Contribution to IN2P3 Scientific Council

IN2P3 contributions to an all-layer monolithic pixel vertex detector for the Belle II upgrade

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1 Executive summary

The Belle II experiment started its data taking in 2019, exploiting collisions provided by the SuperKEKB accelerator. The Belle II physics program extends in the next ten years and its completion requires a peak luminosity of $6 \times 10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In 2026-27, the interaction region will undergo a modification to allow this higher instantaneous luminosity. To guarantee optimal detection performance, the Belle II collaboration intends to upgrade its vertex detector during the shutdown used for the machine upgrade.

The three IN2P3 laboratories already analyse actively Belle II data and participate to the present strip detector operation as well as to the improvement of the current beam-pipe cooling (2022-23). Along with other European laboratories, CPPM, IJClab and IPHC, propose, for the vertex detector replacement, to build a 5-layer pixel system based on the CMOS sensor technology. The main guideline of this VTX project is to exploit a sensor technology, which detection performance for the Belle II conditions have been proven, and integration solutions already explored. This strategy drove the choice to develop the VTX sensor on the basis of the existing TJ-Monopix chip and to adopt the structure of ALICE-ITS2 ladders for the outer VTX layers.

Owing to their recognized expertise, the main focus of IN2P3 laboratories for this upgrade concerns the development of the CMOS pixel sensors, the data acquisition boards and the thermo-mechanical management of the beam-pipe and the VTX inner layers. Performance simulation for geometry optimisation and reconstruction software development complement the activities undertaken.
The VTX project schedule foresee a development phase until 2024, followed by the production over two years in order to install the new vertex detector within Belle II in 2027.
The budget request from the IN2P3 groups amount to 610 k$ over the period 2023 to 2027.

2 Scientific context

2.1 Belle II physics program and ongoing activities at IN2P3

• Belle II physics program

The standard model (SM) of particle physics is very powerful to explain the phenomena observed at particle physics experiments and it has proven to be successful in many respects, including the predictions of the existences of then unknown particles such as the top quark, the W and Z bosons, or even the Higgs boson. Despite this success, the SM fails at providing an explanation for dark matter, and, more fundamentally, it entails a high number of free parameters which limits its predictive power (the couplings between quark flavours, for example, can not be estimated in the frame of the SM). These limitations of the SM justify the searches for phenomena beyond our current understanding of particle physics which would be a signature of new physics (NP).

In contrast to LHC experiments (ATLAS and CMS) operating at the energy frontier, wherein new particles are sought via direct production that is limited by the accessible beam energy, Belle II will search for NP at the intensity frontier [1]. With the unprecedented luminosity accessible at the upgraded SuperKEKB facility [2], Belle II will seek indirect evidence of NP by searching for signatures of new particles or processes through measurements of suppressed flavour physics reactions or deviations from SM predictions. Any observed discrepancies could then be interpreted in terms of NP models. This enables a probe for NP to energies above 10 TeV. Despite of a more modest B meson production compared to LHCb, Belle II benefits from a formidable efficiency, whatever is the final state, even when containing neutral particles (e.g. K_S^0, π^0, γ). Furthermore, because the B mesons are produced by pairs (and nothing else), the flavour tagging (for time-dependent analyses) is much more efficient while B-tagging becomes the tool of choice to search for missing energy modes ($B \to K\nu\overline{\nu}$, $B \to \tau\nu$, $B \to K\tau\tau$...). Finally, an efficient trigger and effective background rejection allow to dominate the low multiplicity physics (τ sector and dark sector searches).

• Belle II data taking

The Belle II detector is a substantial upgrade of the Belle one and operates at the SuperKEKB energy-asymmetric e^+e^- collider. The design luminosity of the machine is 6×10^{35} cm^{-2} s^{-1} and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor. Belle II collected its first collisions in 2019, and is expected to operate for the next decade, see figure 1. In a first phase (run I: 2019-

2022), SuperKEKB has reached an instantaneous luminosity of 4.7$\times 10^{34}$ cm^{-2} s^{-1} and Belle II could accumulate a data sample of 430 fb^{-1}, a typical B-factory statistics. A long shutdown of one year (LS1) is needed to replace the two layers of pixels, while the run II (2023-2027) will provide a data sample close to 10 ab^{-1}. An upgrade of various Belle II sub-detectors is now being discussed [3] to be installed around 2027 (LS2).

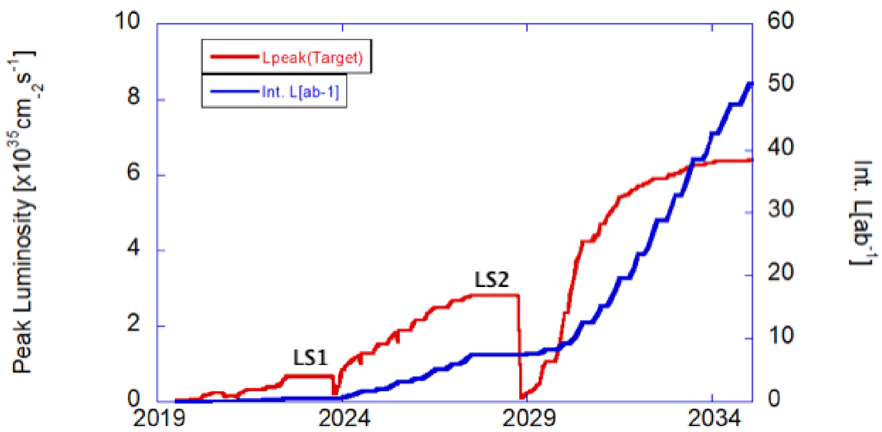

Figure 1: Operation plan as presented at the June 2022 Belle II general meeting.

- **Belle II detector**

Figure 2 provides a brief introduction to the Belle II detector, while a detailed description can be found in [4]. The instrument follows the standard concept of collider 4π experiments with two distinctive features. First, the energy asymmetry of the beams leads to the forward part of the acceptance being more instrumented and in practice very busy. Then, the nano-beam scheme exploited by the SuperKEKB machine requires to locate the final focusing magnets (QCS) close to the interaction point and inside the instrument, which in turns strongly constrains the available room for the inner detectors.

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

DEPFET[1] sensors equip the two first layers, known as the PXD [5]. These layers located at 14 and 22 mm radius, weight an equivalent 0.2% X_0, for a pixel size varying

[1] 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.

from 50×55 to 50×80 μm 2 and an integration time of 20 μs (to be compared to the 30 kHz average trigger rate).
Double sided silicon strip detectors populate the four VXD outer layers, known as the SVD [6], featuring an average material budget of 0.7% X_0. 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 the APV25 chip [7], which samples the strip signals for 60 or 120 ns and allow a final time resolution for hits of the order of 3 ns.

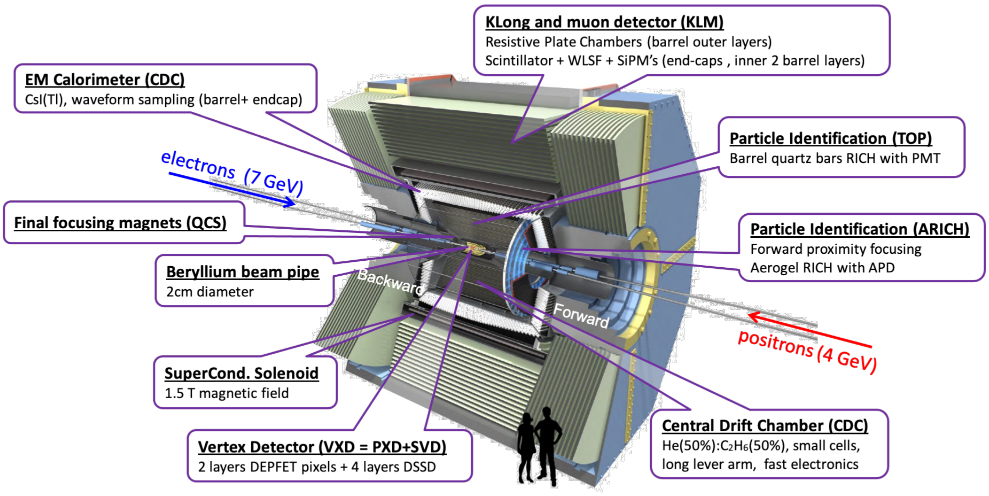

Figure 2: Sketch of the current Belle II apparatus with a short description of its sub-elements.

• IN2P3 groups in Belle II

IN2P3 joined Belle II in 2017 and was able to make significant contributions in the commissioning of the detector and studies of the machine induced background (phase 2), in the cooling and operation of particle identification detector (ARICH) and in data quality assurance monitoring for the first data. Since 2019, IN2P3 is involved in the operation with the Silicon Vertex Detector (SVD) and in tracking performance.
We have been selected in 2019 to upgrade the Belle II data acquisition (DAQ) system with PCIe40 cards in order to improve the Belle II detector performance. The hardware installation at KEK started during the 2020 summer shutdown period with the installation and commissioning of boards for a couple of subsystems. The rest of the DAQ system is and will be installed and commissioned during the shutdown period of 2021

and 2022.
Since, we also got involved in the High Level Trigger development (in operation since 2021). Belle II France with CCIN2P3 is also contributing significantly to the processing of raw data from 2021 (15% of the data).

The French Belle II groups play a major role in the exploitation of the large data sample, and are focusing their efforts on the search of NP with electroweak penguin $b \to s$ processes: $b \to s\ell\ell$, where at least one of the leptons is a τ; $b \to s\nu\overline{\nu}$ with the specific channel $B \to K\nu\overline{\nu}$; and $b \to s\gamma$ with $B \to K\pi\pi\gamma$ channels. An ambitious physics program on τ physics (mostly on the Lepton Flavour Violating decays) is also put in place.

IN2P3 researchers are well visible in the Belle II collaboration: K.Trabelsi (IJClab) is currently deputy spokesperson (2019-2023) and was recently elected to become the next spokesperson (from June 2023 for 2 years), I.Ripp-Baudot (IPHC) is a member of the speakers committee, J.Serrano (CPPM) is a member of the publication committee, F.Le Diberder (IJClab) and J.Baudot (IPHC) are members of the statistical advisory committee.

The Toshiko Yuasa France Japan Particle Physics Laboratory (TYL-FJPPL, lead by I.Ripp-Baudot) plays an important role in increasing the French and Japanese communities. Various projects were and are hosted by the TYL-FJJPL, on physics analysis and also on instrumental R&D: beam-background measurement with CMOS pixel sensors, thermo-mechanical management of the current beam-pipe and inner detection layers, R&D on CMOS sensors.
Finally, the French Belle II physicists are actively contributing to the flavour physics community through the GdR Intensity Frontier, through talks at GdR meetings, lectures and topical workshops organised with the GdR support. The GdR is currently co-coordinated by G.Dujany (IPHC).

2.2 Rationale for a Belle II upgrade

As illustrated by figure 1, accumulating over about five years a data sample beyond 10 ab^{-1} for the Belle II physics program will require a jump in the peak luminosity, with a target around 6×10^{35} cm^{-2} s^{-1}. **An upgrade of the interaction region (IR) and possibly of the final focusing magnets (QCS) is needed to reach such a specific luminosity value and the corresponding beam lifetime driven by the Touschek effect.** This machine upgrade leads to the long shutdown 2 (LS2) foreseen in 2026-27.

The understanding of the beam-induced background with the current machine is quite accurate [8] and allows to extrapolate that the present Belle II detector will continue efficient data taking under these luminosity conditions of run II .

The peak luminosity rise beyond LS2 will significantly increase the beam-induced background. While TOP and CDC seem to currently be the most critical sub-detectors, present indications suggest that also VXD (both PXD and SVD) would approach their occupancy limits - about 3 % - under such conditions. Such limits, see [9], actually originate from two effects. On the one side, occupancy around 3 % will saturate the bandwidth of the current acquisition system. And on the other side, full Belle II simulations show various degradation of the tracking performance (track finding and impact parameter resolution) beyond the same 3 % occupancy level.

Furthermore, a few options to upgrade the interaction region are considered but are yet neither decided nor detailed to the point where reliable beam-induced background can be estimated robustly at peak luminosity of 6×10^{35} cm^{-2} s^{-1}. **Consequently, the main goal for an upgraded VXD is to guarantee operation and performance of Belle II under high background levels after LS2**.

Additional improvement targets for a new VXD come from the following considerations.
Belle II triggering relies on a first hardware stage (L1) followed by a software high level trigger (HLT). Tracking is performed at the HLT stage albeit without PXD hits, which event memory size exceeds by far the HLT capacity, preventing the HLT decision to exploit the full impact parameter precision[2] and ultimately limiting triggering efficiency. The large PXD event weight stems from the long integration time - 20 μs- of the DEPFET sensors. It is then highly desirable for an upgraded VXD to provide light weight events where tracking can be performed over all layers at once, including at the HLT level.
Performance of the outer detectors depends to various extent on the material budget of the inner detector and the amount of shielding allowed in the interaction region which is currently busied by the inner detector services (cables and cooling pipes). Hence an upgraded VXD should target a lower material budget and an overall system simpler than the present VXD.

3 Project overview

3.1 The VTX concept

The three French laboratories (CPPM, IJClab and IPHC) initiated, with other European groups, a proposal to upgrade the VXD into a fully pixelated vertex detector. The project concept, called VTX, relies on a single type of pixel sensor technology

[2] PXD hits are never used for track finding but are associated to reconstructed tracks with SVD and CDC information in the offline reconstruction chain.

combining high segmentation and short integration time in order to, on the one side preserve efficient tracking and precise vertexing in a dense particle environment, and on the other side maximise simplicity at the system level.

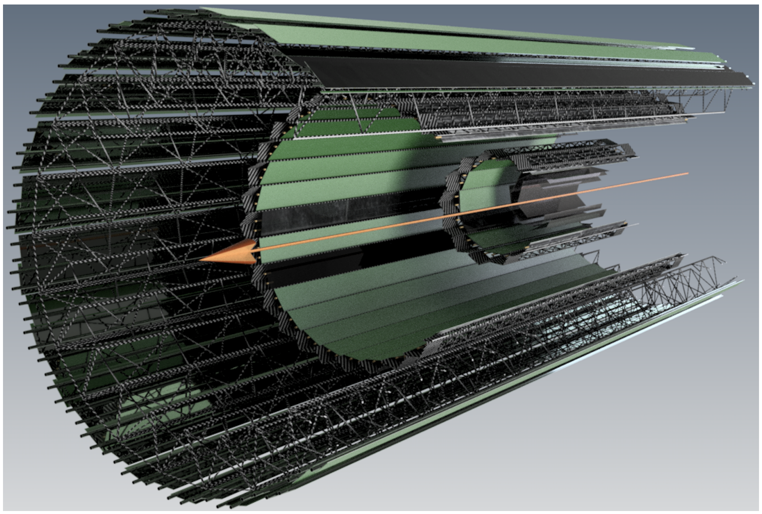

Figure 3: Simplified CAD model representeing the 5 layers of the VTX, without outgoing cables and overall mechanical support structures.

The VTX proposal consists of a fast (25 to 100 ns sensor integration time), highly granular (pixel pitch in the range 30-40 μm), limited power dissipation (maximum allowed of 200 mW/cm^2) and light (below 3% X_0 overall material budget) 5-layer vertex detector, covering entirely the existing radial and angular coverage of the present VXD and fully connected to the high-level trigger (HLT). It is implemented using a thin and radiation-hard[3] fully depleted monolithic active pixel sensor in CMOS technology (MAPS or DMAPS) based on developments inherited from the design of the ALICE-ITS2 pixel chip (ALPIDE [10]), in particular the TJ-Monopix family [11] proposed for the ATLAS Inner Tracker (ITk). The design of the detection layers depend 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.
Table 1 reviews the main specifications of the baseline VTX geometry, featuring 5 layers and covering approximately 1 m^2. Layer positions indicated in table 1 follow approximately the positions of the current VXD layers. Optimisation with the full simulation are ongoing especially regarding the third layer location and the potential

[3]The radiation tolerance levels for the VTX are: fluence 10 n_{eq}/cm^2/year and total ionising dose 100 kGy/year.

benefits of adding a 6^{th} layer.

layer	**1**	**2**	**3**	**4**	**5**	**Total**
radius (mm)	14	22	39	90	140	
length (Δz mm)	12	12	24	48	71	
# ladders	6	10	8	18	28	**70**
# sensors	24	40	128	576	1344	**2112**
material budget (% X_0)	0.15	0.15	0.5	0.8	0.8	**2.4**
max hit rate (MHz/cm^2)	120	50	7	2	2	
max bandwidth (MHz)	300	121	61	43	51	
maw power (mW)	27	45	144	650	1517	**2384**

Table 1: Main specifications of the VTX concept.

The two innermost layers, or iVTX see figure 4, 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 outer layers, or oVTX see figure 5, 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 [12] 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.

The proposed VTX has the ability to cope with large beam-induced background levels, within a safety factor $\times 5$ with respect to the current expectation from the luminosity increase[4]. Due to smaller pixels and shorter integration time window, the average occupancy on the first layer of the VTX drops down to 0.002% compared to 1% for PXD at the same radius.
Such clean VTX events allow including the inner layers in the track-finding algorithm, contrary to the present situation. Tracking performance with the VTX has been studied within the full Belle II simulation and reconstruction software and demonstrated to be robust against background [13]. Figure 6 illustrates two performance improvements, especially important at small momentum. Further studies are being conducted with physics channel benchmarks and showing improved performance in term of reconstruc-

[4]Highest hit rate for the innermost layer assumed is 120 MHz/cm^2.

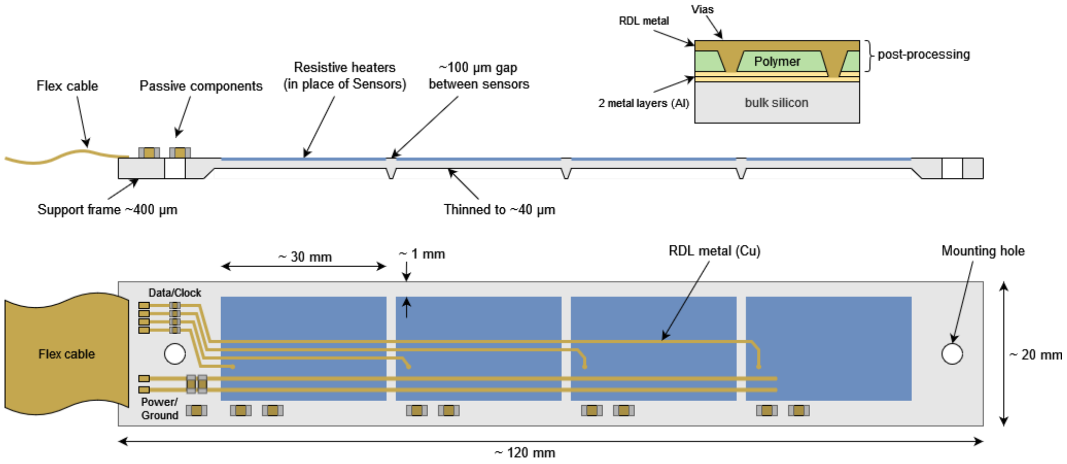

Figure 4: iVTX concept represented from the short-side view (top), long-side view (middle) and top view (bottom), where the redistribution layer interconnecting the four sensors and the non-uniform thinning are depicted.

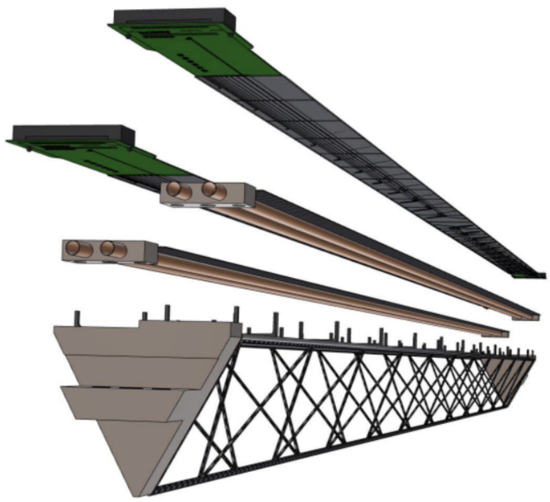

Figure 5: oVTX concept for the longest and outermost layer 5, hosting two rows of sensors connected to a flex cable (top), then glue to a cooling plate (middle) and finally supported by a truss structure.

tion efficiency and vertex precision (see https://agenda.infn.it/event/22092/contributions/166670/, accepted in NIM A).

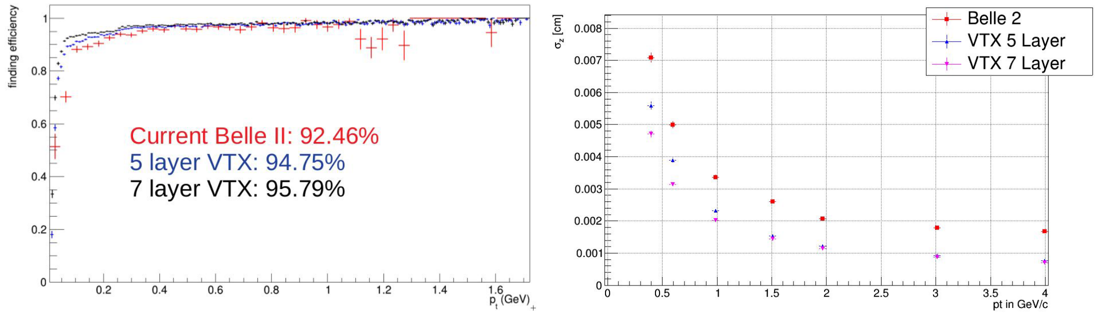

Figure 6: Tracking performance simulation, comparing the present detector setup and two VTX geometry options. On the left, the tracking efficiency and on the right, the impact parameter resolution along the beam axis.

The whole VTX event weight is currently estimated at 25 kB, to be compared to the 100 kB/event limit of the HLT system, allowing for the swift (below 10 ms, 10 times faster than the current system) online use of the precision tracking offered by VTX for the trigger decision.
The VTX concept also introduces a simplified and then more robust operation in the inner layers compared to the DEPFET technology: neither special gated mode[5] nor specific reduction mechanism[6] in the data acquisition is needed.
Since VTX relies only on dry air and water cooling, the specific complexity of handling CO2 pipes at -20 C vanishes. Neither insulated pipes nor cold/warm dry volumes separation to prevent the problem of condensation in the CDC volume is needed, decoupling de facto the operation of the two subdetectors. Fewer cables running in front of the ECL would decrease the electromagnetic showers and be beneficial to the performance in terms of photon efficiency and threshold energy scale.

3.2 The VTX project organisation

As mention in the previous section the VTX project was established by about 18 European laboratories, listed in addendum 9.2. These laboratories currently collaborate and share resources on a non-constrained way, on the basis of their R&D grants. Still a board of four people organises the current R&D tasks with the following attributions.

- Jérôme Baudot (Strasbourg) sensor design & talks management

[5] The DEPFET integration time of 20 μs exceeds the beam revolving time around the ring, which requires that sensor switch off their sensibility to any particles (gating) when newly and particularly noisy injected beams goes through.

[6] DEPFET does not use the standard Belle II acquisition boards but specific ones that can exploit the definition of a region of interest by the HLT-tracking in order to trim out unnecessary hits.

- Stefano Bettarini (Pisa) mechanics and integration design
- Carlos Marinas (Valencia) project leader, also Belle II technical coordinator
- Benjamin Schwenker (Goettingen) performance simulation

This organisation will evolve when the project needs to start additional activities (like data acquisition and system services) and enter the production phase. The group uses the (private) online documentation system provided by Belle II and meets every week, alternating general topics with sensor development. Since 2021, about 12 talks have been given to workshops and conferences by project members (without accounting for general Belle II upgrade contributions).

The VTX project is included in the larger Upgrade Working Group set by the Belle II collaboration and coordinated by Francesco Forti (Pisa). An additional Belle II Upgrade Advisory Committee (UAC) oversees the activities of the different upgrade proposals, reviews technical documents (expressions of interest, conceptual design report) and advises on the timely decision for technology choices. The UAC is composed of core members (T.Browder, P.Križan (chair), L.Lanceri, C.Niebuhr, S.Uno, E.Won) and contact persons from the various key collaboration groups or boards regarding the upgrade (technical coordinator, upgrade working group, spoke person's office, machine detector interface group, physics performance group).

The timeline for the documents required by Belle II and decisions related to the upgrade are discussed in section 4. Figure 7 displays a rough schedule of the VTX project itself, starting with the development phase then moving to the production and installation phases, currently set for 2027 (LS2).

3.3 Introduction to the proposed IN2P3 contribution

Aside from their commitment to the physics analysis the three IN2P3 laboratories participating to the Belle II collaboration are also involved in the detector operation and data reconstruction.

Both CPPM and IPHC contribute to the current silicon vertex detector (SVD) operation, with expert shifters (IPHC, CPPM) and operation coordinator (CPPM), and reconstruction software. In particular the two teams lead a strong effort to reach an accurate estimation of the position resolution and an optimised tuning of the simulation to match the data behaviour. IPHC also supports the continuous development of the online system and will help in the re-installation of the SVD during the current LS1. The two teams have also contributed to the tracking software development and CPPM has recently hosted the Belle II tracking meeting [7].

[7] May 2022, https://indico.belle2.org/event/6621.

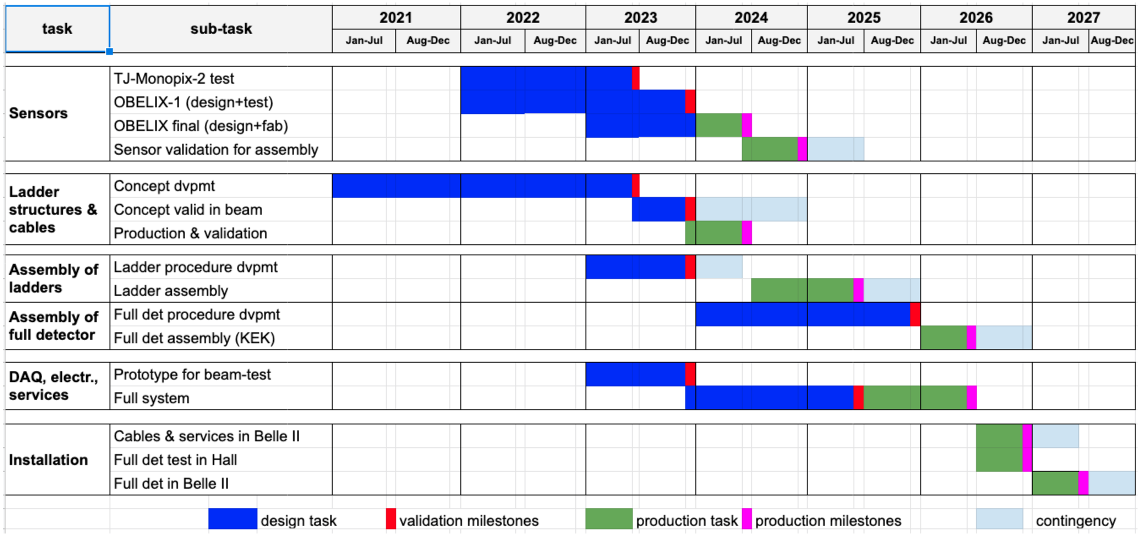

Figure 7: Rough schedule of the VTX development, production and installation.

IJClab has an impact on three aspects of Belle II operations. First the group plays a key role in the on-going upgrade of the hardware of the DAQ system, for which IJClab provided PCIe40 boards (developed at CPPM for LHCb). Then, the team contributes to continuous development of the HLT system software in order to maintain the triggering performance with increasing peak luminosity. Finally, IJClab has been working on improving the cooling system for the new beam pipe introduced during the current LS1, see more details in subsection 7.4.

All three laboratories have long tracks in developing silicon-based sensors and the corresponding mechanics for vertexing and tracking (ALICE, ATLAS, CMS, STAR). CPPM and IPHC have strong on-going R&D programs on monolithic CMOS pixel sensors. Such sensors were already operated within the Belle II apparatus by IPHC during the 2018 commissioning phase of SuperKEKB [14].

In view of the importance of the LS2 upgrade for the Belle II physics program, the three IN2P3 groups decided to join their forces in a coherent and integrated effort to set-up the VTX proposal, which relates to their expertise both in Belle II (beam-pipe, VXD, tracking, HLT) and in instrumental R&D (CMOS sensors, thermo-mechanics, detector assembly).

Beyond the connection with the internationally recognised expertise on CMOS sensors, the choice of the VTX among other proposals to upgrade the VXD, see section 5, derives from the teams' conviction that the VTX can be realistically developed, built

and installed within a few years while still matching the requirements discussed in section 3.1.
Each laboratory proposes to actually contribute for the VTX development and production through various topics, listed below.

- **CPPM** CMOS sensors, ladder assembly tools.
- **IJClab** DAQ, HLT, beam-pipe and inner layers thermo-mechanical integration.
- **IPHC** CMOS sensors, detection module assembly.

It is also expected that all groups participate to the VTX installation.The technical details of the proposed contributions are described in section 7, while the corresponding resources required are described in section 6. In addition, the groups already contribute to the accompanying software activities, currently focused on the design optimisation and will later get involve in the data reconstruction.
The proposed activities range over key topics regarding the construction of a new subdetector, namely sensors, thermo-mechanical aspects, assembly and data acquisition. A special emphasis is set on the contribution to CMOS pixel sensors, which makes the backbone of the VTX project, and for which IPHC and CPPM are major actors. Nonetheless, it is the ensemble of all the foreseen contributions which builds up IN2P3 visibility in the project.

4 Schedule

The recognition of the need and subsequent brainstorming for an upgrade of the vertex detector started in 2019, especially with an open workshop at CERN in July (https://indico.cern.ch/event/810687/, co-organised by J.Baudot). The initial VTX collaboration was then forged with a follow-up meeting at Valencia in December 2019 (https://indico.ific.uv.es/event/3862/).

The Belle II collaboration requested expression of interests for any kind of detector upgrades on a large time-scale. The VTX letter, signed by the three IN2P3 groups, was handled in February 2021 and extended with an addendum in January 2022, with physics performance studies and tests from early prototyping activities. These documents are private to Belle II , but can be accessed by the members and experts of the IN2P3 Scientific Council at this address: https://box.in2p3.fr/index.php/s/EN6DW4c8z5xzXFZ. The public document describing the entire Belle II upgrade program is one of the collaboration contributions to the US-Snowmass process [3].

Regarding the upgrade of the vertex detector, a total of 4 proposals were made and are succinctly presented in section 5. The next horizon for the Belle II upgrade project during LS2 is the publication of a conceptual design report (CDR) by mid-2023. The

UAC already underlined the compulsory need to downscale the number of options for the upgraded VXD. The ideal case would consist in a baseline choice and a back-up solution. The year 2023 will then most probably see the organisation of a collaboration for an upgraded VXD with complete status and clear commitments from the member groups. In parallel, the VXD upgrade project will then be fully integrated in the Belle II technical activities and reviewed as such.

Section 2.2 already introduced the fact that the change in the machine interaction region to allow for peak luminosities around 6×10^{35} cm^{-2} s^{-1} are not yet fully known. The solution will be in fact decided early 2024, in view of first observations after SupeKEKB resumes operations at the end of LS1.

This relatively late choice with respect to the foreseen installation in 2027 for LS2, stresses the need for a technical choice for the upgraded VXD which is both robust and adaptable. According to the technical schedule from figure 7, the VTX concept can still be adapted in terms of geometrical structure and integration since the production of the detection modules would not have been started. This is not the case for the sensor, which should thus be designed with enough safety factor regarding the potential occupancy.

The three IN2P3 groups each informed their laboratory direction in details about their technical plan to contribute to the Belle II upgrade program. Only CPPM went through a formal presentation of the VTX project in front of the laboratory scientific council, from which the group received a strong support signal. The directions of IJClab and IPHC have so far supported as well the R&D activities in their respective laboratories. The IPHC groups has handed a formal project to its direction to be reviewed in the coming 6 months along with other projects involving heavily the core facility C4pi for CMOS pixel sensor development.

5 State of the art

5.1 VTX proposal perspective

The VTX proposal stems from the successful application of MAPS in heavy-ion experiments (STAR [15] and [12] ALICE) and extensive R&D programs conducted in the framework of international research projects targeting various instruments in subatomic physics (ATLAS-ITk [11], CBM-MVD [16], ILC-VTX [17]). As discussed later in section 7.1, the current chosen baseline for the VTX CMOS pixel sensor, the TJ-Monopix familly, has already demonstrated its detection performance in harsher conditions than the one expected at Belle II .
Similarly, the largest area of the VTX correspond to its outer layers (oVTX). The me-

chanical and cooling solutions for the oVTX derive from the successful implementation made in the current ALICE-ITS2 detector [12].
In addition, the groups already committed to the VTX proposal carry all the necessary expertise to finalize the design. Currently all key aspects (sensors, detection layers with cooling, power supply and data transmission) have been already addressed, as described in section 3.1. These critical features could be validated by the time the CDR is completed by mid-2023. The other necessary sides of the VTX design can be started afterward and completed once the details regarding the potential modification of the interaction region are fixed early in 2024.
Consequently the VTX concept is considered an already mature and robust solution, which can be built within the short time span before LS2 starts. A risk analysis is conducted in section 8.

5.2 Other proposals for the VXD upgrade

Expression of interest to propose other technologies for the Belle II vertex detector upgrade were submitted in February 2021 and are present in the Snowmass contribution [3]. An overview is provided in table 2 and each proposal is briefly described and commented below. Note than the Thin strips and DEPFET proposals have to be combined with one of the other options, while the VTX-DMAPS or SOI proposals can serve a a single technology for a new VXD.

Proposal	**Sensor type**	**VXD coverage**	**Main proponents**	**Cost** (M$)
Thin strips	strips	only outer layers	KEK, Tokyo, India	4
DEPFET	pixel	only inner layers	Munich	4*
SOI	pixel	either inner layers or all VXD	KEK, Japan, IHEP	5.8
VTX-DMAPS	pixel	either inner layers or all VXD	Europe, see sec. 9.2	4.5

* Only include the sensors and electronics.

Table 2: Overview comparison of the various proposals for the VXD upgrade. Note the cost estimate is made in USD.

- **DEPFET**

The Halbleiterlabor (HLL[8]) designed and built with its in house foundry facility, all the DEPFET sensors of the current PXD and its second version to be installed during the LS1. HLL continuously develops the DEPFET sensor technology for various applications and hence made a proposal for slightly improved sensor for an upgraded VXD. Such new modules would feature an integration time of about 3 μs, a pixel pitch around 55 μm, and present only marginal interest with respect to the requirements described in section 2.

Furthermore, the estimated costs of the sensors (2 M$) and associated read-out electronics (2 M$) are already relatively large, beside considering other costs. Currently there is no collaboration building up around this proposal.

- **SOI**

The KEK group developing pixel sensors with the silicon on insulator technology proposed a dedicated architecture for the VXD upgrade. The sensor named DuTiP features a 45 μm square pixel pitch and a 62.9 ns integration time. Currently the second prototype, with a size of 6×18 mm^2 is being tested [18]. The concept for the mechanical structure of the detection layers has been described on paper.

While the SOI technology is successfully exploited for X-ray imaging, it has never been operated routinely in a collider experiment or even a beam telescope instrument. Prototypes [19] have been developed and have been tested in the perspective future e^+e^- colliders, which have a requirement for radiation hardness an order of magnitude lower than Belle II vertex. The full validation of the technology for the VXD upgrade is one of the main technical challenge for this project.

- **Thin strips**

A number of KEK physicists propose to reduce the material budget of the present double sided silicon strips from 0.7 % X_0 to 0.5 % X_0 and increase its tolerance to high rate at the level required after LS2. For that, new sensors are needed, featuring a larger area of 100×100 mm^2, a smaller pitch along the beam direction of 75 μm, a thinner sensitive volume of 140 μm and a faster shaping read-out circuit of 55 ns. They are currently testing smaller area sensors 52.6×59 mm^2 from Micron Semiconductor. The read-out circuit, SNAP128 chip, is also under development.

The challenge with thin sensors is of course to demonstrate the signal-over-noise ratio is large enough under the Belle II conditions to ensure a satisfactory detection efficiency. Also, the outer layers will not be simpler in terms of system as the current SVD and an additional technology would still be needed for the inner layers.

[8] Max Planck Munich, https://www.hll.mpg.de.

All proponents of this project participated to the SVD design and construction, but major players of this effort are now committed to the VTX proposal. It is finally interesting to note that the present SVD was roughly produced within 3 years after the end of its development phase.

5.3 Beam-pipe replacement

Aside from the VXD technology upgrade, a new beam-pipe will certainly be required depending on the modifications of the interaction region for the luminosity increase. This replacement is only partly independent of the technology chosen for the VXD due to the thermo-mechanical connection with the inner layers. Also, the amount of gold coating absorbing the X-rays generated by synchrotron radiations depends on the maximum hit rate the new VXD technology can sustain.
The beam-pipe material budget, currently 0.8 % X_0 with 10 μm gold coating, is critical to the final vertexing performance. At present, there is no detailed study investigating the possibility to decrease the beam pipe thickness.
The KEK group, recently joined by the IJClab team, develops beam-pipes for Belle II. There is no competing proposal for this activity, discussed further in section 7.4.

6 Resources

A first estimation of the full cost of a 5-layer VTX detector is 4.5 million USD, see table 3. The test setups required for the characterisation and the validation are included in the relevant component contribution (e.g. sensors and ladders). Note that the assembly encompasses both the ladder construction and the mechanics to support the ladders in a full detector. It is assumed that no specific heavy equipment are required for assembly, they are expected to be already present in participating laboratories.
Due to some system parts not yet designed (for instance, services), a 5% contingency was included on the production cost. Also, we still don't know what and how much parts can be re-used from the existing VXD.
This budget does not cover the fabrication of a new beam-pipe, for which the KEK group is in charge.

The proposed contributions by IN2P3 groups were introduced in section 3.3. They are listed again below with the corresponding coordinators. Then, we provide table 4 for the budget request and table 5 for the personnel contributions and their timeline. The content of the tasks themselves are detailed in section 7.

When already known, an overall full time equivalent is provided per task, to be understood as the sum of the participant commitment.

- **Overall coordination** J. Baudot (a technical coordination is under discussion)
- **CMOS sensor** H. Pham, P. Pangaud
- **Assembly** M.Barbero, E. Vigeolas
- **DAQ** P Robbe, D. Charlet
- **Beam-pipe & thermo-mechanics** E. Kou, J. Bonis
- **Installation** to be defined later

Component	Development	Production	Total (k$)
Sensors	380	920	**1300**
Ladders	120	730	**850**
Assembly	130	630	**760**
DAQ & services	280	1060	**1340**
Installation	-	100	**100**
Total	**900**	**3500**	**4500**

Table 3: Cost estimate of the VTX, with a 5 % contingency on the production budget.

Task	Development		Production	
	cost (k$)	**Timeline**	**cost** (k$)	**Timeline**
Sensors	130*	2021-23	360	2023-24
Ladders	-	-	-	-
Assembly	30*	2022-23	50	2024-25
DAQ	-	-	40	2025-26
Beam-pipe	10*	2022-23	60	2024-27
Installation	-	-	60	2026-27
Total	**170**		**570**	

Table 4: Budget required for IN2P3 contributions to the VTX.

Task		FTE	IN2P3 contributors	timeline	collaboration with
Performance	physicists	-	J.Baudot, G.Dujany, C.Finck, E.Kou, G.Mancinelli, I.Ripp-Baudot, J.Serrano, K.Trabelsi	whole project duration	performance group
	postdocs	-	TBD		
	doc	-	TBD		
Sensor (design & test)	physicists	1	M.Barbero, J.Baudot, C.Finck	till end of 2024	Bergamo, Bonn, Pavia, Dortmund, Valencia, Vienna
	engineers	4	P.Barillon, P.Breugnon, C.Hu, L.Federici, D.Fougeron, P.Pangaud, H.Pham, I.Valin		
	CDD	1	A.Kumar, D.Xu		
	doc	0.3	R.Boudegga		
DAQ	physicists	0.2	P.Robbe	at least till 2027	KEK
	engineers	0.3	D.Charlet		
Beam-pipe	physicists	1	E.Kou, F.LeDiberder, M.Winter	till installation in 2027	KEK
	engineers	1	D.Auguste, J.Bonis, Y.Peinaud		
Assembly	physicists	0.1	M.Barbero, J.Baudot	2023 to 2025	Pisa, Valencia, Vienna
	engineers	1	F.Agnese, O.Claus, E.Vigeolas, C.Wabnitz		
	CDD	0.5	TBD		

Table 5: Person-power committed to the VTX project at IN2P3 (TBD=to be defined at a later project stage).

7 Technical contributions

The different contributions introduced in section 3.3 and listed in tables, 5 are described in detail below.

7.1 CMOS sensor

The MAPS technology is at the core of the VTX proposal, placing CPPM and IPHC in key positions within the project, due to their large expertise on CMOS pixel sensors. The CPPM team, along with the group from Bonn University, took part in the development of the TJ-Monopix series [11], serving as the prototype of the Belle II dedicated OBELIX sensor. Currently, CPPM participates to the characterisation of TJ-Monopix-2, see figure 8, whose pixel matrix will be replicated and extended in OBELIX-1. Microelectronics engineers are now joining the effort to finalise the OBELIX-1 design.

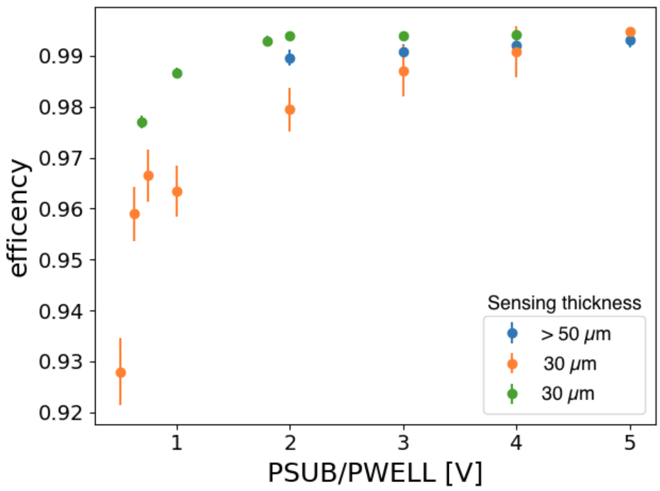

Figure 8: Initial result of the detection efficiency obtained with a 6 GeV electron beam at DESY in Summer 2022 for the TJ-Monopix2 sensor operated at high threshold (500 e-) and for three different samples.

At IPHC, the core facility C4Pi has already led the design and characterisation of large sensors (ALPIDE [10], MIMOSIS [16]) in the selected Tower-Jazz 180 nm process. C4Pi designers are currently leading the design of the first version of the VTX sensor OBELIX-1, being in charge of the matrix design, full sensor floorplan, see figure 9, and organisation of the verification steps. IPHC will also organise the contact with the foundry to submit the design files and supervise the sensor fabrication during winter 2022-23. Test work in Strasbourg will start in 2023 for TJ-Monopix2.

Both laboratories will extend their characterisation effort on and OBELIX-1 and continue the same commitment for the design and test of the second and final sensor version OBELIX-2 in 2023-24.

The other groups within the VTX collaboration contributing to the OBELIX design (digital logic, power regulators, slow-control), characterisation and production tests are Bergamo, Bonn, Dortmund, Goettingen, Pavia, Pisa, Valencia, Vienne.

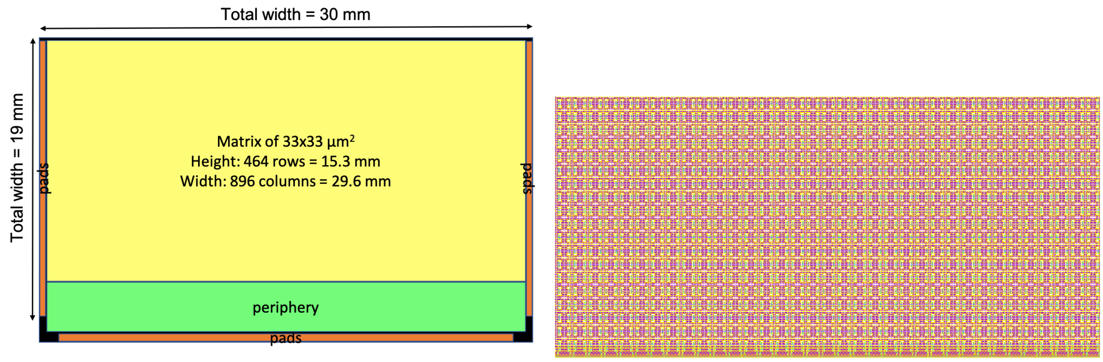

Figure 9: Left: rough floorplan of the OBELIX sensor sketch the position of the various functional elements. Righ: part of the OBELIX pixel matrix layout.

Owing to the leading role IN2P3 teams play on the VTX sensor work package, a substantial fraction of the total sensor cost is required to IN2P3 (strongly in contrast with the other workpackage), see tables 3 and 4. The cost estimate is based on prices for masks (150 k$), non-recoverable costs (70 k$) and wafers (3 k$ per wafers for about 140 wafers to fabricate) known from projects conducted in the recent years. However, these prices can fluctuate up depending on the international integrated-circuit market situation for Tower Semiconductors (now Intel). Another uncertainty comes from the possibility of a severe defect in OBELIX-2 leading to a compulsory fix and an additional fabrication to reach the final sensor: OBELIX-3. This would represent an additional maximal cost of around 250 k$ (possibly 80 k$ for IN2P3) in case all masks need to be re-created.

Both CPPM and IPHC benefit already from test infrastructures needed for the development of OBELIX. Nevertheless, some test equipment are specific to the project. They essentially cover electronic boards and smaller accompanying appliances dedicated to control and command for laboratory and beam tests. Additional budget taken into account covers secondments for beam tests and collaborative work on the sensor design.

7.2 Assembly

The design, prototyping and fabrication of the ladder structure for the iVTX and oVTX parts is the charge of laboratories outside IN2P3, especially Pisa and Valencia. With prominent roles in the design of sensors and thermo-mechanical aspects connected to the beam-pipe, French labs are nevertheless involved in the design discussion.
The production of the all-silicon iVTX ladders requires techniques from the semi-conductor industry. Currently, IZM-Berlin[9] is in charge of prototype iVTX ladder production. The procedure to handle the ultra-light final ladders and mount them on the final detector support will most probably be operated in a single laboratory but is still to be developed.
Regarding the oVTX, the assembly procedure will follow steps very similar to the ones used for the ALICE-ITS2 production. They require first positioning, gluing and bonding thin sensors and flex cables into modules. Then the second step consists in positioning these detection modules over the supporting mechanical structure with high precision. Considering the 54 oVTX ladders (without spares) to be produced within a year, about 4 to 5 laboratories will be required to operate the production in parallel.

A valuable expertise in integration and module loading is present with the CPPM team, which also benefits from equipment for handling and measuring complex and delicate mechanical assemblies.
Consequently, CPPM proposes to collaborate with labs designing the assembly procedure (detection modules, ladders and full detector) in order to share this expertise and contribute to the design of the tools necessary.

The IPHC-C4Pi micro-techniques group participated to the assembly of detection modules for the ALICE-ITS2, which is expected to be very close to the one applied for the oVTX. Hence, the group can offer to re-use the equipment on site to take in charge part of the production for the oVTX modules during one year.

The budget requested for this activity aims to cover the development of dedicated precision tools for the assembly.

7.3 Acquisition

The replacement of COPPER cards by PCIe40 cards, designed for the LHCb and ALICE experiments, is in progress and those cards should be used until the Belle II data

[9] Fraunhoeffer Institute, https://www.izm.fraunhofer.de/.

collection is complete. They have been delivered to KEK in summer 2020 and installed in 2021-2023 on all sub-detectors (in 2021, for TOP and KLM detectors, in 2022, for ARICH, then the rest of sub-detectors, SVD, CDC, ECL and TRG, for 2022-2023), except the pixel detector (PXD). We had a stable running during data taking so far, with performances several times larger than the old system, limited by network and CPU bandwidths.

The IJCLab is also participating in the development of firmware and software in collaboration with KEK, IPMU and the University of Hawaii. Establishing a solid working relationship with the KEK online group, they recently asked French experts about the PCIe40 cards usage to acquire data at higher rate than that planned for the first phase of upgrade currently carried out. There is now an effort to increase the robustness of the system by using two PCIexpress interfaces instead of one, allowing to double bandwidth between PCIe40 and PC, going from 50 Gb/s to 100 Gb/s. This will also allow to do event building in software instead of firmware. It might be advantageous to also use PCIe40 cards (or even the future PCIe400 board) for this new vertex detector. Since these cards are universal, they could be easily adapted without additional effort. The clean environment of the VTX would allow a much faster reconstruction for an HLT based more, if not exclusively, on the VTX. This would be a natural extension of the current work on HLT optimization/operation of the current system.

7.4 Beam-pipe and inner layers thermo-mechanical integration

The new beam pipe design and production for the LS1 upgrade is well under way. The IJCLab team has been working on improving the cooling system of the new beam pipe in collaboration with the KEK IR mechanics team. This work includes the thermal simulation of the IR beam pipe, thermal tests with a beam pipe mockup at IJCLab as well as tests with the Phase 2 beam pipe at KEK.

The IR beam pipe components of SuperKEKB result from several consecutive upgrades of the KEKB accelerator. Through the LS1 upgrade, the IJClab team was given the opportunity to work with the KEK engineers, who made the initial design of the IR beam pipe, and to participate to the assembly and installation of the new pipe elements. This cooperation with KEK will allow the IJClab team to acquire skills in the specific metallurgy of the IR: emblematic examples are the welding of specific metals composing the beam pipe elements such as tantalum, titanium and beryllium, as well as surface treatments and thin layer deposits on these materials. The geometry of the IR is itself a matter of experts and this project will offer a valuable opportunity to acquire expertise on the production and assembly strategy of the IR of e+e- colliders at large, such as FCC-ee where a very similar kind of IR beam pipe design is proposed. The cooperation with KEK will also reinforce the synergy between the research teams

Figure 10: The new cooling block designed by IJCLab, (center & right) the final thermal test in collaboration between KEK/IJCLab engineers/researchers, July 2022 at KEK.

anticipated to play a prominent role in highly challenging future projects, such as an ultimate upgrade of the SuperKEKB machine or a Higgs factory.

The current IR beam pipe is composed of a central straight section (with beryllium & titanium components) and a part called crotch (made of tantalum). The latter, which separates the incoming and outgoing particles, exploits the concept of high intensity nano-beams composed of particle bunches colliding according to the crab waist concept. The former part allows to widen the coverage of the vertex detector. In order to avoid the high background as well as exceeding heat, internal sputtering of the pipe elements has been tested with various materials. On top of these two parts, a mounting scheme of the vertex detector is comprised in the current design. The whole design shall be revisited to accommodate the higher luminosity expected after LS2 as well as the new vertex detector. The IJClab team intends to contribute to this task in collaboration with the KEK mechanics team. Moreover, the space available for the service of the vertex detector depends also on the design of the IR beam pipe. This configuration promotes the visibility of the IJClab team working on both the innermost part of the VTX (iVTX) and the IR beam pipe.
The IJClab involvement in the design of the IR beam pipe is not contingent on the technology choice made for the vertex detector.

Having the experience of working on the IR beam pipe, the IJClab team was given the task to develop the cooling of the innermost part of the iVTX. One of the goals is to mitigate the complexity of the current PXD services due to its two-phase CO2 cooling. Exploiting the lower power dissipation anticipated for the OBELIX sensor, dry air cooling may entirely replace the complex CO2 system. So far, the study concentrated on the thermo-mechanical simulation of a single ladder, see figure 11. The results obtained indicate that air cooling might be sufficient for the DMAPS iVTX (work presented by the Belle II collaboration [10]).

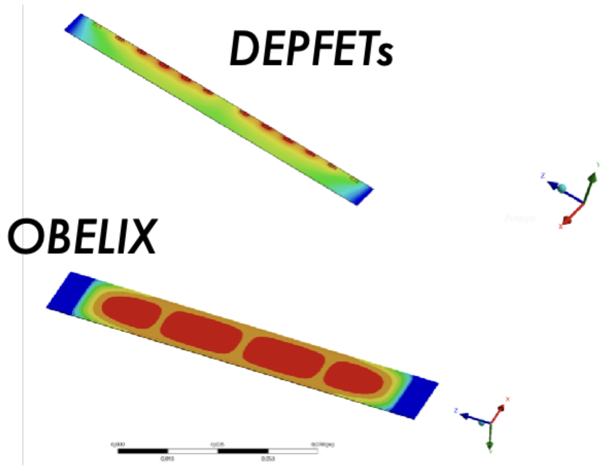

Figure 11: First thermal simulation result by IJCLab: comparison between the present, DEPFET based, ladder design and the one anticipated with the OBELIX sensor.

The next step is to address the cooling of the complete set of two layers composing the iVTX. It will start with a mechanical and thermo-fluid simulation study of the cooling air flows. The next step should consist of a test bench study based on a (thermo-mechanical) ladder prototype. To be able to visualize the air movement and to measure the temperature of the different elements will indeed be essential for the validation of the air cooling design. As the elements to be installed are located in the innermost parts of the Belle II detector where space is very limited, a precise knowledge of the detector configuration is necessary to design the device. The IJClab experience accumulated by working in the IR region will help design the air inlets and outlets. In coherence, the involvement of the IJClab team in the PXD2 installation provides simultaneously an excellent starting ground to gain the expertise and skills awaited for the upgrade development.

We emphasise that this contribution to the beam-pipe and inner layer thermo-mechanical management is independent of the technology choice and will have to proceed in any case.

7.5 Installation

The installation and test of the full system in the experiment at KEK is the final step of the project, but also a critical one. During this period expected to last for about one year, the visibility of the groups is indeed maximal since their achievements

[10] https://indi.to/y9GNJ

somehow materialise and their activities forebode their future role during the operation of the detector. The cost indicated corresponds to the secondments at KEK for 30 person.months or 5 people during 6 months.

8 SWOT analysis

The present activity proposal for IN2P3 groups within the VTX project is established from the current design state of the future vertex detector. The key elements are already known and correspond to activities described in this document. Other parts of the system are still under discussion or not even yet addressed. For instance, this is the case for the mechanical support of the detection layers or for the services. A detailed production plan is also not yet established.
The seriousness of this weakness should be mitigated in view of the experience acquired on the current VXD by the various groups committed to the VTX proposal. The Pisa and Vienna groups played a key role in the design and construction of the SVD, while the current VTX coordinator was a strong contender of the PXD design and acts as the current Belle II technical coordinator. Also experience are being acquired by the French groups with the VXD and beam-pipe re-installation during LS1.
The writing of the conceptual design report, to be delivered in 2023, offers the opportunity for Belle II to clearly sets the baseline for the VXD upgrade, which we believe can only be the VTX option for reasons explained in section 5. Hence, we expect new international groups to join the VTX project and thus bring additional resources to finalise the VTX technical design. A strong link with the KEK team is especially important and explains long term efforts from French labs to collaborate with KEK staff through the TYL-FJPPL structure, as already underlined previously.

We don't foresee technological risks related to the sensor or structural design choices, since the VTX concept essentially re-uses solutions already successful in other experiments (see section 5). This is not entirely true for the air-cooled all-silicon iVTX concept. However, it has to be underlined that the iVTX design validation is a strong R&D topic for the project and should deliver a conclusion within the next six months. In addition, alternatives to reach very low material budget with MAPS have already been proven. One is the PLUME concept [20], which was developed by IPHC and already operated in Belle II during the SuperKEKB 2018 phase-2.

The uncertainty on the interaction region design for the peak luminosity increase bears the risk that the present VTX geometry will not be suited. We consider this threat as manageable. First, the VTX detection layer concepts for iVTX and oVTX allow to cover a wide range of radius and can also be easily adapted to slight acceptance modifications. Secondly, the VTX production time is short enough to actually afford for such a late re-design.

Finally, considering the overall VTX cost of about 4.5 MEUR in regards of the already participating countries (Austria, Germany, Italy, France and Spain) funding the project should not be a serious threat.

As stressed multiple times in this document, the VTX presents an excellent opportunity to exploit existing expertise of the three IN2P3 participating laboratories (especially on CMOS pixel sensors, intricate thermo-mechanical systems and DAQ systems) in order to impact critically the physics output of Belle II experiment and increase IN2P3 visibility in a major scientific experiment in high-energy physics.
Additionally, the VTX will be the first vertex detector based on the MAPS technology and with ultra-light material budget to operate in an e^+e^- collider. Consequently there is a valuable know-how to gain for IN2P3 teams in being major actors of the project, in view of the future collider prioritized in the European roadmap for particle physics.

Finally, the main strength of the French community proposal regarding the participation to the VTX project lies in the coherence and complementary activities proposed by CPPM, IJClab and IPHC.

9 Addendum

9.1 Acronyms

- CDC central drift chamber, main Belle II tracking device
- iVTX inner VTX layer concept
- HLT high level trigger based on a software farm for online event reconstruction
- QCS final focusing magnets of SuperKEKB used to implement the nano-beam scheme
- oVTX outer VTX layer concept
- SVD silicon vertex detector, based on double-sided silicon strip modules, and equiping the four outer layers of the current Belle II vertex detector
- TOP time of propagation detector used for particle identification in the Belle II barrel part
- VTX upgraded Belle II vertex detector based on monolithic CMOS pixel sensors
- VXD current Belle II vertex detector made of two sub-detectors PXD and SVD

9.2 Signatories of the VTX expression of interest

- **HEPHY** Vienna (Austria)
- **CPPM** Marseille (France)
- **IJCLab** Orsay (France)
- **IPHC** Strasbourg (France)
- **University of Bonn** Bonn (Germany)
- **University of Dortmund** Dortmund (Germany)
- **University of Goettingen** Goettingen (Germany)
- **KIT** Karlsruhe (Germany)
- **University of Bergamo** Bergamo (Italy)
- **INFN** Pavia (Italy)

- **INFN & University of Pisa** Pisa (Italy)
- **IFAE** Barcelona (Spain)
- **IMB-CNM-CSIC** Barcelona (Spain)
- **University of Barcelona** Barcelona (Spain)
- **IFCA (CSIC-UC)** Santander (Spain)
- **IMSE-CNM-CSIC** Seville (Spain)
- **IFIC (CSIC-UV)** Valencia (Spain)
- **ITAINNOVA** Zaragoza (Spain)

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