DRD project: Fine-pitch CMOS pixel sensors with precision timing for vertex detectors at future Lepton-Collider experiments

DRD technology areas and working groups

The project targets the technology area DRDT 3.1 - *Achieve full integration of sensing and microelectronics in monolithic CMOS pixel sensors*. It will therefore mainly be performed within DRD3 WG 1 - *Monolithic CMOS sensors*. Support for access to the chosen imaging technology and the related design and testing tools, as well as ASIC design, validation and submission support is expected to be provided by DRD7 WG 7.6 (*Complex imaging ASICs and technologies*) and DRD7 WG 7.7 (*Tools and technologies*). The design expertise and IP blocks developed within the project will be made available to the community in the context of DRD7 WG 7.6.

Proposing participants and contributions

Institute	Contact	Foreseen main areas of contribution
APC Paris	M. Bomben	Simulations, testing
CERN	D. Dannheim	Testing, DAQ, ASIC design support
DESY	S. Spannagel	ASIC design, testing, DAQ, simulations
IPHC Strasbourg	A. Besson	ASIC design, testing
Oxford University	D. Hynds	Testing, simulations
Zurich University	A. Macchiolo	Testing, DAQ, simulations

A total of 5 FTE ASIC designers and 10 FTE physicists and test engineers are currently foreseen to be made available in the participating institutes. The proposal is open to additional collaborators and contributions.

Development targets and strategy

The physics goals and experimental conditions at high-energy Lepton Colliders (LC) result in stringent requirements for the silicon vertex detectors. High spatial and temporal measurement accuracy needs to be combined with very low mass and power consumption, and the readout scheme needs to be optimized for the expected duty cycle and background particle rates at the different accelerators. This proposal concerns the development and evaluation of monolithic fine-pitch pixel sensors implemented in advanced CMOS imaging processes, targeting the LC requirements as outlined in the ECFA detector roadmap. Key development targets include ~3 μm single-point resolution, down to ~5 ns time resolution as required for some of the LC proposals, thinning to below 100 μm, an average power consumption below 50 mW/cm^2, a minimal inactive periphery area, and a sensor architecture scalable to a large-area detector system.

A new generation of low-mass high-resolution beam-telescope sensors is needed to support the various ECFA detector-roadmap developments and to provide accurate reference measurements. The precision requirements for these instruments are similar to the ones for lepton-collider vertex detectors, while the constraints on the power budget and periphery area can be relaxed. It is therefore foreseen to develop high-resolution beam-telescope sensors as an intermediate target in a first R&D phase. In a second phase, the developed sensor architecture will be adapted and further optimized in terms of power consumption and periphery area towards the LC requirements.

The proposed staged approach allows for a further refinement of the development targets for the later LC-focused stages, following the conclusions of the next update of the European Strategy for Particle Physics (2027/28). In particular, the choice of the accelerator technology for the lepton collider (linear or circular, with a significant difference in duty cycle) will affect the sensor power-reduction strategy and the trade-off between low power consumption and high timing precision for the rejection of beam-induced background particles. The first-stage development of a beam-telescope sensor relaxes the low-power requirement and therefore allows for an investigation of the technology and optimization of the sensor performance in terms of the other requirements, namely time and spatial resolution.

Foreseen activities, milestones and deliverables

The following activities, milestones and deliverables with indicative completion dates are foreseen towards the final project goals:

- Characterisation of recently produced monolithic pixel sensor demonstrators with small collection electrodes implemented in the modified TPSCo65 CMOS imaging process with 65nm feature size (APTS, DPTS, H2M, CE65v2, DFE) in laboratory and test-beam measurements. Comparison of the observed performance to simulations as well as the requirements of beam-telescope sensors and lepton collider vertex detectors.

  Milestone 1: report on characterisation results for each of the demonstrators. [end 2024]
- Design of a small demonstrator pixel matrix (<= 64 x 64 pixels) in TPSCo65, targeting the requirements of beam-telescope sensors. Main features: pixel dimensions compatible with position resolution of 3 μm in both directions; per-pixel arrival-time measurement at the few-nanosecond level; readout of digitized hits with an architecture that is scalable towards instantaneous

particle-hit rates of up to approximately 50 MHz/cm^2. Alternative pixel geometries, such as hexagons, will be studied in terms of time and position-resolution benefits. Design to be based on the results obtained with the previously characterized demonstrators (Milestone 1) and optimized using TCAD and Allpix-Squared Monte Carlo simulations. More advanced technologies under study within DRDT 3.4 (Develop full 3D-interconnection technologies for solid state devices in particle physics) will also be considered, in case they become available as cost-effective Multi-Project-Wafer (MPW) submissions. Submission for production in a shared run, targeting the EP R&D WP 1.2 MLR2 submission scheduled for end 2025. Design and production of readout printed-circuit boards compatible with the Caribou modular DAQ system.

Deliverable 1: beam-telescope demonstrator matrix available for testing. [beginning of 2026]

- Integration of the beam-telescope demonstrator matrix in the Caribou DAQ system. Characterization in laboratory and test-beam measurements. Comparison of the observed performance to the requirements of beam-telescope sensors and LC vertex detectors.

  Milestone 2: report on characterisation results for the beam-telescope demonstrator matrix [end 2026].

- Evolution of the beam-telescope demonstrator design to a full-size telescope sensor matrix (>= ~2 cm^2) with all features required for beam telescope sensors. Target technology: same as demonstrator matrix. Submission in a shared engineering production run. Design and production of readout printed-circuit boards compatible with the Caribou modular DAQ system and with existing beam-telescope infrastructure. Commissioning of the sensors in laboratory and test beams.

  Deliverable 2: beam-telescope sensors available for integration in existing telescopes [mid 2028].

- Further development of the beam-telescope sensor architecture towards low power consumption and minimal periphery area, compatible with the requirements for LCs. Design of a full-size LC sensor demonstrator matrix (>=1 cm^2) to be based on the results obtained with the previously characterized demonstrators (Milestones 1 and 2) and optimized using TCAD and Allpix-Squared Monte Carlo simulations. Submission in a shared engineering production run. Design and production of readout printed-circuit boards compatible with the Caribou modular DAQ system.

  Milestone 3: LC sensor demonstrator matrix available for testing [mid 2029].

- Integration of the LC sensor demonstrator matrix in the Caribou DAQ system. Characterization in laboratory and test-beam measurements. Comparison of the observed performance to the requirements of LC vertex detectors.

  Deliverable 3: report on characterisation results for the LC sensor demonstrator matrix [mid 2030].