

Snowmass 2021 Letter of Interest:
STOPGAP - a Time-of-Flight Extension for the TOP
Belle II Barrel PID System as a Demonstrator for Fast
Timing CMOS Sensors

on behalf of the U.S. Belle II Collaboration

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Thematic Area(s):

■ (IF3) Solid State Detectors and Tracking

The physics program of B factories requires the best possible reconstruction of individual final state particles of a given event. The differentiation of charged pions, charged kaons and protons is accomplished by dedicated particle identification (PID) subdetectors and further assisted by the specific energy loss (dE/dx) as measured in the tracking system. The Belle II barrel region is instrumented with the Time of Propagation (TOP) particle identification system, which precisely measures the detection time of Cherenkov photons transmitted by total internal reflection in its sixteen $2625 \text{ mm} \times 450 \text{ mm} \times 20 \text{ mm}$ quartz radiator bars arranged around the interaction point. The measured photon arrival time is the sum of the time of flight of the initial particle and the photon propagation time, which is a function of the Cherenkov angle^{1;2}.

The mechanical design of the TOP modules leaves gaps in the azimuthal direction ϕ of about 2 cm width in between the individual quartz bars, accounting for about 6 % of missing geometric coverage in the nominal TOP acceptance. Tracks passing through the outermost edges of a TOP bar also show reduced particle identification performance, effectively widening this gap to around 7 % of tracks without TOP PID.

A possible solution to remedy the gaps in the TOP acceptance is to install supplemental instrumentation that covers the dead area between adjacent quartz bars. Since the available space around the installed TOP bar modules is limited, one or multiple layers of silicon detectors lend themselves to measure the time-of-flight of tracks that would otherwise escape the TOP coverage. Supplemental TOP Gap Instrumentation (STOPGAP) became feasible with the advent of modern silicon sensor types with very short signal collection times and excellent time resolutions in the range of a few tens of picoseconds, which is sufficient to separate charged pions and kaons with the momenta and dimensions at B-factory experiments as Belle II. [Figure 1](#) shows a conceptual sketch of a possible STOPGAP module cross section.

To estimate the particle identification performance of a STOPGAP system, a Monte Carlo (MC) study based on the full Belle II simulation of $\Upsilon(4S) \rightarrow B\bar{B}$ events has been conducted. Several contributions to the total time resolution have been considered, both reducible and irreducible: sensor readout resolutions from 20 ps to 100 ps, global clock distribution jitter (10 ps), SuperKEKB bunch overlap time (15 ps), and track length uncertainty, parametrized assuming a 5 mm resolution on the impact point of the track in the Z direction. The particle identification is then performed by evaluating a likelihood constructed from the same time resolution components. The resulting selection and mis-identification fractions for charged pions and kaons are shown in [Figure 1](#).

A STOPGAP system with a combined time resolution for sensor and readout of 30 ps would perform significantly better than the TOP system. A 50 ps would still perform better than TOP for $p < 2 \text{ GeV}$. Apart from the pure time resolution for MIP hits, the most important driver of the overall PID performance is the MIP efficiency of the used sensor technology. Estimations of expected beam backgrounds lead to very tame requirement on the sensor readout granularity in the order of cm^2 and radiation hardness ($< 1 \times 10^{12} \text{ Neq/year}$).

Several sensors technologies exist that could already feasibly fulfil the requirements, such as low-gain avalanche diodes as used for the CMS and ATLAS timing endcap projects^{3;4} or fast scintillating crystals with silicon-photomultiplier readout as used for the CMS barrel timing layer project⁴. However, neither of these technology options currently show the potential to be integrated into a full "4D" tracking detector. A possible future technology that could achieve the required level of integration are fully depleted, thinned HV-CMOS sensors. Several groups are already

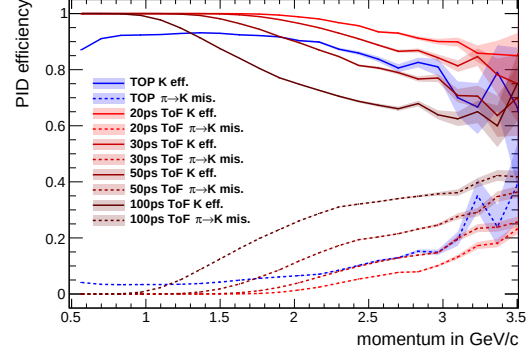
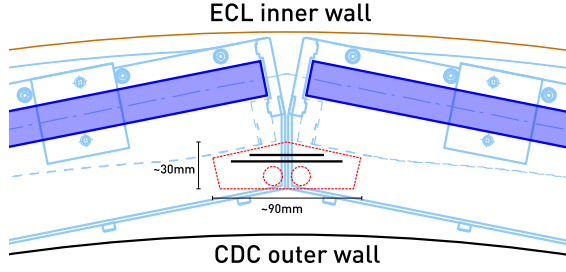


Figure 1: Left: Conceptual sketch of a supplemental TOP gap instrumentation module in the cross section of two adjacent TOP modules as seen from the backward side. Right: Selection and mis-identification probabilities at $LL_K - LL_\pi > 0$ of a simulated time-of-flight PID system for charged kaons as a function of particle momentum, shown for different effective time resolutions of the sensor + readout system.

working towards the theoretical limits of the single-MIP time resolution of such devices^{6,7}.

The STOPGAP project is a prime test bed for RD on such future fast-timing CMOS developments. A demonstrator module of limited size could be built and installed into the Belle II detector as early as the next planned extended shutdown in 2022. Such a demonstrator module could incorporate several sensor technologies to enable a direct comparison in the realistic conditions of a running collider experiment. Ultimately, a cost/benefit analysis based on the detailed results of the demonstrator module as well as accompanying simulation studies will determine the optimal choice of detector geometry and technology.

References

- [1] T. Abe et al. Belle II Technical Design Report. *Tech. rep.*, KEK, 2010
- [2] D. Kotchetkov et al. Front-end electronic readout system for the Belle II imaging Time-Of-Propagation detector. *Nucl. Instrum. Meth.*, A941 (2019) 162342, 2019
- [3] The ATLAS Collaboratio. Technical Design Report: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade. CERN-LHCC-2020-007
- [4] The CMS Collaboration. A MIP Timing Detector for the CMS Phase-2 Upgrade. CERN-LHCC-2019-003
- [5] CERN picTDC project, *Presentation* <https://indico.cern.ch/event/863068/contributions/3752492/attachments>
- [6] M. Barbero et al. Radiation hard DMAPS pixel sensors in 150 nm CMOS technology for operation at LHC. *Journal of Instrumentation* 15 P05013, 2020
- [7] L. Paolozzi et al. Time resolution and power consumption of a monolithic silicon pixel prototype in SiGe BiCMOS technology. *Preprint* arXiv:2005.14161