Development of vertex detectors on electron-postitron colliders

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The Large Hadron Collider (LHC) at CERN, currently in operation, is the largest and most powerful collider ever constructed. It was responsible for the groundbreaking discovery of the Higgs boson in 2012, made by the ATLAS and CMS collaborations, and has since led to a wealth of new measurements and searches. Following the LHC, the High Luminosity upgrade (HL-LHC) will continue operations until 2041, generating an unprecedented volume of data that will further expand our understanding of particle physics.

Looking beyond the HL-LHC, the international scientific community has already set its sights on the next major collider: an electron-positron collider. Electron-positron colliders are crucial for exploring physics beyond the Standard Model, offering a uniquely clean environment that allows for extraordinarily precise measurements. These precise measurements will enable detailed scrutiny of the Standard Model and may reveal deviations that could point to new, undiscovered physics.

One of the most widely supported colliders after the HL-LHC is the Future Circular Collider (FCCee). With the ability to operate at various center-of-mass energies, the FCCee will offer a comprehensive exploration of flavor physics, the Higgs mechanism, and top quark physics. At lower energies, the Super KEKB factory, currently the largest electron-positron collider in operation, along with its associated Belle II detector, investigates critical topics such as flavour physics and potential violations of leptonic flavour and universality.

To fully realize the physics potential of such colliders, their detectors must achieve exceptional precision. Specifically, the innermost detection layers, known as vertex detectors, are equipped with ultra-precise silicon pixel sensors. From a technical standpoint, the key requirements for these sensors include a pixel size of less than 30 μm, a distance from the interaction point of no more than 20 mm, and a material budget of only a few percent of a radiation length. The material budget refers to the amount of matter a particle traverses as it moves through the detector, which can cause unwanted perturbations and degrade the resolution of the particle's trajectory. Each of these three factors-pixel size, the radius of the first detection layer, and material budget-are critical in determining the precision of a vertex detector.

The proposed PhD research aims to tackle key aspects of the development of future vertex detectors, for the FCCee, planned beyond 2040, and for the Belle II upgrade, scheduled after 2030. The favourable timescales, along with the strong synergies and complementarities between the two projects, make this combined thesis a unique opportunity to maximize impact in both fields.

One of the key challenges in designing the FCCee vertex detector geometry is minimizing the material budget and reducing as much as possible the first detector radius, while preserving a maximum coverage of the detection acceptance. This will be achieved through the development of bent silicon sensors using MAPS technology, allowing for curved sensors with a radius of curvature closely matching that of the vacuum pipe containing the beam. The IPHC group is leading an original effort to thin and bend sensors in order to fulfil the specifications. The first task in this thesis will be to evaluate, through simulations, the performance of vertex detector geometries based on curved layers. In parallel, the bending of existing well-known sensors (MIMOSIS) is being explored to create prototypes of the foreseen curved layers. An additional research focus will be conducting extensive tests to ensure that the known functionalities and detection performance of the bent sensors are preserved after bending, and to assess the stability of these layers over time. Tests of bent sensor will include performance measurements with beam particles at dedicated facilities.

The Belle II collaboration is on the other hand foreseeing an upgrade of its vertex detector in the early 2030s. This instrument could be a stepping stone of vertex detectors for ee colliders. While the detector geometry is already defined, the dedicated sensor for the experiment (OBELIX) is currently being fabricated.
The main activity proposed in this thesis relates to its characterisation. Beyond functional tests, the position resolution and the detection efficiency achieved with the sensor should be evaluated with high energy particle beams at DESY or KEK, therefore performing similar tests as for the FCCee bent sensors. However, the Belle II sensors have unique considerations due to their high temperature operation(around 40 °C), and relatively high radiation dose (non ionising energy loss fluence of 5×10^{14} n_{eq}/cm^2). The sensors should hence be irradiated in advance of the test, which should also include specific instrumental setup to control the temperature.

In summary, the PhD student will contribute to the R&D of next-generation vertex detectors for high-energy physics. The project will begin with full detector simulations to optimize the geometry of the FCCee vertex detector. Real bent sensors will then be characterized through extensive testing campaigns. Similar tests will be conducted for the Belle II experiment, with a focus on the specific requirements of the OBELIX chips. By combining the complementary approaches of the FCCee and Belle II projects, this thesis will cover critical aspects of detector development, from simulations to instrumental characterization. The PhD work with therefore lead to close collaborations between the IPHC's FCCee and Belle-2 teams. The outcomes of this work will be pivotal for advancing the next generation of vertex detectors.