Proposal for Touschek-Polarization Measurements in the SuperKEKB HER

Belle II/SuperKEKB e$^-$ Polarization Upgrade Working Group:

U. Wienands, M. Hoferichter, C. Hearty, I. A. Koop, A. V. Otboev, Yu. M. Shatunov, B. Parker, V. Teotia, A. Schwartz, A. Vossen, A. Accardi, M. Kuriki, Z. Liptak, F. R. Le Diberder, A. Martens, K. Trabelsi, F. Zomer, M. Yoshida, D. Zhou, Z. Zong, Sw. Banerjee, W. Deconinck, M. Gericke, J. Mammei, A. Signori, R. Baartman, T. Planche, A. Beaubien, T. Junginger, C. Miller, K. Moorthy, Y. Peng, N. Tessema, J. M. Roney

AND OTHERS

Draft v1: 2 June 2024

Executive Summary

Chiral Belle is a project proposed to expand the capabilities of SuperKEKB and the physics goals of Belle II by colliding longitudinally polarized electrons with unpolarized positrons. The physics is accessed by studying asymmetries between the measurements of processes when the electrons are left-handed compared to when the electrons are right-handed. The electrons would be injected into the High Energy Ring (HER) as transversely polarized and the spins rotated to longitudinal before the interaction point (IP) and then rotated back to transverse after the IP. The polarization is to be measured in real-time using a Compton polarimeter located between the up-stream spin-rotator magnets and the IP.

Before proceeding with the full implementation of the construction and installation of the spin rotator magnets near the IP and the Compton polarimeter, we propose a near-term experiment to be conducted at the end of the 2025c running period to demonstrate the ability to inject and transport transversely polarized electrons in the HER and to validate the long term tracking studies that predict long polarization lifetimes in the HER. The polarization lifetime is to be determined using the well-established method of measuring the change in the beam's Touschek lifetime when the beam is polarized compared to when the beam is unpolarized. This will test the predictions that the polarized spin vectors are maintained around the main ring with long polarization lifetimes, without installing a Compton polarimeter in the HER. In a second stage of this Touschek-Polarization project, once we establish that we have stable polarized beams, the impact of e^+e^- collisions on the polarization can also be measured and the beam energy can also be precisely determined via the well-established resonant depolarization method.

This document includes a schedule for preparing for the measurements.

1 Introduction

Among the proposals now being considered to extend the lifetime of both the SuperKEKB accelerator facility[1] and the Belle II experiment is the inclusion of polarized electrons in the high-energy ring. This modification would include the addition of a polarized electron source, spin rotator magnets before and after the interaction point (IP), and a Compton polarimetry system. While the design, development and deployment of all the above components is a longer-term effort planned for the next SuperKEKB long shutdown, we propose a smaller-scale project involving only the polarized electron source for installation and testing on a shorter timescale of 1-2 years. This project would demonstrate the feasibility of the Chiral Belle project, confirm simulations of polarized beam transport in SuperKEKB, and provide valuable experience for the full proposed project.

More details on the physics motivation and efforts to develop the polarized source, spin rotator magnets and Compton polarimeter can be found in[2–4]

2 Physics Motivation

The weak mixing angle θ_W is a fundamental parameter of the Standard Model (SM), and precision measurements of neutral currents are considered one of the highest-priority avenues for discovery of physics beyond the SM. Any measurement finding a deviation of $\sin^2\theta_W$ from SM prediction would be a clear indication of new physics.

The introduction of an electron beam spin-polarized above 70% would open a new avenue for measurement of weak neutral currents in a manner complementary to existing experiments. In particular, a polarized beam would enable Belle II to measure the weak neutral vector coupling constants of the b and c quarks and muon with a substantial improvement in precision over past experiments [5, 6].

Figure 1 displays the predicted precision of weak neutral vector current measurements with a data set of $20\,\text{ab}^{-1}$ taken with a polarized beam. In addition to precision, it can also be seen that Belle II's measurements would be in a parameter space of order 10 GeV, complementary to existing higher- and lower-energy range searches and sensitive to dark sector physics[2].

Furthermore, recent predictions also indicate that measurement of a chiral asymmetry in the process $e^+e^- \to \tau^+\tau^-$ at 1% precision would provide determine the τ anomalous magnetic moment a precision that is 100 times more precise than another proposed approach. It provides a unique way of probing the current tension in the SM related to the μ g-2 [7], but without the need for precision QCD. Such a measurement would be a new avenue at investigating anomalous lepton magnetic moments without the need to build a dedicated accelerator or experiment. The Chiral Belle physics program includes a number of other topics, which are discussed in [2].

3 The Touschek Lifetime Experiment

While the full physics plan described above will require the inclusion of spin rotator magnets and a Compton Polarimeter, we propose to make use of the effect of polarized electrons on the beam Touschek (intra-beam interaction) lifetime. The relationship between beam polarization and the Touschek effect was first calculated by Baier and Khoze in 1967 [9]. With the HER injected with a 70% polarized beam the Touschek lifetime would increase by 4% (see Figure 2).

Because this effect is present with electrons polarized in the transverse state, it is possible to measure the beam polarization in the HER without a dedicated Compton polarimeter. The SuperKEKB beam background group has demonstrated the ability to assess the contributions to

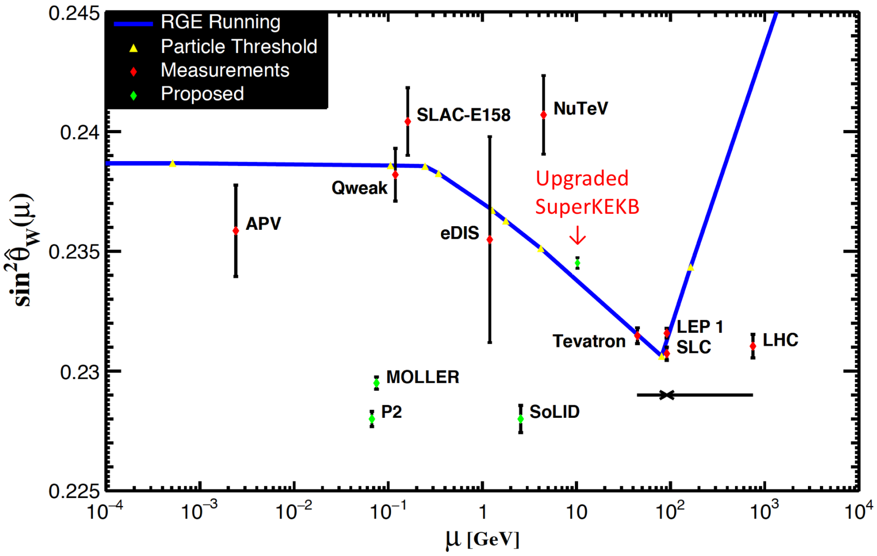

Figure 1: Scale dependence of $\sin^2\theta_W$ (giving the weak mixing angle) defined in the $\overline{MS}$ renormalization scheme. Adapted from reference [8] to include projected errors on proposed/upcoming experiments at particular energy scales, including that at an upgraded SuperKEKB that includes polarized electron beams.

beam lifetimes as a result of Touschek interactions and other sources (e.g., beam-gas interactions) in both the beam commissioning [10] and physics taking [11] phases of SuperKEKB at the several per-mil level, a precision that is sufficient to measure the effect of polarization on the Touschek lifetime, predicted to be 4% for 70% polarized beams.

We propose to use several dedicated shifts at the end of the 2025c run period to collect sufficient data to detect differences between unpolarized electrons and those in both vertical polarization states.

3.1 Beam Source Generation

To achieve the stated physics goals, a high beam polarization ($\geq$ 70%) is desired. GaAs sources have in the past been demonstrated to produce polarization > 90% with a quantum efficiency (QE) of 1.6% [12], but a wide band gap makes accelerating the generated electrons difficult. To alleviate this issue, research is underway in the development of thin-film Negative Electron Affinity (NEA) surfaces applied to the GaAs cathode [13, 14]. While this technique has been in use in the past, cathode lifetimes are notably short. Work is currently ongoing to create more robust cathodes with longer lifetimes while maintaining high polarization rates.

Because this Touschek-Polarization experiment is explicitly structured as a short-term test to confirm the presence of spin polarization in the HER, the lifetime and high-spin polarization and QE requirements on the cathode that would be necessary for a longer-term or permanent electron source can be relaxed. In particular, for a modest reduction in spin polarization and QE, a strained superlattice GaAs-AlGaAs cathode with only a thin Cs or similar coating has been shown to achieve polarization of up to 76% [15] with a well-studied Cs_2O NEA surface. A reduction in QE can be compensated for by means of a more intense laser system. Any reduction in spin or QE requirements can translate to a reduction in the necessary vacuum requirement for the electron source, and therefore a reduction in cost and development time for the project.

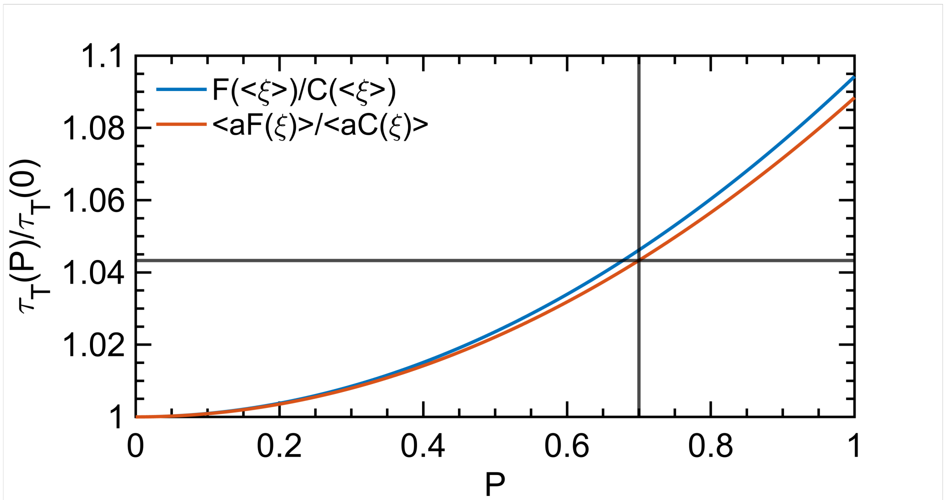

Figure 2: Predicted Touschek lifetime as a function of beam polarization in the HER normalized by the Touschek lifetime for an unpolarized beam assuming an overall momentum acceptance of 0.6 %. Courtesy of A. Martens.

The SuperKEKB linac source team is also currently investigating several promising avenues for electron generation which would alleviate much of the space constraints associated with the installation of a keV-scale source while providing beam at the nC level for injection into SuperKEKB. Source team members are actively involved in finding a solution for installation in the source area.

3.2 Spin Rotation at Generation

Electrons produced from the cathode have spins aligned (anti)parallel to the direction of beam propagation, and thus to avoid unwanted changes in direction when passing through beamline dipole elements, must be rotated to the transverse (vertical) direction. This is to be achieved using a Wien Filter consisting of perpendicular electric and magnetic fields chosen such that

$$\beta c = E/B \tag{1}$$

so that the polarization vector of the electrons is rotated with a net force of 0 on electrons with velocity β. Since being implemented at SLAC in the 1990's, much work has been done at SLAC, CEBAF and others to improve upon Wien filter design and construction for a range of electron gun energies. We are drawing on this experience for this part of the project.

3.3 Spin Transport Simulations

After generation, the beam must be transported first through the SuperKEKB linac, followed by the beam transport lines for injection into the HER, where the beam is stored. Several areas along this injection path may prove challenging: the J-arc is a 180 degree hairpin turn, and the beam transport lines have approximately 10 m of vertical descent before injection into the ring. The HER itself also includes several bending sections, all providing possible sources of instability.

Beam simulations carried out in the BMAD [16] framework have indicated that spin transport in the vertical state is preserved through the accelerator and can in fact be maintained for very long beam lifetimes [17]. As shown in Figure 3, apart from brief changes induced by the areas listed above, the desired vertical polarization states are restored after injection and preserved through the ring. In addition, simulations also predict beam polarization lifetime (that is, time to depolarization)

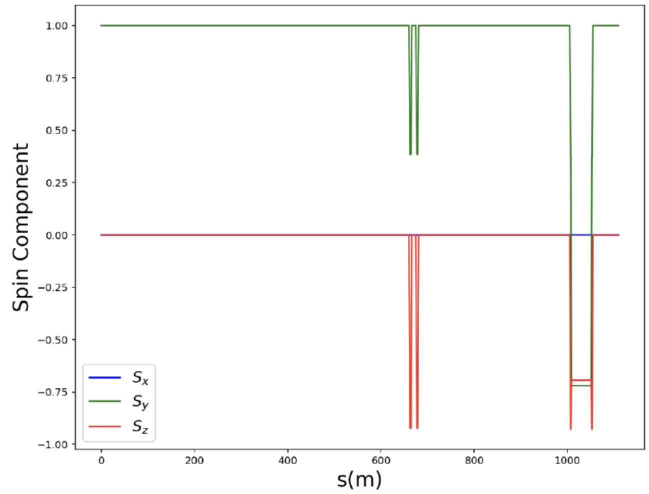

Figure 3: Simulated polarization vectors for electrons moving through the SuperKEKB linac, assuming 100% polarization at generation. The green line represents vertical spin. Brief drops from 100% occur at known positions within the accelerator, particularly the Beam Transport lines [17].

at 10 h, as shown in Figure 4. As this is significantly longer than normal beam lifetimes during operation, depolarization is not predicted to be problematic.

Beam-beam interactions have not yet been fully simulated, and the Touschek Polarization Lifetime experiment is expected to provide valuable feedback on the effect of the interacting beams.

3.4 Polarimetry

While the Compton Polarimeter setup will not be used in the proposed Touschek Polarization Lifetime experiment, measurement of the polarization at the source is necessary to understand the results of the project. For this purpose we plan to use a Mott polarimeter to measure the polarization rate after generation, while electrons are still at relatively low energy (≈200 keV). Due to space limitations in the SuperKEKB source area, we plan to set up a test bench for polarization measurement.

4 Draft Schedule for Touschek-Polarization Measurements

1. Winter-Spring 2023/24: Submitted proposal to US-Japan committee.
   - US-Japan Submission includes request for funds at KEK for Touschek Polarization Experiment
   - funds at BNL for spin rotator RD; and modest funds at Hiroshima for further source RD
   - Currently awaiting decision
2. Spring-Summer 2024 complete planning for polarized source development and prepare formal written proposal for:
   - Procurement of source (possibly existing DC gun), DC power supply, etc
   - Laser/laser control system with polarizer etc.

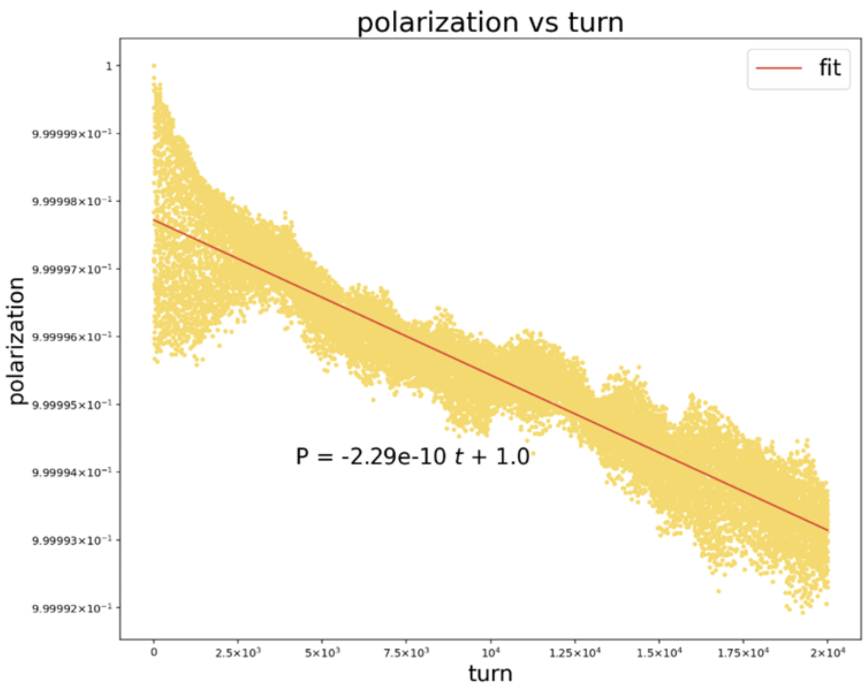

Figure 4: Simulated beam polarization lifetime by number of turns around the Main Storage Ring in SuperKEKB. The fitted line gives a depolarization lifetime of approximately 10 hours [17].

- Wien filter design
- Assembling and testing before installation; use Mott polarimeter in test setup
- Preparation of infrastructure to couple into LINAC and related alterations to the beam-line

3. Summer 2024 submit formal written proposal for EB approval to proceed with other formalities in moving the Touschek-Polarization Lifetime Experiment forward
4. By summer 2025: Complete design, construction and testing outside source room
5. Summer 2025: perform necessary alterations to beamline and install
6. Perform runs at end of calendar 2025 and in 2026, complete analysis of data taken and publish

5 Summary

As a first step towards the inclusion of a polarized electron beam at SuperKEKB and a proof-of-concept for the larger Chiral Belle project, we propose measuring the beam polarization lifetime with a few shifts of operation at the end of the 2025c run period. This would entail only the addition of a polarized electron source and low-energy spin rotator at the SuperKEKB source area. Using the already demonstrated ability to precisely determine the amount of Touschek scattering in the SuperKEKB beams, we expect to be able to differentiate between transversely polarized and unpolarized beams and to measure the polarization lifetimes.

This project would provide valuable feedback for the proposed extension of SuperKEKB's physics program via the polarization upgrade along with experience and know-how for the future. In addition, it would confirm polarized beam simulations already carried out as well as provide valuable information about beam-beam effects on the polarized electron beam.

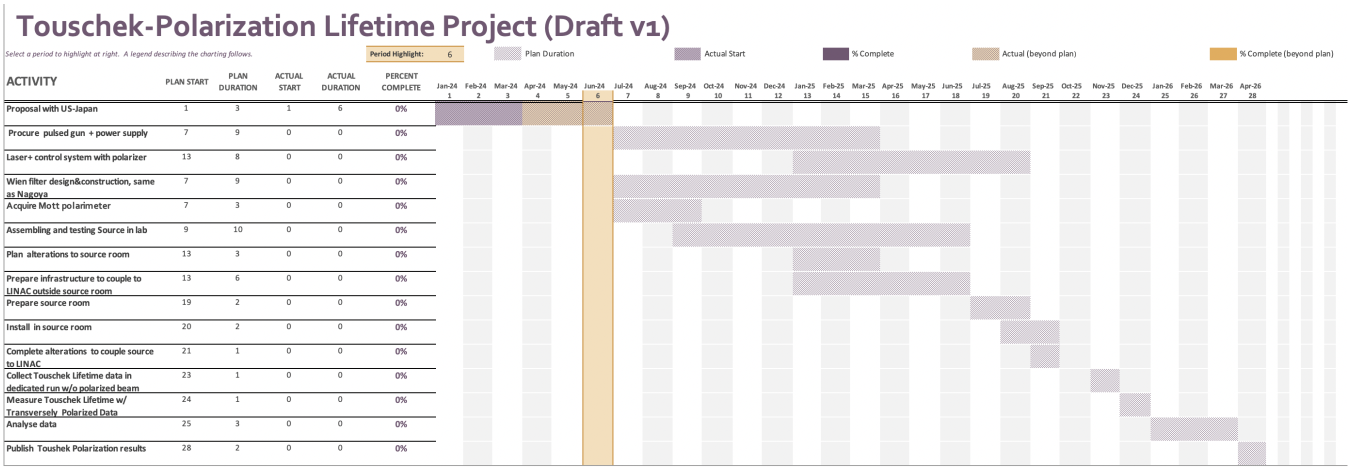

Figure 5: Gantt Chart of Project

References

[1] Y. Ohnishi *et al.*, SuperKEKB Design Report, Nucl.Instrum.Meth. A907 (2018) 188-199

[2] US Belle II Group and Belle II/SuperKEKB e- Polarization Upgrade Working Group, Snowmass 2021 White Paper Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation(2022), https://arxiv.org/abs/2205.12847

[3] D. Charlet *et al.*, Conceptual study of a Compton polarimeter for the upgrade of the SuperKEKB collider with a polarized electron beam, J. Instr. 18 (2023)

[4] G. Bardin *et al.*, "Conceptual Design Report of a Compton polarimeter for Cebaf Hall A", Technical report, 2012.

[5] A. Aleksejevs, S. Barkanova, C. Miller, J. M. Roney, and V. Zykunov, "NLO radiative corrections for Forward-Backward and Left-Right Asymmetries at a B-Factory", Phys.Rev.D 101 (2020) 5, 053003

[6] J.M. Roney, "Precision electroweak physics with polarized beams at SuperKEKB", Proceedings, Lepton Photon 2019

[7] , A. Crivellin *et al.*, "Towards testing the magnetic moment of the tau at one part per million", eprint 2111.10378 (2021)

[8] J. Erler and A. Freitas, "Electroweak Model and Constraints on New Physics", in M. Tanabashi *et al.*, (Particle Data Group), Phys. Rev. D 98, 030001 (2018).

[9] V.N. Baier and V.A. Khoze, "Effect of particle scattering in a beam of polarized electrons in a storage ring", At. Energ. 25 (1968)

[10] Z. J. Liptak, A. Paladino, L. Santelj, J. Schueler, S. Stefkova, H. Tanigawa, N. Tsuzuki *et al.*, "Measurements of beam backgrounds in SuperKEKB Phase 2", Nucl. Inst. Meth. A 1040 (2022)

[11] A. Natochii *et al.*, Measured and projected beam backgrounds in the Belle II experiment at the SuperKEKB collider, Nucl. Instrum. Meth. A 1055 (2023)

[12] X. Jin, B. Ozdol, M. Yamamoto, A. Mano, N. Yamamoto, and Y. Takeda, "Effect of crystal quality on performance of spin-polarized photocathode", Applied Physics Letters 105, 203509 (2014)

[13] M. Kuriki, Z. J. Liptak, L. Guo, X .Jin and N. Yamamoto, "GaAs cathode activation with Cs-K-Sb thin film", J. Phys. Conf. Ser. 2687 (2024) 2

[14] L. Guo *et al.*, "Rugged bialkali photocathodes encapsulated with graphene and thin metal film", Sci. Rep. 13 (2023)

[15] M. Tawada *et al.*, "Quantum-efficiency dependence of the spin polarization of photoemission from a GaAs-AlGaAs Superlattice", *Jpn. J. Appl. Phys.* 36 (1997) 2863-2864

[16] Bmad code by D. Sagan, Cornell, "Bmad: A relativistic charged particle simulation library",Nucl.Instrum.Meth. A558 (2006) 356-359. see https://www.classe.cornell.edu/bmad/.

[17] Y. Peng, Spin Tracking Studies for the SuperKEKB Polarization Upgrade, FCC epol Workshop, 2022