensor modules and cooling
- direct feedback from LHCb / Belle II PID requirements to WP1 sensor R&D

WP3 is the system-level bridge between photodetector technology and experiments.