IPHC Scientific Council 2023-06
Support document on CMOS MAPS projects

ALICE, Belle-II, PICSEL teams and C4π platform

2023-06-12

Abstract

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This document aimed at supporting the review of DRS instrumental projects related to vertex and internal track detectors with CMOS pixelated sensors, including upgrade programs of the ALICE, Belle 2 experiments, as well as R&D programs aimed at the development of detectors for future e^+e^- colliders.

Contents

I Introduction

The Monolithic Active Pixel Sensors (MAPS) sensors, based on CMOS technologies, is of an upmost importance for high energy physics detectors. In the past few years, MAPS sensors are driving an increasing level of interest. Indeed, their high precision, low power consumption, and low masses provide some of the most interesting features for future particle physics detectors. The recent design and construction of the Alice-ITS2 detector is on of the most striking illustration of the high potential of this technology. For the high energy community, it is therefore of critical relevance to support generic R&D on MAPS sensors, as well as R&D specific to well defined experiments.

The IPHC laboratory is a long standing actor of the R&D of CMOS sensors for various scientific applications, and in particular has a strong involvement on the application of such technology for high energy physics detectors. Thanks to the strong technical expertise of the micro-electronic and micro-technique C4Pi platform, and thanks to the strong scientific expertise of the IPHC research teams, IPHC is at the forefront of the MAPS R&D and is internationally recognise as a key contributor to this field.

In that context, the IPHC direction wants to support the MAPS activities and to ensure that each major projects the laboratory is supporting has the required resources. Secondly, the IPHC direction wants ensure that teams' objectives are compatible with the need to maintain, and to develop, the expertise of IPHC agents, both for the scientists and the technical personnel. For these reasons, the IPHC direction called for a Scientific Council of IPHC on MAPS R&D projects of the Alice, Belle-2 and Picsel IPHC teams. Naturally, the C4Pi platform being at the crossroad of all of these projects, it should participate to the discussions.

This present document aimed at supporting the review of DRS instrumental projects related to vertex and internal track detectors with CMOS pixelized sensors, including upgrade programs of the ALICE, Belle 2 experiments, as well as R&D programs aimed at the development of detectors for future e^+e^- colliders. As a reminder, the questions asked and aspects to be considered by the Scientific Council can be found in Appendix A.

II Presentation of the C4PI platform

II-A Operation model

The C4Pi facility gathers technical staff with expertise in the design, test and operation of CMOS-MAPS[1]. This expertise was built up in the past twenty years. The facility itself was created at the end of 2019 with the mission to work with scientific groups of IPHC and IN2P3 intending to apply the MAPS technology in their experiments.

Roughly, activities at C4Pi fall into two categories. First research and technological developments aim at improving the performance of CMOS monolithic pixel sensors, or said differently, at realizing the full potential of this technology. This first type of activities usually involve the creation of rather small prototypes used to validate one or a few specific figures of merit, either on an already well know CMOS process or exploring a new one. Creation of functional blocks (analog-to-digital or digital-to-analog converters, discriminators, etc...), not necessarily new in their absolute performance but new in the process considered, also enters here.

Though there is no restriction on the timeline for such R&D activities, they usually proceed in cycles of about three years and are connected with the research topic of a PhD student.

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[1] MAPS (monolithic active pixel sensors), CPS (CMOS pixel sensors) and CMOS-MAPS used throughout this document all refer to the same type of monolithic sensors designed and fabricated in a CMOS technology (Complementary Metal Oxyde Semiconductors).

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When a specific set of sensor requirements for a scientific experiment is matched by proven prototype performances, then the development of an application sensor can start at C4Pi . Such projects typically span over three to five years and imply two to three fabrications to reach the final sensors. They connect closely C4Pi with the scientific group for turning the experiment requirements into sensor specifications. The scientists from this group review the decisions during the sensor design and integration, as well as participate to the sensor characterization and validation.

Obviously, C4Pi cannot address all possible applications, which also means that not all types of performance will be developed by specific R&D. The general orientations of developments shall be driven by the scientific policy of IPHC and IN2P3. Nonetheless, three main expertise domains shall be kept as strong assets of the facility due to their strategic importance for the development of complete sensors: basic charge collection properties of the sensing node, matrix read-out architectures and global sensor integration. The technological R&D conducted by C4Pi is discussed in section II-C.

For both types of activities, technological R&D or application sensor development, three tasks are involved: microelectronic design, microtechnique integration and test. These tasks structure the three C4Pi subgroup listed in Figure 1, which resources are described in the next section.

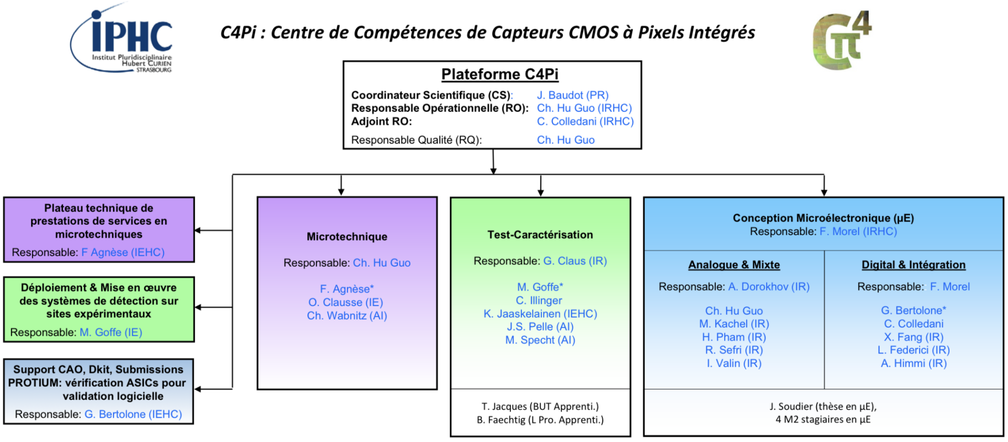

Figure 1: Organisation of the C4Pi facility.

The expertise, know-how and equipment of C4Pi induce requests for payed services out of the range of pure MAPS development. They mostly relate to micro-technique tasks, especially bonding, and are completed within a few weeks at most involving a small fraction of the activities. Some requests might nevertheless require a long term commitment, possibly extending to one or two years. These service tasks are only accepted if they do not hinder the scientific projects the C4Pi facility are committed to.

Throughout its technical developments, education of the future generation of technical experts is also an important mission of the C4Pi facility. About ten students are trained per year. Though the supervision of such temporary personnel naturally takes some time, it also brings a benefit to the platform beyond their contribution to projects. Past students are indeed very often the core applicants to permanent positions opened at C4Pi .

To conclude this introduction, it should be noted that the C4Pi facility has a clearly established set of rules to accept a project, involving its various internal and supervising bodies. The procedure depends on the type of tasks, the resources and time span required

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for reaching the goals. The projects discussed in this document relate to scientific experiments and will impact C4Pi resources on a large scale. They belong to the category of endeavors involving the laboratory scientific strategy.

II-B Resources

II-B.i Personnel

The C4Pi facility composed of 21 permanent technical staff spread over the three following subgroups.

- **twelve** microelectronic engineers have in charge the design of analogue, mixed and digital microcircuits as well as of the charge collection node. Design shall be understood here as including the definition of the specifications, the creation of circuit schematics and layouts, their simulation and verification.

- **five** test engineers develop the necessary hardware, firmware and software to fully characterize MAPS. They also maintain all setups in the laboratory and a beam telescope deployed outside IPHC when needed. Also for the application sensors developed at C4Pi , the test group might procure to external groups the system to operate the chips. In addition in some cases, the command and data acquisition of a mid-size application could be entirely taken in charge by the group. However such project are kept as exceptional events as possible, since they mobilize a large fraction of the available engineers up to a few years.

- **three** technical staff are devoted to the integration of MAPS, which include fabrication of printed circuit boards, chip placement and gluing, chip bounding, fabrication of detection modules and the associated metrology with micro- and micro-scopes.

A number of technical tasks are outsourced from C4Pi . First comes the fabrication of ASIC (Application Specific Integrated Circuits), which is subcontracted to a foundry. The thinning and dicing of the produced wafers are also performed by dedicated companies or semi-public facilities, the C4Pi does not own neither the necessary machines neither the expertise to operate them. The printed circuit boards (PCB, possibly in a flex form) needed to connect sensors and to build test systems are also fabricated by dedicated companies. Some small and simple PCBs can be fabricated in house. Mounting discrete components on these PCBs is mostly outsourced but could also be done internally.

In addition to the permanent staff, the 4Pi facility welcomes in average 2 PhD students, 4 Master students (usually 6 months from February to July) and 1 or 2 Undergraduate students for internships. About 2 apprentice, so far at the undergraduate level, are also working on a year basis for the platform projects.

II-B.ii Equipment

The facility owns or have to access the following equipments.

- Licence for Electronic Design Automation (EDA) and Technology Computer Aided Design (TCAD) tools are accessed through IN2P3 and University agreements.

- Computing stations and infrastructure allowing to run these design tools and store the related data.
- PCB fabrication and component mounting machines.
- Bounding machines.
- Various macro- and micro-scope, including 3D capabilities, for metrology and diagnostic on complex PCBs, small mechanical devices and more generally detection modules.
- Probe stations (8").
- X-ray gun for illuminating sensors with X-rays from 5 to 17keV.
- Various control and acquisition instruments to characterize sensors, actually bought by the scientific groups (mostly PICSEL) but all located in the same large test room.

It is important to note that the number of CMOS processes used to design sensors at C4Pi can not be arbitrarily large due to the maintenance of the process-specific computer-based tools (process design kits or PDK) required by such complex design and the associated expertise to use them properly. Currently, C4Pi essentially work with two technological nodes of the foundry Tower Semiconductor (180 nm and 65 nm).

II-C Internal R&D activities

The technological R&D activities are critical to ensure that the C4Pi stays at the cutting edge of the MAPS technology and can keep providing scientific projects state-of-the-art sensors.

Signal collection properties is the first topic of such R&D. C4Pi benefits of plenty of opportunities to fabricate small matrices that are exploring continuously various parameters of the collection nodes and immediate analogue front-end. A more specific project started in 2023 is the development of signal impact amplification in the silicon, which is expected to bring a number of benefits for the sensor detection performance. This activity will be conducted mostly by a PhD student within the three next years.

An associated research line involves the measurement of the charge deposited in the sensor, either with high precision for spectroscopic purpose and over a dynamic suited for the detection of ions in nuclear physics. These R&D occur through additional resources obtained for instance with European project (currently the H2020-infrastructure STRONG project).

A second R&D theme tackles a key functionality of pixel matrices, namely the ability to extract the information from fired pixels as swiftly as possible with a minimal power consumption. A PhD student started to work on matrix read-out architectures in 2021. The work is oriented toward the usage of asynchronous logic. A first prototype is expected in 2024, which characterisation will need to be perform by another PhD student or post-doc, still to be recruited.

Instrumentation for high-energy physics follow a strong trend to bring more intelligence inside detectors and hence sometimes in the front-end ASICs. The C4Pi facility pursue such activities so far at a modest scale, through master student projects, targeting to include processors in MAPS. This line of development will grow in the future through IN2P3 collaboration and also ECFA-DRD7 connected project.

It should also be underlined that development of reticule-size sensors devoted to a specific scientific application, though they are not geniunnely R&D activities, also contribute to develop specific expertise. A clear illustration is the digital-on-top design methodology, which was essentially introduced at C4Pi through the MIMOSIS sensor (for the CBM experiment and lead by the local PICSEL group) and MOSS sensors (for the ALICE experiment).

Aside from ASIC design themes, the microtechnique team has engaged in the recent years in developing the tools to bend large sensor of typically a few 100 cm^2. The activity currently continue within the ALICE-ITS3 project but clearly interests the PICSEL group as well.

Because of the strategic value of most of these technological R&D activities, they count among the themes of the ECFA detector R&D roadmap. As such they will also be continued inside the ECFA Detector R&D collaborations DRD3 and DRD7.
Regarding the person power committed to these activities, it has already be underlined that the core contributors to the ASIC design parts are Master or PhD students. Their supervision and participation to these projects require from 0.5 to 1.5 FTE from the designer team and a similar amount for the test team. For microtechnique integration where so far no student contributions, about 0.5 FTE is devoted to the R&D.

III Presentation of the DRS projects

IV ALICE ITS3

IV-A Upgrades during Long Shutdown2 [2019-2021] for ALICE

The ALICE experiment has been approved for the two upcoming data-taking campaigns at the LHC, Runs 3 [2022-2025] and 4 [2029-2032]. At the beginning of 2022, the collaboration completed the installation of major upgrades [1] that will remain in place for the next ten years. This includes notably the time projection chamber with novel GEM-equipped readout planes (TPC-2) [2], and, as far as some French teams are concerned, the inner trackers based on silicon pixel sensors, positioned at central rapidity (ITS2) [3] and at forward rapidity (MFT) [4]. The electronic readout [5] of the whole experiment was completely revisited to accommodate the triggerless/continuous readout now enforced in the experiment, the master piece of such an upgrade strategy hinging on the so-called Common Readout Unit cards (CRU) integrated in the completely new online-offline software environment [6].

IV-B Inner Tracking System, version 2 (ITS2)

The ITS2 consists of 7 coaxial layers divided into 2 groups: the 3 internal layers installed closest to the beam pipe (r_{pipe} = 1,82 cm) at distances $r_{L0} \approx$ 2,3 cm, $r_{L1} \approx$ 3,2 cm and $r_{L2} \approx$ 3,9 cm, and the 4 outer layers positioned between $r_{L3} \approx$ 19,5 cm and $r_{L6} \approx$ 39,3 cm. The 7 layers are instrumented to cover a range of pseudorapidity at least equal to $|\eta| < 1.3$ (see Tab. 1.1 in [3]). The detector is composed of a set of pixelated monolithic active sensors (MAPS) exploiting a 180-nm CMOS technology, following an ALPIDE architecture specially developed for this purpose. The whole ITS2 accounts for about 10 m^2 of active silicon surface, segmented into 12.5 billions pixels of about 27x29 μm^2 each. The main characteristics of the detector are listed in the first column of Tab. B.1 of this document. The ITS2 will already increase for the LHC Run 3 the detection efficiency of charged particles at low transverse momenta (*e.g.* at p_{T} = 0,1 GeV/c, $\varepsilon_{tracking}$[ITS-1($h^{\pm}$)] $\approx$ 10 % vs. $\varepsilon_{tracking}$[ITS-2($h^{\pm}$)] $\approx$ 60 %, see Fig. 7.12 in [3]).

The IPHC groups in Strasbourg participated and participates to the ITS2 project on several fronts:

- The design of the ALPIDE chip ([7] and Sec. 2.3 in [1]) equipping the ITS2 was partially carried out in Strasbourg (C4Pi , PICSEL)
- The module assembly, for which the IPHC was one of the 5 sites in charge in the ALICE collaboration (a module consists of 2x7 sensors positioned, glued and wire-bonded on a flexible printed circuit); 585 functional modules, defining about 25% of the grand total of modules, have been produced, between November 2017 and May 2019, requiring 4.5 FTE/year (C4Pi , ALICE-IPHC).
- Technicians and engineers further committed themselves at CERN during the installation, to cable the various parts of the detector and set up its operation (implement detector slow control and cooling); they followed, intervened and/or co-organised aspects related to the electronic connection-reconnection during the various ITS2 relocations, from Meyrin to LHC point-2 ground to the underground ALICE cavern (C4Pi , PICSEL, ALICE-IPHC).
- In parallel with the activity on the hardware side, Iouri Belikov from the IPHC ALICE team has been in charge (since the time of the ITS2 TDR, in 2013) of the software working group dedicated to detector simulations, tracking and reconstruction with the ITS2 (international group of about 50 persons in the collaboration).

IV-C Timeline in LHC run 3 [2022-2025] and run 4 [2029-2032]

The current planning for LHC campaigns over the next decade is not fully settled. A likely timeline is given in Fig. 2 below. The next decade will cover two LHC runs of 3-4 years each. Each year typically restarts around March with beam recommissioning, then moving, around middle spring, to proton beams typically accelerated up to maximum energy (6.8 TeV in 2022-23), delivering collisions at $\sqrt{s} = 13.6$ TeV, meant for physics in the experiments. Towards the late fall of the year, a dedicated data taking should take place for 3-5 weeks, with typically Pb-Pb collisions with $\sqrt{s_{\rm NN}}$ around 5 TeV [8]. pp campaigns at an energy different from the top energy will be covered during such periods typically, also including further p-Pb data. Special runs of O-O and p-O, for short periods ($\mathcal{O}$(day-s)), are foreseen in 2024. One should not forget that ALICE also takes data in pp collisions at 13.6 TeV, the top LHC energy in Run 3. In a first stage, the pp data taking will focus on the collection of Minimum Bias events (500 kHz); it will later move to a data skimming approach via software trigger, meant to inspect integrated luminosities of about 200 pb^{-1} and focus on i) high-multiplicity events ii) diffractive events and iii) rare signals such as production of light nuclei (d,t,^{3}He,^{4}He...) or of heavy-flavour jets [9]. As of September 2022, the international context of the year (*e.g.* energy cost) made the 2022-December Pb-Pb run postponed to 2023 with an extended Pb-Pb data taking (5 weeks). In November 2022, a test Pb beam of two fills with pp-like optics took place (*i.e.* low intensity).

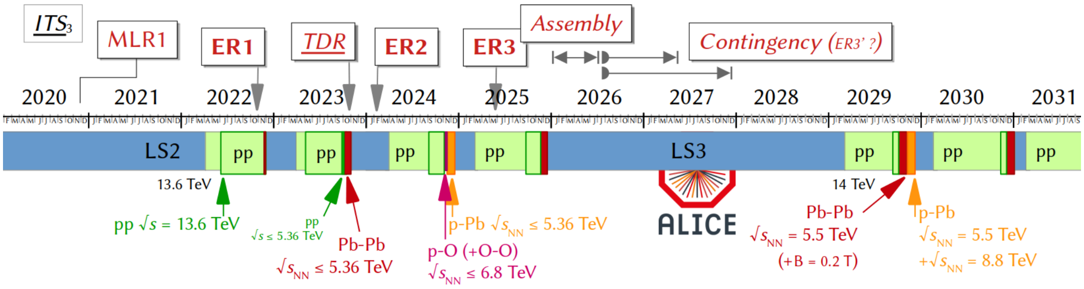

Figure 2: Tentative overview of the LHC campaign planning for Run 3 [2022-2025] and Run 4 [2029-2031(2032)], as currently anticipated from the ALICE experiment perspective. See LHC updates at lhc-commissioning.web.cern.ch. As far as it is foreseen in June 2023, the exact colliding energies ($\sqrt{s_{\rm NN}}$) are essentially defined for A–A in 2023 but not yet fully settled for p–A and later A–A periods; it depends on collimation and training quench performances. On the upper part of the timeline, one can see the major milestones attached to the ITS3 project.

IV-D Key specifications of the ITS3 detector

Keywords: 3 internal layers, hypergranular [$\mathcal{O}$(20x20 μm^2) pixels] and ultra-thin [0.05% x/X_0 per layer] sensors of large scale [$\mathcal{O}$(silicon wafer)], bent sensors, perfectly cylindrical geometry of the layers, absence of flexible printed circuit, stitching between sub-sensors, $r > 1.8$ cm.

The ITS3 project [10] aims at replacing the 3 innermost layers of the ITS2 (see Sec. IV-B). It will be implemented during Long Shutdown 3 [2026-2028], for a commissioning phase accompanying the start-up of the HL-LHC in Run 4 [2029-2032]. The pseudo-rapidity coverage (η) is very slightly extended compared to Run 3 ($|\eta| < 2.7$, 2.4 and 2.2 for the new internal layers with respect to $|\eta| < 2.5$, 2.3 and 2.0 of the current ITS2) but remains limited by the 4 outer layers ($|\eta| < 1.5$ to 1.3) which remain those of ITS2 [3]. The layout of the detector is shown in Fig. ?? below. The main characteristics of the ITS3 are summarized in Tab. 1.

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In a nutshell, the guideline of this upgrade is not the collection of larger instantaneous luminosities (on this point, preserving temporal performance is targeted: 2-5 μsof timing resolution, in a continuous readout devoid of any triggering) but a better spatial precision (granularity + radial location of the 1_{st} layer closer to the primary collision point) coupled with a minimum thickness of the detection layers. This last aspect relates to thinning of the silicon substrate but also ultimately to layers that, once they are integrated in terms of mechanics, cooling, readout, … still manage to remain broken free from all limiting factors. We will see below what it means.

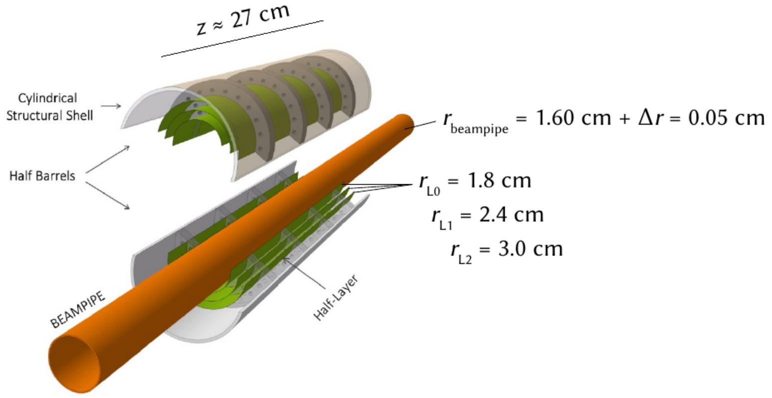

Figure 3: Sketch of the ITS3 layout (Fig. 7 in [10]), with the 6 silicon sensors (green) folded as two hemi-cylinders around the beam pipe (orange).

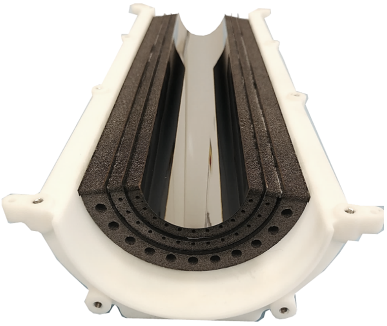

Figure 4: Photograph of Engineering Model 2, done during 2022. Mock-up of one hemi-cylinder using *dummy* silicon sensors, having the proper thickness (40 μm), the desired length (Z = 28 cm), bent to proper radii (r_0 = 1.8 cm, r_1 = 2.4 cm, r_2 = 3.0 cm) and mounted on carbon foams (longerons along Z and half-rings at the extremities).

The ITS3 will again rely on MAPS CMOS sensors as the ITS2, but a **65-nm CMOS** technology is targeted in this case.

Linked to the question of the material budget : The sensors have the ambition to overcome three technological limitations in terms of material budget. The detector will be : *i*) freed from any mechanical supports in the form of carbon ladders; *ii*) freed from any forced-cooling circuitry, allowed only upon drastic specifications on the power consumption and dissipation ($<$ 20 mW/ cm^2 on the pixel matrix); *iii*) devoid of assemblies on the usual flexible printed circuits, needed for the supply of power, slow control and for the extraction of data. In turn, the absence of flex requires sub-units of sensors sutured together (**stitching**), directly on the substrate, i.e. at the stage of silicon lithography by the foundry. This requires a radical revision of power management, voltage distribution, remote control and low-level acquisition. The finished objects will then become active sensors gathered in blocks of **large surface** [$\mathcal{O}$(10x27 cm^2)], on which the detector steering and the data extraction will be relegated to the periphery of the large active circuit.

In the end, the combination of the three above specifications makes it possible to reduce the material budget to its bare minimum, namely 30-50 μm of silicon thickness per layer (30 μm of silicon corresponds to **0.03 % x/**X_0). The sensors become therefore flexible and consequently **bendable**; a few large sensors can thus be wound and joined together in a perfectly cylindrical geometry, resulting in an almost uniform distribution of the material budget per detection layer..

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Linked to spatial resolution : the improvement in spatial precision (localization of the path of a charged particle and distance of closest approach to the primary vertex) is related to two technological points: *i*) The aforementioned structural flexibility allows the layers to be rolled with a small radius, allowing sensors to be placed at smaller **radial distances** from the beam axis ($r_{L0} \approx 1.8$ cm, $r_{L1} \approx 2.4$ cm and $r_{L2} \approx 3{,}0$ cm), around a beam pipe of still smaller size (rtube = 1,60 cm). *ii*) The 65-nm technology makes it possible to push the **hypergranularity** a little further down [pixel $\mathcal{O}(20\text{x}20\ \mu\text{m}^2)$] compared to ALPIDE chips, well below what can typically be obtained with hybrid pixels ($> 50\text{x}50\ \mu\text{m}^2$).

IV-E State of the art (June 2023)

The ITS3 project is regularly monitored by the LHCC and benefits from a very positive feedback from the latter (see minutes from LHCC meetings [CDS], going from the 139^{th} session in September 2019 [LHCc-139] to the 153^{rd} in March 2023 [LHCc-153].) R&D by the collaboration has been underway since mid-2019 and is progressing with promising results:

- The bending of flexible sensors while preserving their detection potential is now acquired, on the basis of the tests carried out on the ALPIDE chips (NB: 180-nm technology) [11]. An "ITS3-like" mini-configuration, based on ALPIDE chips, has been extensively tested; the curvature for radii between 1.8 and 3 cm does not alter the detection efficiency (>99%).
- The 65-nm technology exhibits the same characteristics as the 180-nm technology in terms of detection efficiency. This conclusion proceeds from multiple test campaigns, in the lab and under beam test (CERN-PS $\pi^{\pm}$ 5-10 GeV/c, CERN-SPS $\pi^{\pm}$ 120 GeV/c, DESY-PETRA $e^{\pm}$ 3.4 GeV/c), with or without irradiations (10^{13} to 10^{15} 1-MeV $n_{eq}.cm^{-2}$ NIEL / 1-10 Mrad TID). Note that, to date (June 2022), the bending of such detectors in 65-nm has not yet taken place (preparation to do so with 2020-submitted chiplets [MLR1, see below] and plan to do so with 2022-submitted sensors [ER1, idem]). Radiation hardness is studied over time in parallel of new versions of chips being submitted to the foundry. So far, the 65-nm technology exceeds the needed specifications (ITS3 requests > 3.10^{12} 1-MeV $n_{eq}.cm^{-2}$ for Non-Ionising Energy Loss, 0.3 Mrad for Total Ionising Dose). It is already validated with > 2.10^{14} 1-MeV $n_{eq}.cm^{-2}$ and > 1 Mrad irradiations, at room temperature.
- The issue of stitching and its performance will be addressed for the first time with the fall-2022 submission.
- Integration studies are in progress (cooling by air flow, mechanics on carbon foam, connections to the outside world (readout/Slow control/power), etc.)

IV-F Milestones and roadmap of the overall ITS3 project

The ITS3 upgrade project concerns a relatively modest surface to be equipped (0.12 m^2 of active surface, compared to 9.9 m^2 of the whole ITS2 or 0.41 m^2 of the MFT).

Keys :

- Foundry : Tower Semiconductor (bought by Intel, 15 Feb. 2022), facilitated access via an existing market at CERN for ALICE ITS development (without competitive tendering) and running at least until 2025, within a predefined money volume covering the Engineering Runs.
- New technology : from 180-nm process (ex: ALPIDE ITS2) to 65-nm one.
- The production yield by the foundry for chips of large scale remains an open question to date, specific to the R&D phase of the project, which will be addressed with the upcoming 2022 submission.

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Table 1: Main characteristics of the ITS-2 and ITS-3 silicon trackers of the ALICE-2 experiment. Data in *italics* relate to the outer layers ($L3$ to $L6$) of the trackers, when they differ from the inner layers ($L0$ to $L2$); these outer layers remain those of ITS-2 for the next decade.

	ITS-2 [3]	ITS-3 [10]
LHC period(s)	Run3 [2022-2025] + Run4	Run4 [2029-2032]
Number of layers	3+4	3 (*+4 ITS-2*)
beryllium pipe inner radius R_{pipe}	1.82 cm [CERN-news]	1.6 cm
(thickness ΔR)	(0.08 cm, = 0.22% x/X_0)	(0.05 cm, = 0.14% x/X_0)
r_{L0} / r_{L1} / r_{L2} ... r_{Last}	2.3 / 3.2 / 3.9 ... *39.3* cm	1.8 / 2.4 / 3.0 ... *39.3* cm
Magnetic field Bsolenoïd	0.2 and 0.5 T	0.2 and 0.5 T
Material budget per layer	0.3 % to *0.8 %* x/X_0	0.05 % to *0.8 %* x/X_0
CMOS technology	180 nm	65 nm *(180 nm)*
Pixel size	≈ 27 x 29 μm^2	≈ 20 x 20 μm^2
		(+ ≈ 27 x 29 μm^2*)*
Size of unitary base sensor	≈ 1.53 x 3 cm^2	≈ (5.6-9.5) x 27 cm^2
Nb of sensors to assemble (3 inner layers)	432	6 (!)
Non-Ionising Energy loss radiation	$> 3.10^{12}$ 1-MeV $n_{eq}.cm^{-2}$	$> 3.10^{12}$ 1-MeV $n_{eq}.cm^{-2}$
Total Ionising dose	> 0.3 Mrad	> 0.3 Mrad
Consumed power [a]	< 35 mW/cm^2	< 20 mW/cm^2
		(+ < 35 mW/cm^2*)*
Time resolution on hits	2-5 μs	≤ 2-5 μs
Time for charge collection per pixel	< 10 ns	≤ 1 ns
Spatial resolution	5 μm	≤ 5 μm
Coverage in η	$\lvert\eta\rvert < 2.0$ to 1.3	$\lvert\eta\rvert < 2.2$ to 1.3
$\varepsilon_{\text{tracking}}$ ITS ($p_T(h^{\pm})$ = X GeV/c)	1 GeV/c: 98%	1 GeV/c: 98%
	0.1 GeV/c: ≈ 60%	0.1 GeV/c: ≈ 75%
Fake hit rate	<< 10^{-6} $event^{-1}.pixel^{-1}$	< 10^{-7} $event^{-1}.pixel^{-1}$
Particle hit density	5 $MHz.cm^{-2}$	8.5 $MHz.cm^{-2}$
Total costs [R&D + Construction]	≈ 15.2 x10^6 CHF	≈ 6.0 x10^6 CHF
(+ beam pipe, out of the given project)	(...)	(1.5 x10^6 CHF)
Nb of institutes / Nb of countries	30 / 16	(≥ 19) / (≥ 8)

[a] in the active volume, *i.e.* over the pixel matrix, not true in the periphery...

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- In this project, detector R&D and technology development is the central aspect, taking a large fraction of the time and resources. The final production only takes a relatively short time and comparatively modest resources.
- The reduction of two orders of magnitude in the number of unit sensors to be produced makes it possible to significantly accelerate the construction phase. The actual assembly of the 6 final “wafer-scale” sensors will be an extremely delicate phase (large and fragile objects) but rather fast in its implementation.
- The construction of the final detector will take place at CERN directly (given the small size of the final product and the low number of building objects).

The major milestones of the project hinge on the 4 Engineering Runs of the project. These main steps must take place at a typical rate of 1.5 run/year. The typical cycle time between the submission and the chips returned to ALICE on bench for test is approximately 6-7 months (submission validation 1 month, production 5 months, thinning and dicing 1 month).

2020-12 tape-out: ***MLR1 submission*** *:*

. Objective (validated): *i*) Learn technology features of 65-nm node vs. 180-nm ALPIDE, *ii*) Characterize charge collection (cluster, timing, ...) and detection eff. (>99%), *iii*) Validate radiation hardness.
. Flag: “generic R&D” (*i.e.* WP1.2 MAPS CERN, within the CERN EP R&D)
. Technology node: 65 nm
. → 54 different prototypes of sensors (analog and/or digital sub-blocks), including 3 major prototypes [APTS (CERN), DPTS (CERN), CE65 (IPHC)] declined with many variants (pitch, doping, ...), all of (very) small surfaces $\mathcal{O}$(1.5x1.5 mm^2) (from 6x6 to not more than 64x32 matrix, *i.e.* "chiplets" in comparison with ALPIDE having 512x1024 pixels)

2022-11 tape-out: ***ER1 submission*** *:*

. Objective: stitching 1D (+ assess yields by the foundry)
. Flag: “generic R&D”
. Technology node: 65 nm, pixel pitch: 18 and 22,5 μm
. → 24 wafers with: 51 chiplets (*e.g.* DPTSv2, CE65v2, ...) + notably 2 large-sensor variants : MOSt and MOSs. MOSs (see Fig. 5) is 1.4 x 25.9 cm^{2}and consists of 10 sub-units ("RSU") of ($r\varphi$xz) = 1.4 x 2.55 cm^2 each, repeated along z that is, stitched “natively” on the wafer, in the close spirit of what ITS3 should look like. MOSs comes with safety margins regarding line spacing and circuit density to avoid shorts; MOSt is more aggressive on such aspects but this is to allow a very fine-grained way of turning off possible malfunctioning parts, it thus comes with alternative distribution of power and data distribution.

Expected 2024-02 : ***ER2 submission*** *:*

. Objective : power and readout, one single sensor ITS3-like (+ foundry yield), that is, aim for a full-scale demonstrator with complete set of ITS3-like functionalities, notably power management and readout
. Flag: “ALICE ITS3-specific R&D”
. Technology node: 65 nm, pixel pitch likely only one, 18 x 22,5 μm

Expected 2025-06 : ***ER3 submission*** *:* . Objective: a priori, last fixes and final run for the production, *i.e.* final large-scale sensors
. Flag: “ALICE ITS3-specific R&D”

2026 : final construction : including qualification of the sensor prior to assembly, meant to happen within a few months.

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Notes:

. The available contingency is currently of 1-2 years, allowing for a potential ER4 during LS3 [2026-2028], if need be.

. A Technical Design Report (TDR) is expected for October 2023, following the first characterisations (including lab- and prime beam tests) of the ER1 sensors back from foundry in April 2023.

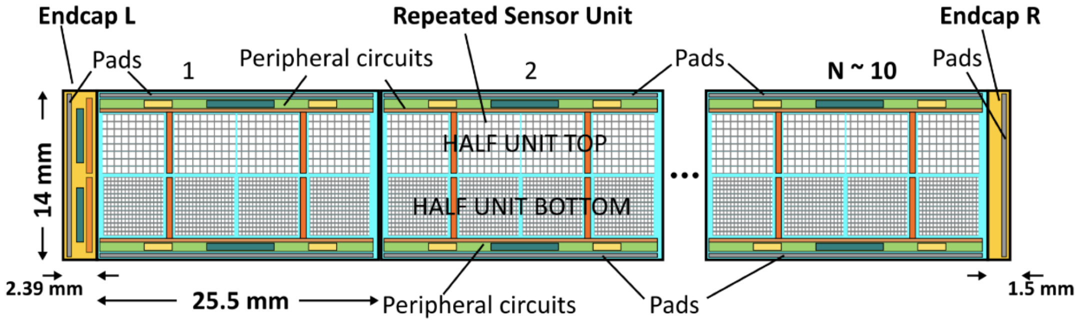

Figure 5: Sketch of the MOSS chip submitted to ER1 of ITS3 (2022-11), where one can identify the 10 sub-units of ($r\varphi$ x z) = (1.4 x 2.55) cm^2 that are repeated 10 times along the z axis. From [Mager-ICHEP22].

IV-G Budget, sub-collaboration and project organisation for ITS3

IV-G.i Global budget for the project (2019+)

The overall budget for the ITS3 project is around 6.5 MCHF (for core costs, not consolidated for Human Resources, but with institutional partners giving in-kind contributions). The first estimates of the overall budget can be found under the [10] from 2019 (Section 7, p.29, Tab. .8), extrapolated based on the ITS2 experience. In the meantime, a few figures went to be updated, one can find slightly more details in the support document for the 2022-10 Scientific Council at IN2P3 [12]. They concerns essentially : . the costs of a foundry run which now amount to 650-700x10^3 \$ per run, including post-processing like thinning and dicing (and not anymore 300-400x10^3 \$ like for the 180-nm technology node) . 200-300 x10^3 CHF/year for DAQ cards and tests, over 4 years, instead of 60 x10^3 CHF/year . Note that, the beam pipe, initially part and parcel of the ITS3 budget (up to 1.5 million Swiss francs), will now be borne by the entire ALICE collaboration and therefore extracted from the ITS3 budget as such.

IV-G.ii Institutional partners, committed or expected

To date, there is no Memorandum of Understanding available. The main partners expected can be grouped in 2 categories, in order of expected commitments (Budget contributions and Humarn Resources) : CERN, Italy (INFN+), France (IN2P3+), the Netherlands (NIKHEF, Utrecht) and then Korea (Inha, Yonsei, Pusan), Sweden (Lund), Norway (Bergen, USN Vestfold), Tchech Republic (Prague Univ, Prague National Academy of Sci). (The position of USA (Berkeley, BNL ? LNL ? Stanford ?) is to be clarified; if happening, it will be in good part linked with instrumental synergies found with EIC collider and/or Cool Copper Collider.)

IV-G.iii Project organisation (2023-06)

The project ITS3 is structured accrording to the following organigram:

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- Project Leaders: Magnus MAGER (CERN) and Alex KLUGE (CERN).

accompanied with 6 Work Packages (Indico link)

. **WP1** - Physics, Simulation and Reconstruction
Fabrizio GROSA (CERN), Andrea ROSSI (INFN Padova)

. **WP2** - Pixel Sensor Design
Gianluca AGLIERI RINELLA (CERN), Walter SNOEYS (CERN)

. **WP3** - Sensor Characterisation and Qualification
Serhiy SENYUKOV (CNRS IPHC), Miljenko SULJIC (CERN)

. **WP4** - Thinning, Bending, Interconnection
Domenico COLELLA (INFN Bari), Giacomo CONTIN (INFN Trieste)

. **WP5** - Mechanics and Cooling
Massimo ANGELETTI (CERN), Corrado GARGIULO (CERN)

. **WP6** - Readout electronics
Ola GROETTVIK (CERN), Felix REIDT (CERN)

IV-H IN2P3 and IPHC in the ITS3 project

IV-H.i IN2P3-level milestones

The ITS3 project in France (*i.e.* at CNRS/IN2P3) has already gone through different steps of validation. At the national level, the French side of the project – encompassing IPHC Strasbourg (CMOS design, sensor test, electronic integration, tracking, simulations), LPSC Grenoble (middle-end electronics = slow control+powering+readout, mechanical integration, simulations) and IP2I Lyon (test, simulations) – have passed the IN2P3 Scientific Council in October 2022 [12]. After getting the on-principle approval, the project went through an IN2P3 "Key Deciscion Point 2" [13], where the exact perimeter (deliverables, timelines, budget, human resources) is reviewed and debated in view of a final agreement between IN2P3 direction and each of the three institutes. (final decision endorsed on 9 June 2023).

IV-H.ii The incentives in terms of physics analyses

Together with existing trackers ITS2 ($y \approx 0$) and MFT (forward y) projects of the ALICE experiment, the ITS3 responds to common interests of the IN2P3 teams from Strasbourg, Grenoble and Lyon altogether, around the physics of dense hadronic matter. The “joint” exploitation of these detectors will allow in Run 4 [2029-2032] to establish a coherent scenario of the physics of collectivity, combining the main research topics addressed by the groups, ranging from the study of the response of the medium according to the quark flavours, the question of the meson vs. baryon productions, or the interaction between the created medium and the parton showers.

[Heavy quarks (c,b) facing collectivity] (*IPHC, IP2I*):
i) a priority will be measuring total cross-section of charm production for $p_{\mathrm{T}} > 0$ and $y \approx 0$ [mesons and baryons: $\mathrm{D}^0(cu)$, $\mathrm{D}^+(cd)$, $\mathrm{D}_s^+(cs)$, $\Lambda_c^+(udc)$, and quarkonia $c\bar{c}$: η_{c}, J/ψ, $\psi(2\mathrm{S})$, χ_{cJ}...]. *ii*) Along the same line, will come the exploration of baryons that are single-charmed (and strange in addition) [$\Lambda_c^+(udc)$, $\Xi_c^+(usc)$, $\Xi_c^0(dsc)$, $\Omega_c^0(ssc)$] and beautiful baryons [$\Lambda_b^0(udb)$, ...]. The objective is especially to inspect the hadronization of charmed quarks (recombination mechanisms) and their sensitivity to the medium (hydrodynamisation, chemical equilibration, thermalisation / transport coefficients) in the quark-gluon plasma. Such an objective requires a drastic increase in the significance of the reconstructed signal and in the spatial precision (on the impact parameter of track, in particular) to reconstruct increasingly complex decay topologies, typically ranging from 2 to 6 bodies.

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[Interactions between hard partons and with medium constituents] (*LPSC, IPHC*): A pivotal analysis here will concern the study of the interplay between (flavour-tagged) jets and the surrounding underlying event in the collision, in pp and in A–A systems.

[Correlations between rapidity domains] (*IP2I, IPHC, LPSC*): Exploiting the correlation between the information from the ITS2+ITS3 (mid-rapidity) and the MFT (forward rapidity) will be an asset in characterizing and mapping the event activity over a large y range, and over the whole gamut of collisions delivered by the LHC, from proton-proton collisions to Pb-Pb collisions. Using the data from the ITS3 and the MFT will also make it possible to establish a separation in phase space between the measurement of the heavy-flavour signals and that of the underlying event (forward-mid or mid-forward), casting a specific light on possible collective effects involving charmed and beautiful quarks.

IV-I IPHC contributions and deliverables

The IPHC groups (ALICE + C4Pi platform + PICSEL) wish to commit on the fronts of software, integration preparation and microelectronic design of 65-nm CMOS chips – depending on the team, *for* or *in connection with* the ITS3 project.

IV-I.i On the aspects linked to pixel chip design (C4Pi, PICSEL)

The very design of the sensors is the cornerstone of the ITS3 project, on the analog side, for the optimisation of the charge collection especially, and on the digital side, to set up all the necessary logic functions/processing and powering within the sensor. The IPHC C4Pi platform has been already involved since the beginning in 2019 (via some upstream generic R&D) but is particularly awaited by the ALICE collaboration in view of the coming engineering runs, ER2 in 2024 and ER3 in 2025 (see section IV-F above for the deadlines). The stakes are to undertake about half of the design efforts (≈ 8 FTE in total for the whole project), essentially along with the CERN design team (related EP R&D WP1.2), as of late 2022; the work is to address key components of the pixel matrix. As such, the participation of the IPHC is crucial and even considered vital by all the participants to the project. This request comes as the load at the IPHC on the design of the MIMOSIS sensors (used by the CBM experiment at FAIR) will be on the downward path; it also comes in parallel with the design of the OBELIX chips for Belle II (see sub-section V-D). For IPHC members, completing version 2 of MIMOSIS, carrying the design of both ITS3 and Belle2 chips appears as a workload essentially proportionate to the workforces of the platform.

CMOS design *(*C4Pi*) :*

. Producing constitutive elements of the matrix (PBS) with notably
  A) analogic very front-end in the pixels (50/50 between CERN and IPHC)
  B) numeric readout architecture of pixel within the matrix (≈ 100% IPHC)
. Validation and consolidation actions
  C) Integration in the matrix of the description *Digital On Top*
  D) Power analysis and behaviour of the power rails

Tests and qualifications *(*PICSEL*) :*

The mission consists in *managing* the WP3 of the international project (see IV-G.iii), the work package dedicated to tests and later qualifications of sensors stemming from the successive Engineering Runs. For what comes in next years, no resource are requested from the subgroup (C4Pi - tests).

IV-I.ii On the front of electronic integration and micro-connectics (ALICE-IPHC, C4Pi)

The bending of sensors over small radii, the crampedness of the available space require advanced thinking on all the integration issues (mechanical structure, cooling by air flow, assembly, wiring, installation). For the IPHC, it is a question of approaching the aspects of electronic micro-connectivity, the interconnection between these large-scale sensors and the outside world; this is done in coordination with the CERN and/or Bari teams (as was done for ITS2).

SuperALPIDE prototype as backup *(*C4Pi*) :* A fall-back solution in case of trouble encountered with the main plan (*e.g.* on 65-nm stitching after ER1) consists in relying on 2x9 ALPIDE 180-nm sensors that remain independent (*i.e.* no stitching) but let together on the wafer (*i.e.* no dicing among them, single mechanical surface). Such a set is further bent, bonded and wrapped into a 3D-printed exoskeleton. Exercising on bending large surface (*i.e.* ≈ 6x14 cm^2 = (2x3$^+$) x (9x1.5$^+$) cm^2) and bonding on curled surface are the keys here.

Electronic and micro-connectic integration for final installation *(*ALICE-IPHC*) :* The project needs a few persons able to manipulate the fragile and raw to semi-finished objects of ITS3, who establish the assembly protocol of pieces in view of their installation on ground or in cavern and exercise themselves to validate/correct such processes. It concerns tooling, glueing strategy, test cards, bonding, Flexible Printed Circuit routing, ...). This requires transversal view across WP3 (tests), WP4 (interconnection, pliage), WP5 (mécanique) et WP6 (readout).

IV-I.iii On the tracking front (ALICE-IPHC)

In a natural extension of the tracking and simulation expertise acquired along with the operation of ITS1 (more generally, ALICE-1) and also along the implementation of ITS2, working on similar issues for ITS3 proceeds with a natural logic for the ALICE-IPHC team. Such developments will be coupled with the study of the physical performances of the ITS3, in particular concerning the reconstruction of mono-charmed and strange baryons with the concept of Strangeness Tracking (*e.g.* $\Omega_c^0 \to \pi^+\Omega^-$), allowing the tracking of charged strange baryons $\Sigma^\pm$, $\Xi^\pm$ and $\Omega^\pm$ themselves (for explanation and illustration, see [14], Section 3.2.1.3, p.65).

IV-I.iv Timeline and Human resources

CMOS design *:*

- source: C4Pi
- (4 ± 0.5) FTE/year, 4 years, [2022-2026[(*i.e.* post-ER3), with a revision at that horizon for possible prolongation (*e.g.* in case of calendar drifting); distributed over 7 permanent staff engineers (2 analogic designers / 5 numeric designers) and 2 PhD students.

Tests and qualifications *:*

- source: PICSEL
- ($0.5^{+0.2}$) FTE/year, 6 ans [2021-2026], with a re-discussion of a possible contribution extension in 2026 (gr. ALICE / gr. PICSEL); over 1 person.

SuperALPIDE prototyping *:*

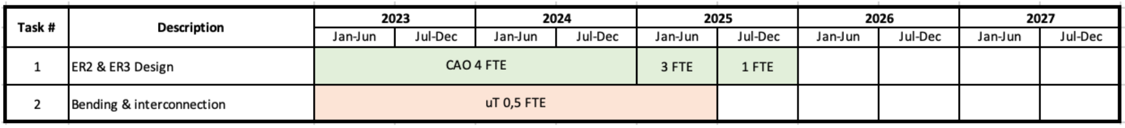
- source: C4Pi, micro-technics sub-group

. 0.5 FTE/year, 3 years, [2023-2025]; over 3 persons, work based at IPHC, costing some material buyings (mandrel, 3D printed exoskeleton, ...) and only few missions to Bari or CERN.

Towards final integration :

. source: ALICE-IPHC
. 0.8 FTE/year, 6 years, [2023-2028]; = over 1 engineer, embedded within a "transversal" trinom stationed at CERN, costing essentially missions: 1 week/month, 10 times/year + intensive 2-month stays every 2 years in synchronisation with major assembly stages after each ERx.

A summary of the IPHC C4Pi Human Resources required for completing the project are summarized in the table 6.



Task #	Description	2023		2024		2025		2026		2027	
		Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec
1	ER2 & ER3 Design	CAO 4 FTE				3 FTE	1 FTE				
2	Bending & interconnection	uT 0,5 FTE									

Figure 6: Organisation of the C4Pi facility.

V Belle-2 VTX upgrade

V-A Overview of Belle II program

The essence of the Belle II project is to search for physics beyond the Standard Model of particle physics by analysing a massive amount of decays of b quarks, c quarks and τ leptons. These final states stem from e^+e^- collisions produced by the SuperKEKB facility [15] at a center of mass energy close to the $\Upsilon(4S)$ mass. A rich physics program can be reached through the accumulation by Belle II of an integrated luminosity from 1 to 50 ab^{-1} as described in [16]. This requires the SuperKEKB machine to operate at the intensity frontier.

The SuperKEKB collider exploits the so-called nano-beam scheme at high beam current in order to reach unprecedented luminosities. Belle II collected its first collisions in 2019 and is expected to operate for the next decade as depicted in Figure 7. In a first phase (run I: 2019-2022), SuperKEKB has reached the world highest instantaneous luminosity of $4.7\,10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and Belle II accumulated a data sample equivalent to 430 fb^{-1}, a typical B-factory statistics.

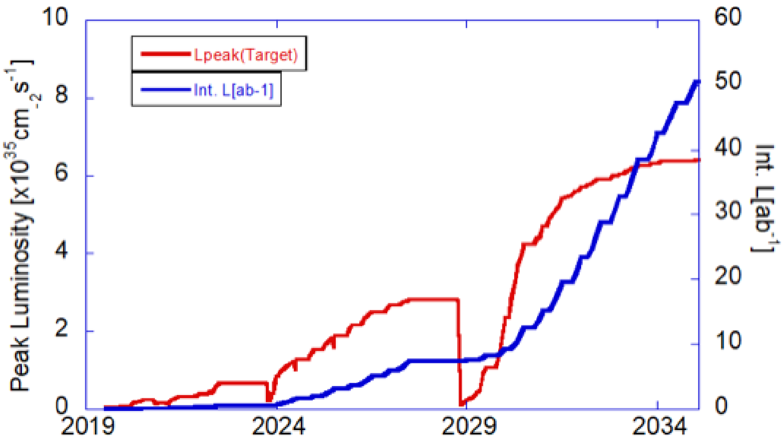


Figure 7: Current luminosity prospects for SuperKEKB and Belle II. Periods with flat instantaneous luminosity correspond to long shutdowns of the collider.

Reaching luminosities beyond $10^{35}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ is however a real challenge and machine experts still need part of the 2024 data taking period to elaborate which upgrades on the final focusing and interaction are needed for that. Their implementation justifies the second SuperKEKB long-shutdown (LS2), currently planned around 2027.

With increasing instantaneous luminosities, the continuous rate of parasitic particles induced by various beam effects - and not elementary collisions - also rises. This evolution combined with the fact that the amplitude of this beam-induced background is not robustly predictable, led the Belle II collaboration to start an upgrade program first discussed here [17] with short, mid (LS2 time scale) and long (beyond 2030) term targets.
The first long-shutdown (LS1) in 2023 is partly required by the short-term upgrade plan and partly to complete the two layers of the present design of the pixel detectors and is not the topic of the present project.

V-B Belle II tracking upgrades

Figure 8 provides a brief introduction to the Belle II detector, while a detailed description can be found in [18]. The instrument follows the standard concept of collider 4π experiments. The main tracker device is the central drift chamber (CDC), which is complemented by a vertex detector (VXD) for low momentum particle tracking and for vertexing.

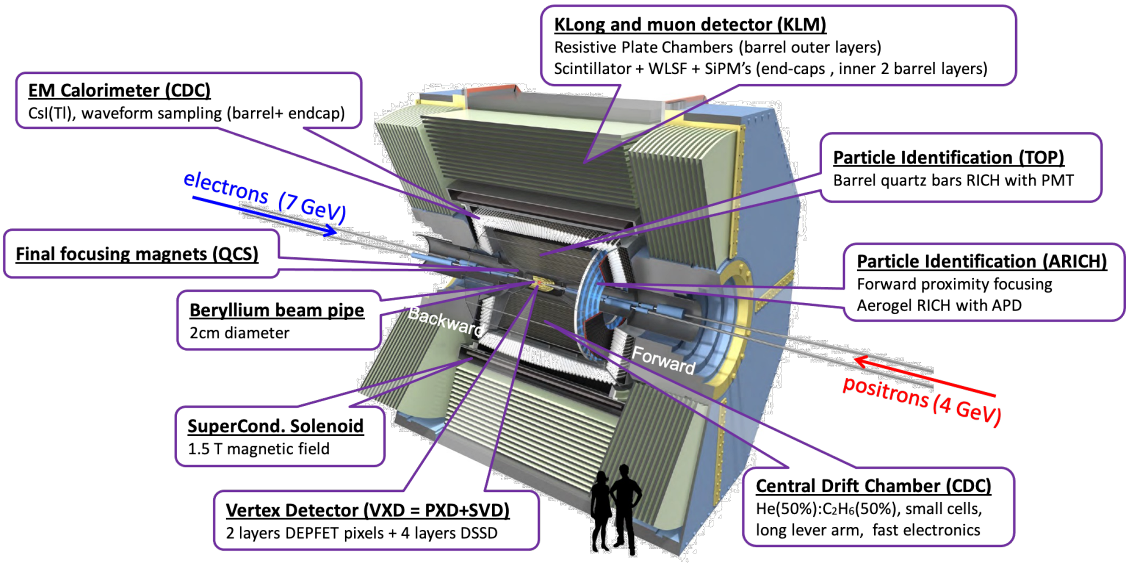


Figure 8: Sketch of the current Belle II apparatus with a short description of its sub-elements.

Two different technologies compose the VXD itself, surrounding a beam-pipe which inner-outer radii are 10 – 12 mm.

DEPFET[2] sensors equip the two first layers, known as the PXD [19]. These layers located at 14 and 22 mm radius, weight an equivalent 0.2 % X_0 per layer, for a pixel size varying from 50×55 to $50 \times 80\,\mu\mathrm{m}^2$ and an integration time of 20 μs (to be compared to the 30kHz average trigger rate).

Double sided silicon strip detectors (DSSSD) populate the four VXD outer layers, known as the SVD [20], featuring an average material budget of 0.7 % X_0 per layer. The SVD layer radii range from 39 to 135 mm, with a strip-pitch varying from 50 to 75 μm in the direction perpendicular to the beam and from 160 to 240 μm along the beam (z-direction). The SVD sensors are read out by APV25 chips [21], which sample the strip signals at 32MHz and allows a final time resolution for hits of the order of 3 ns. In present extrapolation for peak luminosity of $6\,10^{35}$ cm^{-2} s^{-1}, the beam background rate from a pessimistic but not improbable scenario exceeds by a factor 2 the data throughput capability of the first SVD layer.

The Central Drift Chamber is the tracking detector suffering the most from the expected increase of beam-induced backgrounds. However, replacing a large gas volume is currently quite challenging and is typically considered as a long term upgrade, see section V-B.ii.

In contrast, semi-conductor technologies benefit from a strong R&D effort and available sensors already feature performances exceeding those of current DEPFET and to some extent DSSSD. Upgrading the present VXD into a more powerful inner silicon tracker would both allow the vertex tracker to cope with all studied beam background scenarii and partly mitigate the impact on tracking performance due to the expected drift chamber degradation. While the track finding efficiency with the CDC drops severely once the hit rate on wires exceed typically 140 kHZ/wire, the efficiency is recovered from the finding using VTX information without degradation in the presently considered scenario.

Additionally, beam-induced background levels after LS2 bear large uncertainties for two reasons. On the one hand, the solution to upgrade the final focusing system is not

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[2] It is worth noticing that Belle II is the first high energy physics experiment hosting this technology. The PXD is entirely developed, build and operated by German groups.

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yet known. And on the other hand, only the background during beam storage is currently predicted by simulations. The SuperKEKB collider is a top-up machine with frequent bunch injections (25 kHz), inducing noisy bunches known to generate parasitic particle rates one order of magnitude higher compared to storage conditions. This effect forces to adopt a regular veto strategy limiting Belle II data taking efficiency. Sensors featuring much higher resilience to hit rates would help recovering part of this efficiency.

A final argument for an upgrade of the silicon detector layers, relates to the fact that the luminosity upgrade might come with a compulsory change to the geometry of the interaction region (mostly closing in the focusing magnet toward the interaction point). In such a case, the allowed geometrical envelope for the inner detection layers in Belle II would change and require anyway a new detector layout.

For these reasons, an upgrade of the Belle II vertex detector (VXD) is actively under study with a mid-term goal, i.e. for LS2. The corresponding main requirements in terms of detection performance come from the previous considerations and are listed below for the innermost layer.

- Position resolution (for all layers): $< 15\,\mu$m.
- Hit rate: $120\,\mathrm{MHz\,cm^{-2}}$.
- Total ionizing dose: $100\,\mathrm{kGy/year}$.
- NIEL fluence: $5\,10^{13}\,\mathrm{n_{eq}cm^{-2}/year}$.

V-B.i The VTX project

Various expressions of interest to upgrade the VXD were received in February 2021 after a call from the Belle II collaboration. An internal process between the contenders, based on technology readiness level and size of the supporting community, made a baseline option to emerge. This option is the VTX project described here and exploiting the CMOS-MAPS technology. Another sensor technology, Silicon On Insulator (SOI)[22], is kept as a potential alternative depending on the performance demonstrated by the on-going R&D. This strategy is being described in the Conceptual Design Report under writing and planed for 2023.

Austria	HEPHY-Vienna	Italy	Uni. Bergamo, INFN-Pavia, INFN-Pisa
France	CCPM-Marseille, IJClab-Orsay, IPHC-Strasbourg	Japan	KEK-Tsukuba
Germany	Uni. Bonn, Uni. Dortmund, Uni. Göttingen, KIT-Karlsruhe	Spain	IFIC-Valencia

Table 2: Participants to the VTX project.

The VTX project is proposed by a large consortium of laboratories, listed in Table 2. The detector concept aims at covering the acceptance of the current vertex detector (VXD) with 5 layers populated by the same monolithic sensor type for the sake of simplicity. The sensor specifications detailed in table 3 are elaborated to match the requirements stated in section V-B and to enhance granularity in space and time compared to the present technologies. The detection layer design targets simplicity, robustness and adaptability in order to cope with a short development time and potential late modification of the geometrical acceptance. In total, the VTX area represents about $1\,\mathrm{m}^2$ of silicon, made of about 70 ladders and 2000 sensors (assuming the present geometrical acceptance and reticule size type sensors).

	specification	TJ-Monopix2
pixel pitch	$< 40\,\mu$m	$< 33\,\mu$m
senstive layer thickness	$< 50\,\mu$m	$30\,\mu$m and $100\,\mu$m
sensor thickness	$< 100\,\mu$m	-
hit rate in matrix	> 600 MHz cm^{-2}	> 800 MHz cm^{-2}
hit rate for sensor	> 120 MHz cm^{-2}	$\gg 100$ MHz cm^{-2}
trigger delay	$> 10\,\mu$s	-
trigger rate	30 kHz	-
overall integration time	< 100 ns	-
(optional) time precision	< 50 ns	-
Total ionizing dose tolerance	1 MGy	10 MGy
NIEL fluence tolerance	$10^{14}\mathrm{n_{eq}cm^{-2}}$	$1.510^{15}\mathrm{n_{eq}cm^{-2}}$
SEU tolerance	frequent config. flash	-
matrix dimensions	around $30 \times 16\,\mathrm{mm}^2$	$19 \times 19\,\mathrm{mm}^2$
overall sensor dimensions	around $19 \times 19\,\mathrm{mm}^2$	$20 \times 20\,\mathrm{mm}^2$
powering	voltage regulators	-
outputs	one at < 200 MHz	one at 160 MHz

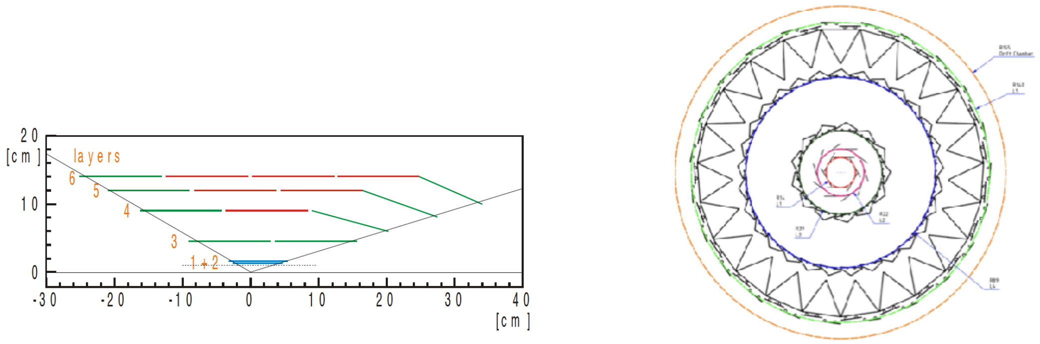
Table 3: VTX sensor specifications, compared to the relevant specification of the TJ-Monopix2 sensor.

The baseline VTX sensor technology is a CMOS-MAPS to be fabricated in the Tower Semiconductor 180nm Imaging process. This technology has been used for the largest detector using MAPS today in high-energy physics, the ALICE-ITS2 [7]. Another sensor fabricated in the same process, TJ-Monopix2 [23] developed in the context of the ATLAS experiment, has shown detection performance very close to the Belle II-VTX specifications, see comparison in table 3. Consequently, TJ-Monopix2 is used as a forerunner for the VTX-dedicated sensor named OBELIX. This strategy is expected to shorten the development time of the sensor in view of matching the relative close date of the LS2.

The design of the detection layers depends on the radius in order to minimise the material budget and allows to have services (cables and cooling) only on the Belle II backward side but for the outermost and longest layer. The two innermost layers, or iVTX, follow an all-silicon concept without any additional material in the fiducial volume but the sensors, cooled by airflow and target a thickness of 0.1 to $0.15\,\%\,X_0$ per layer. The three outer layers, or oVTX, re-use a more traditional design combining lightweight mechanical support structures, flex cables and water cooling pipes. In particular, oVTX layers copy the ALICE-ITS2 [24] approach developed specifically for monolithic sensors and targets a material budget of 0.5 to $0.8\,\%\,X_0$ per layer depending on the radius.

A tentative timeline of the whole VTX development and production is sketched in figure 10, assuming 2028 as the commission year.

The key feature of the VTX is an occupancy lower than 10^{-4} with 5 times the beam-induced background currently expected and hence excellent tracking performance with a comfortable safety factor. The light occupancy brings additional benefits. First it allows a faster tracking for the high level trigger system. Then it also alleviates previous limit set on the luminosity due to the data acquisition bandwidth. Finally it minimizes the number of cables in the inner parts of Belle II, which subsequently allows for more shielding protecting outer detectors against beam-induced background.



(a) Arrangement of the VXD layers in the $r - z$ plane

(b) Arrangement of the VTX layers in the $r - \phi$ plane.

Figure 9: Comparative layout of the present Belle II VXD (left) and the proposed upgraded version VTX (right).

The tracking and physics performances of the VTX have been simulated using the full Belle II software and shown to be at least equivalent to those of the present VXD system [25]. Additional studies are on-going especially with more benchmark analysis channels, some including neutral particles, which reconstruction is among the strong points of the Belle II experiments.

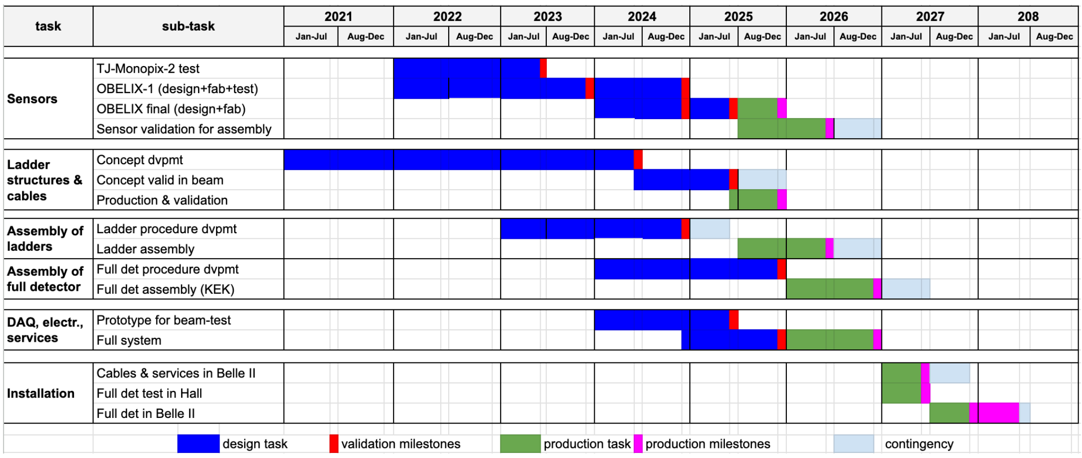


Figure 10: Notional schedule for the VTX project, assuming a commissioning in 2027/2028.

V-B.ii Long-term project

When SuperKEKB peak luminosity will exceed significantly 10^{35} cm^{-2} s^{-1}, the tracking based on CDC will steadily decreased as mentioned earlier. Even though the replacement of the inner silicon layer with the proposed VTX will help mitigate this problem, it is of course desirable to find a long term solution for the main Belle II tracker. Two possibilities are considered, either replacing entirely the gas volume with a silicon tracker, either shortening the radial expansion of the gas volume and replace only the inner part with a silicon tracker.

In both cases, the new silicon tracker has similarities with other future trackers for various experiments ALICE3, LHCb and FCCee. These projects aim to use MAPS as their baseline technology. Based on the experience with the Tower 180 nm process and new findings with the TPSCo 65 nm process, it seems possible to develop a pixel matrix covering a broad range of requirements, making it suitable for all these trackers. The matrix will typically feature a pixel pitch between 30 to 40 μm, a read-out architecture allowing to handle hit rates from 1 to 100 MHz cm^{-2} and to time-stamp hit down to the nanosecond level within

a power budget below 50 mW cm^{-2} and a radio-tolerance up to a few 10^{15} $\mathrm{n_{eq}cm^{-2}}$. Of course the output band-width, time precision and trigger requirements differ significantly between these projects. But these apply to the data treatment outside the pixel matrix, meaning specific matrix periphery would be required.
Hence a first joint R&D would focus on the pixel matrix, after which each experiment would develop its own logic to interface the matrix with the required outputs.

The proposal by the IPHC Belle II team is to foster R&D at C4Pi in the direction for a tracker-dedicated MAPS, as also foresee by the ALICE 3 project. Such activities will be fully included in the ECFA-DRD3/7 programs and are partially in synergy with the development of a vertex-MAPS for future vertex detector. In the coming years, this R&D dubbed Belle/ALICE tracker will mostly be an activity within C4Pi , ramping up from 2025 and expected to gather about 4 full time equivalent designers and 1 full time equivalent staff for test and integration by 2026.

V-C The IPHC-Belle II group project within the VTX collaboration

The IPHC-Belle II group is a prominent proponent of the VTX project, mainly for its early simulation studies to optimize the specifications and for its coordination of the OBELIX sensor development. With the agreement from IPHC and IN2P3, an R&D phase has started late in 2021 and should conclude with the characterisation of the first sensor version OBELIX-1[3].
The present project describes activities proposed by the Belle II group at IPHC to finalize the R&D phase (end of 2024), produce the VTX detector and commission it in the experiment, provided the Belle II collaboration decides on the production and installation of the VTX detector. The corresponding work is briefly discussed here and the specific tasks requested to the C4Pi facility are detailed in section V-D.

Being already involved in the design and characterisation of OBELIX-1, we propose to extend these same activities to the final sensor OBELIX-2, keeping a leading role for the design. The IPHC Belle II group also intends to be involved in the installation, commissioning and further operation of the final detector. This means a commitment at some level to technical activities at KEK and to software (online and offline) developments, as we currently have for the present strip detector SVD.

Beyond these core activities, we propose to consider two additional tasks, which match the expertise existing at C4Pi . The first consists in probe-testing bare OBELIX-2 sensors to select which dies enter the assembly of operational modules. Secondly and considering the construction phase will be quite constraint in time, we propose to assemble part of the detection modules (sensor on flex) for the outer layers. This work is very similar to the one performed for the ALICE-ITS2 and will maintain a good expertise in silicon detector building. Since the production plan is not yet established, it is difficult to estimate the amount of work required now.

In summary, the proposed activities at IPHC span over the whole development and operation phases of the VTX detector, with selected contributions matching the existing local expertise and a leading role on the CMOS-MAPS sensor. Upon the realisation of the VTX project, the IPHC-Belle II group will become a major contributor to the future success of the experiment.
It is furthremore worth noticing the VTX will be the first MAPS-based vertex detector developed for an e^+e^- collider and, as such, will bring an extremely valuable expertise at IPHC.

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[3] Regarding other French laboratories in Belle II , both activities for sensor design and test are also shared with CPPM-Marseille

V-D Details of request to C4Pi

Activities generated by the VTX project to upgrade the current Belle II vertex detector include the three domains of expertise present at C4Pi : microelectronic design, microtechnic and test. However the level of commitment is quite different as discussed in the next section V-E.

The IPHC Belle II group are already and will keep supporting the project in various ways: physics benchmark simulations to assess specifications, specific algorithm development for data reconstruction, sensor design supervision, detector production supervision, participation to tests both in laboratory and in beam.

V-D.i Microelectronic design activities

The design of OBELIX-1 has started in late 2021 and has progressed steadily through 2022 and the beginning of 2023. While the design is targeted to finish in July, the ASIC verification will continue though Fall for an expected submission late 2023. The designers at C4Pi are responsible for the design of the matrix, with the help of colleagues from INFN and CPPM. Also C4Pi is the laboratory managing the common repository for the layout file (through the Cliosoft-SOS package) and is handling the submission to the foundry.

The design of the final circuit OBELIX-2 will start in 2024, while the first tests of OBELIX-1 will be also starting. Currently, there is no new functionalities foreseen between the 1st and 2nd OBELIX versions, hence the design work will focus in correcting unwanted features from the first version. Following the assumption within the schedule of Figure 10, OBELIX-2 submission should occur in the first quarter of 2025.

For the sake of completeness, it is reminded here that design work will be needed for the long-term project targeting a generic pixel matrix for a tracker. This activity should be included within the C4Pi contribution to the ECFA-DRDs.

V-D.ii Microtechnic activities

During the R&D phase, the production of dedicated carrier printed circuit boards and subsequent bonding of a number of OBELIX-1 sensors will be required for characterization. The amount of such simple assemblies is typically between 10 to 20 (since also shared with other partners). It is not expected to increase significantly the load of the microtechnic team and can be handled in the standard flow of such activities.

During the production phase, other assemblies with similar amount will be required for the validation of OBELIX-2.

In addition, probe testing for a fraction of the 3000 sensors can be done at IPHC. The exact amount will depend on the sharing with other partners within the VTX collaboration and what could be considered as a reasonable load for the local microtechnic team. Typically this load could amount to a about 0.5 person.months for a year. However, such testing will require a new probe-station, since the current device is too old and beyond standard maintenance to carry out a production task.

A third task concerns detection module production for the VTX outer layers. The technical details of the assembly of such modules are not yet known, but will be similar to what was realised for the AlICE-ITS2 modules mounted in IPHC since the overall ladder design is similar.

This activity might not be compulsory, depending on how many other laboratories in the VTX collaboration commit to it. Considering the need to assemble about 2000 sensors, having 4 sites would mean handling between 400 to 600 sensors per site over one year, depending on the load sharing. The corresponding work-load is estimated around 1 FTE over one yer. Assembling modules has to be seen as an opportunity for the microtechnic team to maintain its expertise in handling thin MAPS.

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Regarding the installation of the final detector on the experimental site at KEK, usually large manpower are requested to handle various tasks like cabling and manipulation of the detector. Contribution to such activities can be decided later but will be welcome from the microtechnic group if available.

V-D.iii Test activities

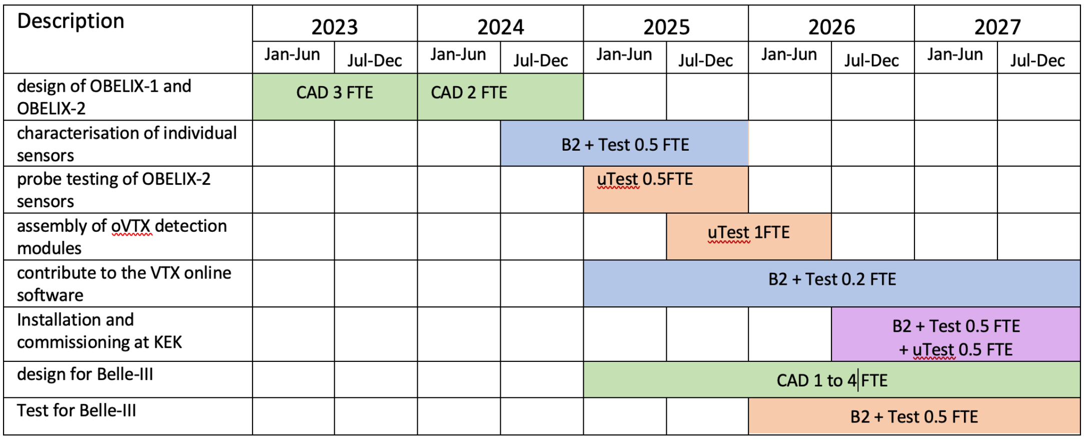
IPHC is neither involved in the development of the acquisition systems for tests nor for the final detector. Nonetheless IPHC should take part in the characterisation of both OBELIX-1 and OBELIX-2. This activity will mostly be handled by physicists from the Belle II group, staff and temporary personnel. A post-doc supported by AIDAinnova, has been recruited from February 2023 to August 2024, to work at 50% on this task. An additional post-doc will be needed to complete the testing of OBELIX-1 and proceed to the evaluation of OBELIX-2.

The help of the C4Pi test team will be required to install and commission test setups. In a similar way, if production activities (probe testing and module assembly) are carried out at IPHC, some help will be needed for the setup.
To some extent, help on the installation of the VTX detector within Belle II in 2026-27 will be welcome, though possibly non essential. This activity has to be seen as an opportunity for C4Pi personnel to get in touch with the final detector they have developed.

Finally, the Belle II group wishes to continue with the fruitful collaboration with C4Pi about the online monitoring of the current silicon strip detector, which amounts to 0.2 FTE. We are also looking to increase our participation in this activity, since we are convinced it will benefit our ability to monitor MAPS in general.

V-E Schedule and budget

The schedule of IPHC activities will naturally follow the overall planning of the project, which current version is presented in Figure 10 and assume an installation in 2027. They correspond to tasks which time span and proposed associated C4Pi staff are displayed in Figure 11.



Description	2023		2024		2025		2026		2027	
	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec	Jan-Jun	Jul-Dec
design of OBELIX-1 and OBELIX-2	CAD 3 FTE		CAD 2 FTE							
characterisation of individual sensors				B2 + Test 0.5 FTE						
probe testing of OBELIX-2 sensors					uTest 0.5FTE					
assembly of oVTX detection modules						uTest 1FTE				
contribute to the VTX online software					B2 + Test 0.2 FTE					
Installation and commissioning at KEK								B2 + Test 0.5 FTE + uTest 0.5 FTE		
design for Belle-III					CAD 1 to 4 FTE					
Test for Belle-III							B2 + Test 0.5 FTE			

Figure 11: Schedule of tasks related to the development of the VTX project at IPHC.

The overall cost of the VTX project is currently estimated at 4.5 MUSD, among which 1.3 MUSD is dedicated to the sensor development, test and fabrication. In the R&D phase up to the characterization of OBELIX-1, funding is essentially coming from the IN2P3 Master Project DICE (now DEPHY), to a lesser extent from the IN2P3 Master Project Belle II and from a IDEX project won by G.Dujany called Probe. This budget fuels the fabrication and the test of the first complete OBELIX version. Already 110 kEUR have

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been secured for the submission of OBELIX-1, institutes outside France will complete the overall 300 k$ needed. Additional 15 kEUR were received for test equipment. In 2023, a budget around 15 kEUR will still be needed for dicing and thinning operations for OBELIX-1 produced wafers.

For the production phase when the decision for construction is taken, a dedicated budget is expected to be allocated to the Master Project Belle II . 360 kEUR is requested to IN2P3 for contributing to the expected 900 kUSD cost of the sensor production and test. If IPHC engages in the validation and assembly activities, some additional budget would be required. On the one side, a budget around 30 kEUR would cover assembly of detection modules (but should be revised once the detailed plan is known). On the other side, performing probe-testing of the final sensors would probably require a new probe station, which means a investment in the range of 350 kEUR.

VI Future e$^+$e$^-$ collider

VI-A Scientific context

VI-A.i Introduction

As stated by the European Strategy Update in Particle Physics in 2021 [26], *An electron-positron Higgs factory is the highest-priority next collider*, beyond LHC. Driven by this faith, the PICSEL team presents its long term project to contribute to the realisation of an inner tracking and vertexing detector whatever the selected electron-positron collider will be.

For the last 20 years, the PICSEL team, closely connected to the platform C4PI devoted to CMOS-MAPS sensors, has been focusing its activities on the research, the development, the fabrication and the exploitation of CMOS-MAPS for subatomic physics. It lead to major successes and very important contributions to establish the CMOS-MAPS technology in the subatomic physics detectors landscape (STAR-HFT, ALICE ITS-2, EU-DET telescopes, etc.). It is clear however that the technology hasn't reached yet its full potential, since the progress of the performances offered by the evolution of the technology carried by the industry is still very significant (smaller feature sizes, new options to optimize the collecting node, new architectures, interconnection, etc.). This progress might even lead to new applications or potential breakthroughs in future tracking systems for subatomic physics.

By being monolithic, the MAPS technology presents the advantage of containing the sensitive layer (silicon layer grown by epitaxy) and the very front end electronics implemented on the same silicon substrate. This allows designing and building very granular pixels and very thin chips which therefore offer a very competitive set of performances in terms of spatial resolution and material budget but also in terms of time resolution, data flux, power consumption and radiation hardness. As a consequence, the CMOS-MAPS technology is particularly well suited in subatomic experiments where the spatial resolution is the leading parameter of the experiment requirements, namely in vertex detector and inner tracker systems. In particular, lepton colliders (namely future Higgs factories like FCCee, ILC, CLIC, CEPC, C3, etc. but also Belle-2 upgrades) and heavy ions experiments (CBM-MVD, ALICE ITS-3, ALICE-3, EIC, etc.) can usually prioritize these requirements with respect to the experimental environment constraints (e.g. radiations and particle flux).

In the long term ($\simeq$ 10-20 years), the main scientific goal of the PICSEL team goal is to contribute to the design and the fabrication of a vertex and an inner tracking detector for a future Higgs factory. Nevertheless, shorter term applications and projects can offer very attractive opportunities and synergies to pursue the effort of the R&D allowing implementing CMOS-MAPS sensors in real subatomic experiments. Not doing only long term R&D, but also contributing to large size sensors fabrication which are used in experiment is a must to confront new ideas and the evolution of the technology to real experimental constraints. Furthermore, it maintains the know-how of the C4PI platform to a world-class level.

The PICSEL team is therefore pursuing its efforts on the long term CMOS-MAPS R&D and also targets mid-term objectives. Such activities can be the development of fully functional chips for real experiments, like the MIMOSIS chip (in 180 nm feature size technology) dedicated to the Micro-Vertex Detector (MVD) of the CBM experiment at FAIR. A second type of activities consist to contribute to generic or dedicated R&D programs (which might be also driven by experiments, as it is proposed by the Belle-2 and ALICE teams of IPHC), like the exploration of the 65 nm CMOS imaging process (TPSCo), during the period 2019-2022 and which is now the baseline for the ALICE-ITS3 project. These midterms projects are excellent opportunities to develop synergies between the different IPHC teams and C4PI and therefore to reinforce the world wide recognized expertise of IPHC on CMOS-MAPS. In addition, it allows maintaining a strong network of international partners and are often a *sine qua non* condition to access to the funding of the different submissions.

VI-A.ii International context

Up to now, the PICSEL team has always positioned its R&D activities inside a large international network and benefited from the european programs of R&D (AidaInnova, Eurizon, etc.).

As it was underlined by the European Committee for Future Accelerators (ECFA) in the 2021 ECFA Detector Research and Development roadmap, Monolithic Active Pixel Sensors (MAPS) are expected to keep playing a major role to equip experiments in subatomic physics in the coming decades.

More recently, the CERN Council requested ECFA to settle the Detector Roadmap Implementation through specific R&D collaborations: *Detector R&D Collaborations* (DRD). Currently, (during Q2/Q3 2023) the DRD proposal teams are preparing full DRD proposals to be evaluated by the *Detector Research and Development Committee* (DRDC) which will submit their recommendations to the *CERN research board* which would grant approval to the DRD collaborations at the end of the year 2023.

The DRD3 (Solid State Detectors) and DRD7 (Electronics and On-detector Processing) will cover the main aspects of CMOS-MAPS R&D. The PICSEL team and C4PI together will therefore join their efforts for the R&D inside this framework in the future. Beyond the end of the MIMOSIS project, since CERN will mainly support the 65 nm TPSCo CMOS imaging process in the coming decade (for ALICE ITS-3 project and also supported by the CERN EP R&D WP1.2), the PICSEL team and C4PI will also prioritize the R&D in this technology after 2024. It is the main reason why PICSEL has cosigned recently a letter of intent concerning the R&D in 65nm, gathering various teams (CERN, DESY, APC, IPHC, etc.) motivated by the R&D dedicated to future Higgs factories within the DRD3/7 framework.

However, because the 180nm technology remains cheaper and since the C4PI has the regular opportunity to drive multi-project engineering runs in 180nm, one doesn't exclude to submit new ideas and small prototypes in this technology beyond 2025.

VI-A.iii National and local context

On the national level, IN2P3 is supported the CMOS-MAPS R&D through 2 master projects (DEPHY and GRAM). The latter is mainly adressed to focus on future lepton colliders and very granular sensors. This activity has been mainly carried by the PICSEL and the C4PI platform in the last two decades. The general concept of the proposed vertex detector was based on 3× double sided layers geometry in order to minimize the material budget of the services and the mechanical supports. Although the R&D of the PICSEL team was driven mostly in the ILC (and the ILD detector concept) context, the concept was generic enough to be adaptable to any Higgs factory machine. Since 2019, one observed a significant global evolution in Japan and in Europe concerning the different Higgs factories projects. IN2P3 therefore decided to support FCCee as the baseline Higgs factory project.

As a consequence, the PICSEL team reevaluated its own strategy to become less project specific than in the past. While there are significant differences between the different project translating into various requirements (e.g. beam pipe and geometry specifications, beam time structure, expected beam background, etc.) the global requirements can be considered as generic enough to be adaptable to any project. With respect to the state of the art of the technology (MIMOSIS, ALPIDE, etc.), the targeted improvements include spatial resolution ($\simeq 2 - 4 \mu m$ range), adapted time resolution ($\simeq 10 - 300 ns$ range), data flux up to $\simeq O(50 - 100 MHz/cm^2)$ while keeping a power consumption under control ($\simeq 20 -$

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$50mW/cm^2$ range to allow air flow cooling) (see table 4). The challenge consists in reaching all these parameters in the same time. The inner tracker detectors in Higgs factories are usually considered as trigerless but a filtering approach to alleviate the occupancy due to beam background is not excluded.

To support the R&D dedicated to future Higgs factories, simulations and physics studies are mandatory to elaborate precisely the detector requirements. The efforts of the community are focusing on the feasibility studies for FCCee (for ≃ 2026) to provide a decision input for the next European strategy update in particle physics (for ≃ 2027). The PICSEL team has started to join to this effort through physics simulation where the vertex detector and the inner tracking system performances are key factors (final state with heavy flavor tagging, long lived particles searches, etc.). A fine description of the detector, including all services (Power scheme, monitoring, data path, cooling and mechanical support, etc.) is a must to deliver reliable conclusions on the detector optimisations. In addition, a realistic response description of the detectors need also to be implemented (from charge deposition and clusters formation up to digitisation). The know how of the team will allow to contribute significantly to this effort.

VI-B Research themes

In order to exploit fully the potential of MAPS, the PICSEL team builds its strategy on three main pillars:

- first, develop MAPS up to their exploitation in subatomic experiments (e.g. MIMOSIS project);
- second, contribute to the generic R&D of the MAPS technology (e.g. 65 nm R&D) which allows to approach the Higgs factory vertex and tracker requirements;
- third, perform physics studies, simulations and optimization of detectors to define more precisely the performance requirements of the detectors (in the context of ILC and FCCee software)[4].

The three pillars are strongly interconnected. The PICSEL team will therefore pursue its activities based on the following axis:

VI-B.i MIMOSIS Program

By fabricating full size sensors, the goal is to contribute to MAPS sensors R&D and chips fabrication dedicated to midterm's applications in order to install these chips in real experiments, allowing maintaining and developing the know-how at IPHC. It is believed that it is the best approach to keep the high level of expertise gathered at IPHC while the long term future remains subject to large uncertainties. In addition, it improves step by step the overall performance of MAPS, improving the range of the parameter space of applications. The MIMOSIS series of prototypes is currently the spearhead action of this approach. The final MIMOSIS chip will therefore be a milestone for the future Higgs factories.

Started in 2015, The MIMOSIS program which design is inspired from ALPIDE, is proposed as a synthesis of the current state of the art of the technology and allow to approach the Higgs factories requirements (spatial resolution ($\simeq 5\mu m$), time resolution ($O(5\mu s)$), data flux ($O(100MHz/cm^2)$), Power consumption ($< 70mW/cm^2$)). It is designed to equip the Micro-Vertex Detector (MVD) of the CBM experiment at FAIR [27]. Similarly to what was done with ALPIDE, the MIMOSIS program includes in-depth studies on variant processes and different epitaxial thicknesses to optimize charge sharing and threrefore radiation hardness vs spatial resolution.

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[4] A joint CMS-FCCee post-doc, starting in July 2023 for 2 years will reinforce this activity.

After a successful campaign of test on MIMOSIS-1 during 2020-2022 [28] [29], the tests of the second large scale prototype (MIMOSIS-2) will occur starting June 2023. The final sensor (MIMOSIS-3) should be fabricated in the beginning of 2025. This program is supported by a very strong effort from the C4PI platform and leads to an intense laboratory and beam test program ($\simeq$ 3 FTE from the test team of C4PI).

Finally, the program allows to maintain a long and very fruitful collaboration with german partners (GSI, IKF) which should be carried on even beyond the end of the MIMOSIS program. It opens also connexions to the nuclear physics communities and NUPEC.

VI-B.ii Generic R&D from 180 nm to 65 nm R&D

The second pillar consists in performing long term R& D with C4PI in order to fully exploit the potential of the technology (which is far from being reached) and approach the future Higgs factory requirement for the inner tracking and vertexing system. In particular, R&D will be pursued on qualifying new feature size technology (65 nm feature size) [30] [31], exploring new readout architecture to optimize performances, optimizing the charge collection node, exploring various charge and time encoding (e.g. ADC, ToT), study preamplification, etc. Those efforts are usually sustained by small size prototypes but sizable prototypes (cm^2 could also be produced as demonstators.

This effort should allow to define the architecture(s) most suited for the future e^+e^- colliders. The midterms objective corresponds to the next update of the European Strategy for Particle Physics (ESPP) process around 2026 and will consist of contributing to a demonstrator dedicated to future e^+e^- colliders that could also target beam telescope applications. This project will be driven in the framework of DRD3/7 and supported by the CERN EP R&D WP1.2 as explained before. The C4PI platform will again play a crucial role and the priorities of the efforts will be defined in a coordinated approach.

The PICSEL team has also decided to join to the ALICE ITS-3 project (cf. the dedicated section), since the generic R&D and the dedicated prototypes for ITS-3 (e.g. MOSS) are strongly connected. However ITS-3 submissions will privilege a focus on stitched sensors not necessarily allowing a R&D covering all future Higgs factories needs and requirements.

The calendar of submissions in the TPSCo 65 nm technology should allow to pursue both efforts (ALICE IT-3 and generic R&D) in a very complementary way.

VI-B.iii Software / detector optimisation

Software expertises play an important role to connect the R&D to the detector optimisations. The PICSEL team has developped a wide range of expertises, from test beam data analysis (e.g. TAF, Corryvreckan), Charge collection studies (e.g. Allpix2) to fast analytical tools for detector design studies (e.g. Guariguanchi, TkLayout). Furthermore, the detectors design of subatomic experiments need to be optimized with a close connection to the technology constraints. The team will continue to develop its expertise on simulations for detector optimization (digitization, vertexing and tracking algorithms, etc.) and perform full physics simulation studies to be used as a benchmark for the detector designs.

VI-B.iv Integration and test systems

Integration: The integration of MAPS in functional modules with a minimized material budget contains a lot of challenges since optimizing the other performances are usually resulting in conflicting requirements. Taking advantages of its experience in fabricating very light double sided modules[32], the PICSEL team will explore two very promising approaches: thinning and bending sensors to minimize overlapping regions of modules in cylindrical geometries and explore the design and tests of large area sensors using the stitching process which allows increasing typical sensor surfaces from few cm^2 to $O(100cm^2)$.

A large fraction of the R&D targeting future e^+e^- colliders rely on an efficient support concerning the tests systems by the C4PI platform. Depending on the program, careful choices have to be made between standalone developments of DAQ systems and more collaborative approaches with the different partners. In the future, synergies will be looked for to minimize the workload whenever it is possible (e.g. CARIBOU system for telescope beams set up, etc.).

VI-B.v Spin-off

MAPS fabricated by the C4PI platform and the PICSEL team can match requirements to applications outside the domain of high energy physics (e.g. beam monitoring, Imaging, X-ray detection, etc.). Collaboration projects can emerge using existing prototypes (like MIMOSIS) or allowing developing dedicated prototypes (like Monolithic-Imager designed by C4PI). Currently, partnerships are ongoing with another IN2P3 laboratory (CENBG) targeting proton spectroscopy in the context of ion acceleration in plasma. Also, in the context of the common laboratory between AERIAL and IPHC, an instrument for beam spectrometry is under investigation. The PICSEL team will continue its efforts to explore opportunities for synergies with various partners of other domains.

VI-C Summary

In summary, despite uncertainties concerning the future of e^+e^- colliders beyond the LHC program, the R&D on CMOS-MAPS is fully in line with the priorities of the community of subatomic physics. The PICSEL team is committed to drive an ambitious R&D bringing the potential of CMOS-MAPS to the next level required at the future Higgs factory. In the future, the group wants to keep playing a major role in the MAPS R&D and the exploitation of the technology, and will continue exploiting the network of collaborations, at IPHC and beyond, it has built in the two past decades. The team, currently composed of 4 permanent researchers, 2 engineers, 1 PhD and 4 post-docs will pay great attention to the distribution of efforts in a context of limited human resources, by responding to calls for projects if the synergies can be exploited.

The PICSEL team expects fruitfull exchanges with the scientific council to help the team to validate its priorities and confirm its overall strategy with respect to the expected workload.

VI-D Annex

VI-D.i Specification summary

The table 4 provides a summary of the specifications both for the MIMOSIS project and for the vertex detector of the future Higgs factories (mainly in the FCCee/ILC context).

VI-D.ii Main partners outside the laboratory

The MIMOSIS program is driven by the CBM-MVD collaboration gathering mainly IPHC, IKF and GSI [27].

The network developed for the future e^+e^- collider is large and varied, including the worldwide ILC and FCCee community, emerging collaborations with french laboratories (e.g. APC, IP2I), partners in the TPSco 65 nm technology R&D inside the framework of the DRD3/DRD7 (CPPM, APC, Zurich, CERN, DESY).

The activities are also supported by European programs like AidaInnova or Eurizon.

VI-D.iii human resources, Gantt diagram and deliverables

The figure 12 represents the knwon human resources of the PICSEL team which dedicates most of its efforts to the described project. The MIMOSIS program, The generic R&D and the simulations represent approximately a equal share workload (about 30 % each). A small fraction is dedicated to spin-off ($\simeq 5\%$) and integration activities ($\simeq 5\%$). The end of

Specification	MIMOSIS (CBM-MVD)	Higgs factories (FCCee/ILC)
Resolution		
Pixel pitch	$26.9 \times 30.2\,\mu\mathrm{m}^2$	$15 - 20\,\mu\mathrm{m}$
Spatial resolution	$\simeq 5\,\mu\mathrm{m}$	$\simeq 3\,\mu\mathrm{m}$
Sensor thickness	$50\,\mu\mathrm{m}$	$50\,\mu\mathrm{m}$
Mat. budget / layer	$0.05\% X_0$ (fixed target)	$\simeq 0.15\% X_0$
Data flow		
Hit rate	$\simeq 70$ MHz cm^{-2}	$10 - 100$ MHz cm^{-2}
Time resolution	$5\ \mu s$	$100 - 500\ ns$ $O(ns)$ (CLIC or backgd reject.)
Output	$8 \times 320\ Mb/s$	t.b.d.
Rad. tol. (inc. safety factor)		
Ionizing dose	5 MRad/year	100 kRad/year
NIEL fluence	$7 \times 10^{13} \mathrm{n_{eq} cm^{-2}}$/year	$10^{11} \mathrm{n_{eq} cm^{-2}}$/year
Integration		
Matrix dimensions	1024×504 pixels	t.b.d.
Sensor area	$\simeq 4.2\ cm^2$	t.b.d.
Power	$< 100\ mW/cm^2$	$20 - 50\ mW/cm^2$
Cooling	in vacuum operation	Air Flow
Stitching	no	optionnal
Bent sensors	no	considered

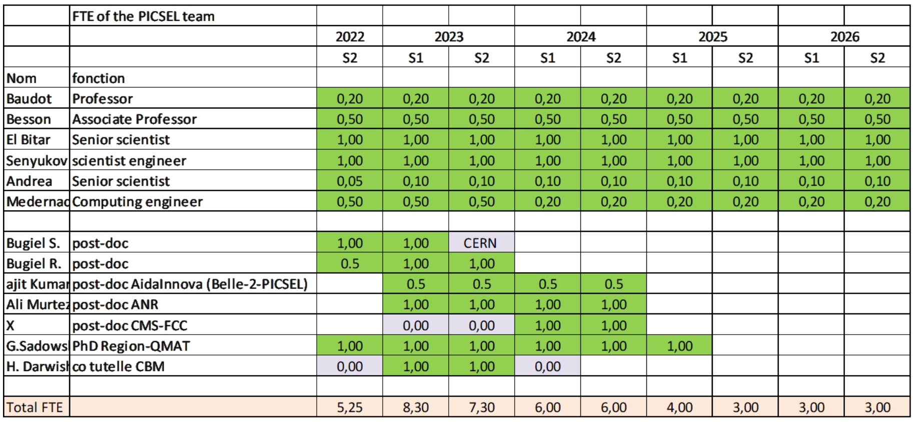
Table 4: General specifications for MIMOSIS and sensors for Higgs factories vertex detectors

the MIMOSIS program after 2025 will allow to release human resources for the R&D line in the 65nm technology. Additional human resources (in particular non permanent positions) are needed beyond 2025 to sustain the same level of activities and will be requested to the funding agencies. Starting 2025, these additional needed resources are estimated to be of the order of ≃ 2 FTEs.

On the period 2024-2028, the estimated resources requested to the C4PI platform are estimated to be:

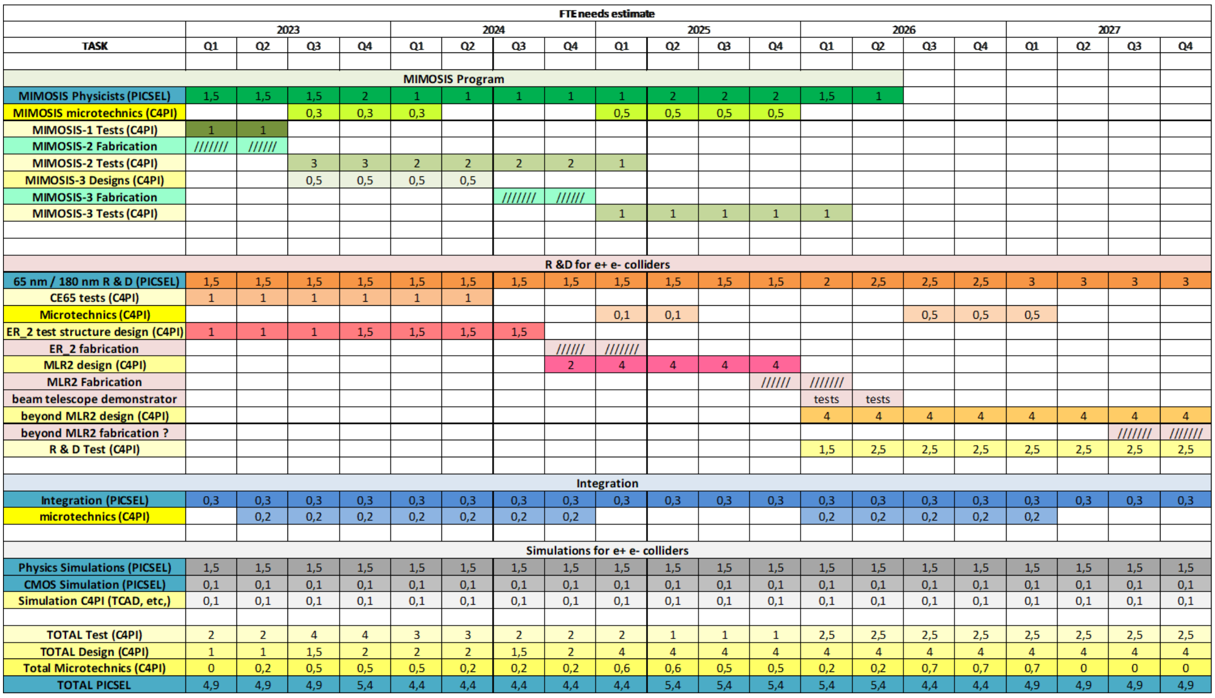
- Microtechnics: ≃ 0.5 FTE
- Tests: ≃ 3 FTE
- Designs: ≃ 2.5 FTE

A more detailed view is provided in the figure 13. Whereas the MIMOSIS calendar is known with a good precision, the R & D activities calendar in the 65 nm technology highly depends on the submission plans. Discussions are also ongoing inside the DRD3/DRD7 framework which will allow to improve the accuracy of the agenda in the coming months. The critical identified period is probably the year 2025.



	FTE of the PICSEL team									
		2022	2023		2024		2025		2026	
		S2	S1	S2	S1	S2	S1	S2	S1	S2
Nom	fonction									
Baudot	Professor	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20	0,20
Besson	Associate Professor	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50	0,50
El Bitar	Senior scientist	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Senyukov	scientist engineer	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Andrea	Senior scientist	0,05	0,10	0,10	0,10	0,10	0,10	0,10	0,10	0,10
Medernac	Computing engineer	0,50	0,50	0,50	0,20	0,20	0,20	0,20	0,20	0,20
Bugiel S.	post-doc	1,00	1,00	CERN						
Bugiel R.	post-doc	0.5	1,00	1,00						
ajit Kumar	post-doc AidaInnova (Belle-2-PICSEL)		0.5	0.5	0.5	0.5				
Ali Murtez	post-doc ANR		1,00	1,00	1,00	1,00				
X	post-doc CMS-FCC		0,00	0,00	1,00	1,00				
G.Sadows	PhD Region-QMAT	1,00	1,00	1,00	1,00	1,00	1,00			
H. Darwish	co tutelle CBM	0,00	1,00	1,00	0,00					
Total FTE		5,25	8,30	7,30	6,00	6,00	4,00	3,00	3,00	3,00

Figure 12: FTE of the PICSEL team



FTE needs estimate																				
	2023				2024				2025				2026				2027			
TASK	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
MIMOSIS Program																				
MIMOSIS Physicists (PICSEL)	1,5	1,5	1,5	2	1	1	1	1	1	2	2	2	1,5	1						
MIMOSIS microtechnics (C4PI)			0,3	0,3	0,3				0,5	0,5	0,5	0,5								
MIMOSIS-1 Tests (C4PI)	1	1																		
MIMOSIS-2 Fabrication	///////	//////																		
MIMOSIS-2 Tests (C4PI)			3	3	2	2	2	2	1											
MIMOSIS-3 Designs (C4PI)			0,5	0,5	0,5	0,5														
MIMOSIS-3 Fabrication							///////	//////												
MIMOSIS-3 Tests (C4PI)									1	1	1	1	1							
R &D for e+ e- colliders																				
65 nm / 180 nm R & D (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	2	2,5	2,5	2,5	3	3	3	3
CE65 tests (C4PI)	1	1	1	1	1	1														
Microtechnics (C4PI)									0,1	0,1					0,5	0,5	0,5			
ER_2 test structure design (C4PI)	1	1	1	1,5	1,5	1,5	1,5													
ER_2 fabrication								//////	///////											
MLR2 design (C4PI)								2	4	4	4	4								
MLR2 Fabrication												//////	///////							
beam telescope demonstrator													tests	tests						
beyond MLR2 design (C4PI)													4	4	4	4	4	4	4	4
beyond MLR2 fabrication ?																			///////	///////
R & D Test (C4PI)													1,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Integration																				
Integration (PICSEL)	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3	0,3
microtechnics (C4PI)		0,2	0,2	0,2	0,2	0,2	0,2	0,2					0,2	0,2	0,2	0,2	0,2			
Simulations for e+ e- colliders																				
Physics Simulations (PICSEL)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
CMOS Simulation (PICSEL)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Simulation C4PI (TCAD, etc,)	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
TOTAL Test (C4PI)	2	2	4	4	3	3	2	2	2	1	1	1	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
TOTAL Design (C4PI)	1	1	1,5	2	2	2	1,5	2	4	4	4	4	4	4	4	4	4	4	4	4
Total Microtechnics (C4PI)	0	0,2	0,5	0,5	0,5	0,2	0,2	0,2	0,6	0,6	0,5	0,5	0,2	0,2	0,7	0,7	0,7	0	0	0
TOTAL PICSEL	4,9	4,9	4,9	5,4	4,4	4,4	4,4	4,4	4,4	5,4	5,4	5,4	5,4	5,4	4,4	4,4	4,9	4,9	4,9	4,9

Figure 13: Gantt Diagram of the necessary resources to allocate to the e^+e^- collider project

VII Interplay between projects

The first bullet in the list of top 4 priorities in the conclusion in the 2021 ECFA roadmap for Detector R&D ([33], ch. 11, p.219) reads: ”Develop cost-effective detectors matching the precision physics potential of a next-decade Higgs factory with beyond state-of-the-art performance, optimised granularity, resolution and timing, and with ultimate compactness and minimised material budgets.” The same document underlines in passing where such R&D can take place (ch. 8, p.176) : experiments like “ALICE, EIC, Belle II and µ3e are natural stepping stones for R&D towards a future e^+e^- Higgs-factory collider” because “luminosity levels are moderate [*e.g.* unlike ATLAS, CMS cases] while precision vertexing and PID are key elements”. Such a family of experiments (ALICE, Belle II, FCCee) addressing quite different topics within HEP do have in fact a significant fraction of technological specifications in common. This is illustrated in the qualitative spider chart in Figure 14 below and similarly illustrated in the solid state chapter of the ECFA roadmap (see visual Fig. 3.1 and quantitative Fig. 3.2 p.60 in [33]).

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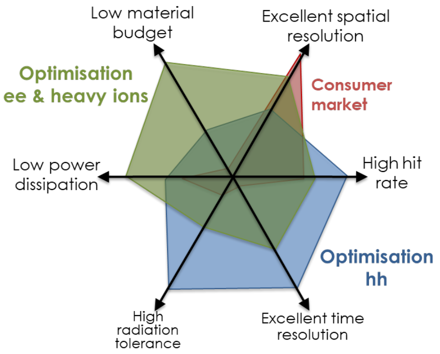

Figure 14: Spider chart showing qualitatively the various characteristics to be optimised on silicon sensors in view of HEP applications for trackers. The chart covers 3 use cases, for experiments focusing on high-luminosity proton-proton collisions (*e.g.* ATLAS and CMS), for experiments related to e^+e^- or heavy-ion collisions (*e.g.* like Belle II, ALICE), for the consumer-driven market.

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With a bit more details, a comparisons of the numerical value of the main chips specifications, for the various projects the IPHC where involved and the future projects of interest, is shown on Tab.5. A visualisation this table can be used to identify the parameters which needs to evolved and the direction to take for design developments. A visualisation of this table can be seen on the spider diagram presented in Fig.15.

chips	Mimosa-28/Star	Mimosis/CBM	Alpide/ITS2	Obelix/Belle-II
Power(mW/cm^2)	170	70	35	200
Pos. resolution (μm)	4	5	5	9
Mat. budget $X/X_0(\%)$	0.37	0.3	0.3	0.15
Hit rate (MH_z/cm^2)	0.1	70	1	120
Time resolution (ns)	200'000	5000	5000	100
Rad. tolerance ($10^{15}n_{eq}$)	0.01	0.05	0.05	0.5
Sensor size (cm^2)	4.6	5.4	4.5	5.7

chips	MOSS/ITS3	vertex/FCCee	tracker ee-type	tracker hh-type
Power(mW/cm^2)	20	20	10	100
Pos. resolution (μm)	5	3	10	15
Mat. budget $X/X_0(\%)$	0.05	0.15	0.5	1
Hit rate (MH_z/cm^2)	10	50	100	200
Time resolution (ns)	5000	500	1	0.1
Rad. tolerance ($10^{15}n_{eq}$)	0.05	0.0011	1	9
Sensor size (cm^2)	300	6	100	100

Table 5: Summary table of the main chips specifications for the various projects where IPHC was/is/will be involved and on the possible future projects.

It should be noted in particular that, in close collaboration with the C4Pi platform, the PICSEL team has led first the effort of IPHC into the exploration of the new "65-nm" technology node, its generic R&D program on MAPS joint in the first place the effort with ITS3. ALICE-IPHC and PICSEL interests converge to quite an extent, following the very similar specifications between the ITS3 detector and the vertex detectors for BEH boson factories (ILC, FCCee). As far as and as and as long as there are common interests and skills to be gained for the Higgs factory projects, ALICE-IPHC and PICSEL team wishes to work together, in concert with the ALICE ITS3 project. The likely re-factorisation of efforts may appear after ITS3 ER2 [tape-out in first trimester 2024], when the sensor design will become 100% ITS3 specific and the submission of MLR2 in EP R&D WP1.2 will need to be prepared.

Due to the individual schedule for developing their respective reticule-size sensor (MIMOSIS and OBELIX) and the difference on the requirements for these chips, the PICSEL and Belle II groups do not have currently synergetic activities. Future opportunities might open, possibly connected to the integration of MAPS on very light structure.

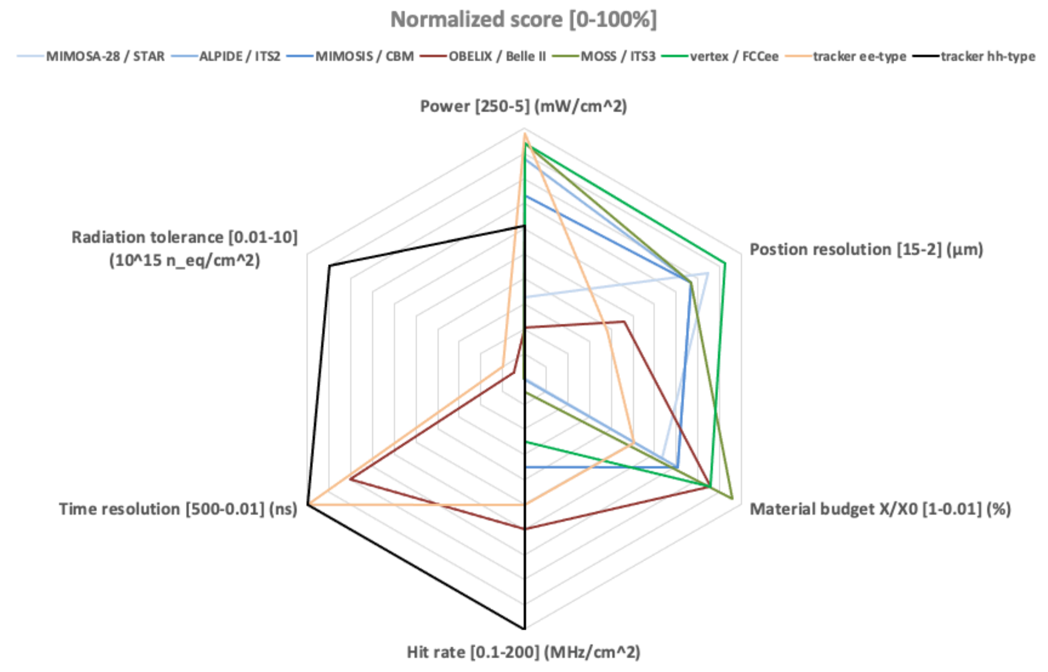

Figure 15: Spider diagram visualizing the content of the Tab.5.

The ALICE and Belle II groups both target the development of a monolithic sensor in the TPSCo 65 nm devoted to a large volume tracker. This activities will start within the ECFA Detector R&D collaboration from 2024. Specifically, the program will start with the design of a pixel matrix adapted to a tracker requirements. Since the same CMOS technology will be used as for the PICSEL sensor aiming for excellent position resolution starting from 2024, a number of developments are expected to be shared (*i.e.* standard functional blocks in the sensor, common testing systems and facilities).

The person-power needs expressed by the various projects to the C4Pi facility have been compiled in graphics, see Fig. 16, showing the evolution with time of the sharing of the C4Pi permanent staff per activities. Evolution in the total number of available full-time-equivalent (FTE) personnel corresponds to recruitment, already planned for the test group in 2024 and wished for both in the design group in 2025 (but compensated by a retirement) and in the micro-technique group around 2026.

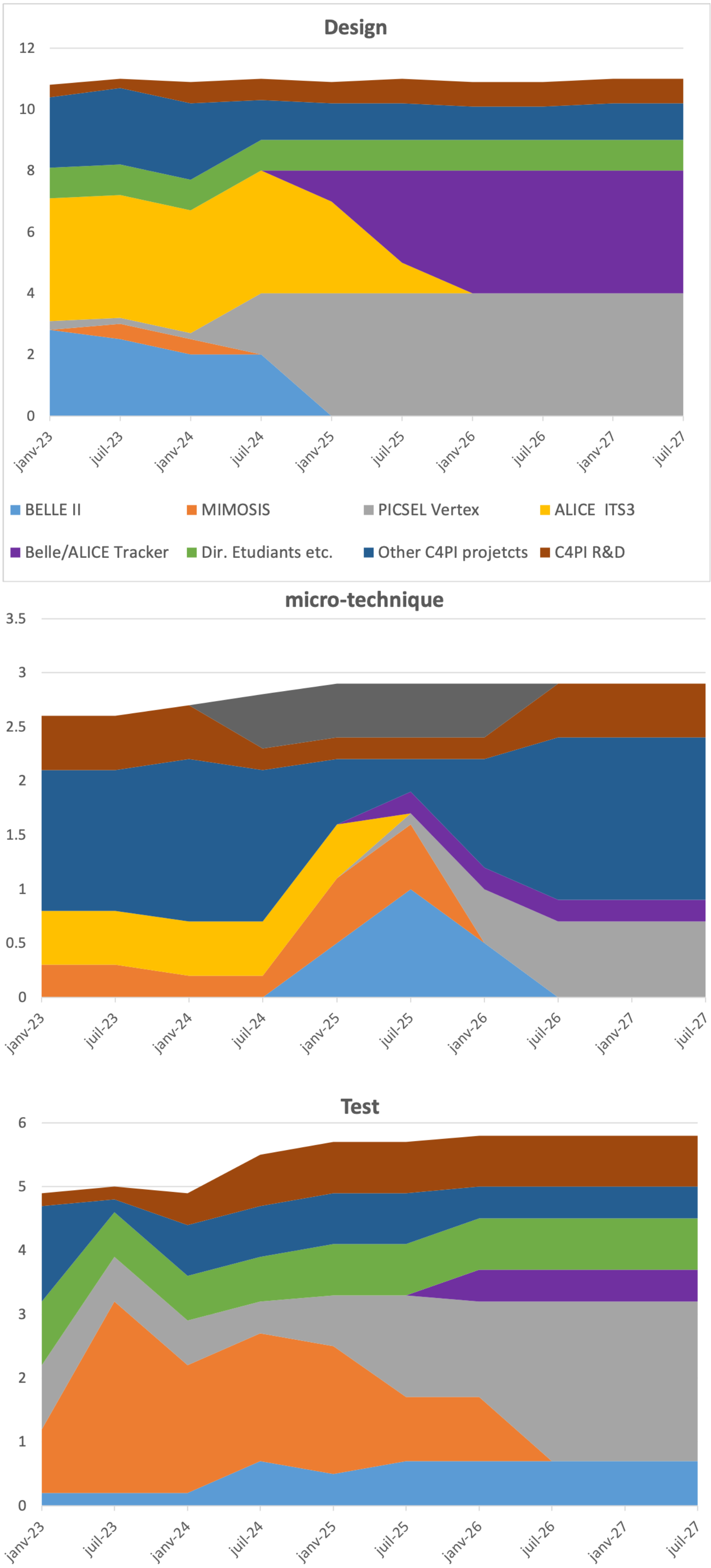

Figure 16: Planed sharing of the full time equivalent (FTE) staffs at C4Pi for each expertise domain and between the various projects. Note that the cumulative number of FTEs is not exactly the total number of staff available to account for their activity not directly related to projects. In addition, the cumulative FTEs evolution reflects recruitment of new staff personnel, see text. As a reminder, the C4Pi platform is composed of 12 designers, 5 persons in charge of tests, and 3 persons at the micro-technique service.

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A Questions asked to the Scientific Council

Several instrumental projects in high-energy physics are being prepared for the next 5 to 10-years within the Subatomic Research Department of the IPHC. These projects are in line with well-established research activities and concern the development, construction and integration of CMOS pixel sensors. These projects, led by the scientific teams, are based on the expertise and know-how of the C4PI platform.

The management of IPHC would first like an opinion from the scientific council on each of the projects presented, their synergies and the adequacy with the resources of the laboratory. Where appropriate, possible long-term prospects may be considered. The evaluation will focus on instrumental themes, and not on prospective physics analyses.

The opinion of the Scientific Council will be requested in particular on the following points:

1. Evaluate the scientific and technical relevance of each of the proposed instrumental projects in the context of national and international collaborations, as well as in the framework of the In2p3 prospective and the European strategy for particle physics (ESPP 2019 Phys. Briefing book + ECFA detector roadmap 2021).

2. Evaluate the degree of feasibility of each project with regard to current know-how, existing means and available resources, in particular human resources.
3. Evaluate the impact of these instrumental projects in maintaining and developing relevant technical skills for the future.
4. Assess the possible synergies and complementarities between the different projects.
5. Evaluate whether the commitment to this set of instrumental projects will leave sufficient room and flexibility for staff training, technological monitoring and the possibility of seizing future opportunities.