DEVELOPMENT OF A POLARIZED BEAM FOR SuperKEKB

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Abstract

The SuperKEKB accelerator is currently in operation in Tsukuba, Japan, with a planned long shutdown in 2026. Among the possible upgrades being considered during this period is the change to a polarized electron beam in the High Energy Ring. Such a change would require modifications in the source generation and transport, geometrical and lattice variations to provide spin rotation, and polarimetry. A Polarized SuperKEKB Working Group has been formed from members of the Belle II experiment and the SuperKEKB accelerator team to investigate the possibilities and challenges of these modifications. This talk lays out the goals of the proposed upgrade, considers the necessary changes to the existing accelerator and their feasibility and lays out the physics motivation behind such an effort.

INTRODUCTION

The SuperKEKB [1, 2] accelerator began operation in 2016 at KEK in Tsukuba, Ibaraki, Japan, and has been providing electron-positron collisions for the Belle II experiment's full physics data taking operation since 2019. While the planned lifetime of the experiment is approximately 10 years, the KEK road map includes several long shutdowns for planned upgrades and maintenance.

At the moment, neither of SuperKEKB's beams are polarized; among the proposed upgrades during that time is the inclusion of spin polarization of the high-energy electron ring. This would open up new areas of measurement for Belle II with minimal changes necessary in the existing beam line.

The major improvements needed to produce a polarized beam are:

- Generation of a highly-polarized beam, and transport of polarized electrons from the electron source to the main storage ring
- Vertical spin preservation during storage in the main ring, and rotation to a longitudinal spin for collisions, followed by restoration to the vertical
- Precision polarimetry

A beam polarization working group, consisting of members of the SuperKEKB accelerator team and Belle II researchers, has been created to investigate possibilities for upgrading to a polarized electron beam and to determine and meet the challenges involved.

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 [3, 4].

Figures 1 and 2 display the predicted precision of weak neutral vector current measurements with a data set of 20 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. Figure 3 shows the predicted resolving power for the vector couplings of the b and c quark compared to current SM predictions.

Furthermore, recent predictions also indicate that measurement of a chiral asymmetry in the process $e^+e^- \longrightarrow \tau^+\tau^-$ at 1% precision would provide a measurement of the τ magnetic moment on the order of the current 4σ tension between the SM and experiment [5]. Such a measurement would be a new avenue at investigating anomalous lepton magnetic moments without the need to build a dedicated accelerator or experiment.

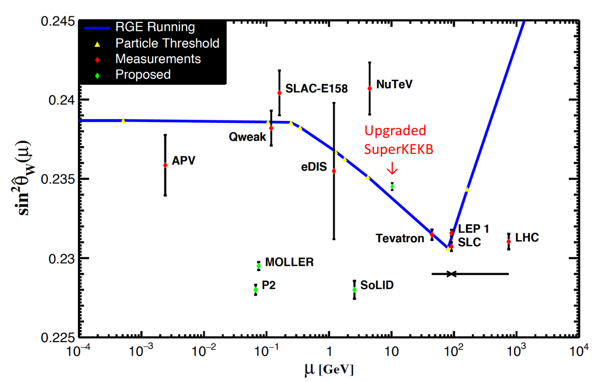

Figure 1: Scale dependence of $\sin^2\theta_W$ (giving the weak mixing angle) defined in the $\overline{MS}$ renormalization scheme. Adapted from Ref. [6] to include projected errors on proposed/upcoming experiments at particular energy scales, including that at an upgraded SuperKEKB that includes polarized electron beams.

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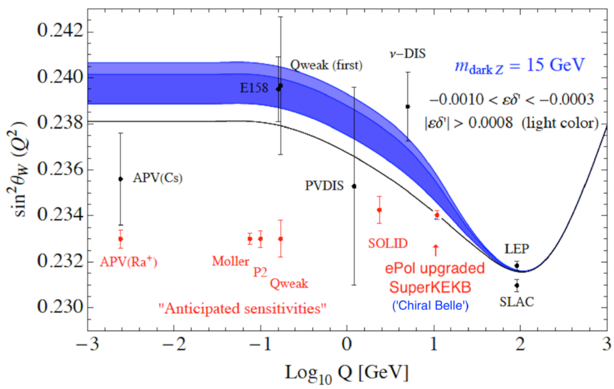

Figure 2: Predicted Q^2-dependent shift in $\sin^2\theta_W$ caused by a 15 GeV mass dark Z, represented by the dark blue band. Adapted from [7].

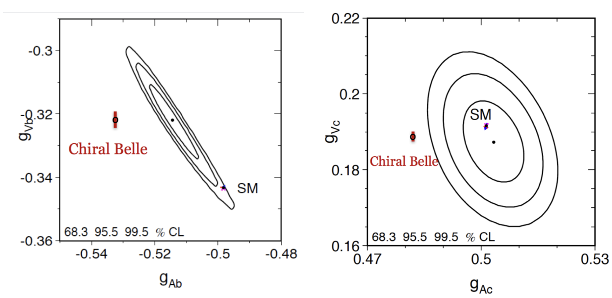

Figure 3: Predicted resolving ability of vector coupling constants of the *b* and *c* quarks with 20 ab^{-1} of data taken with a polarized beam.

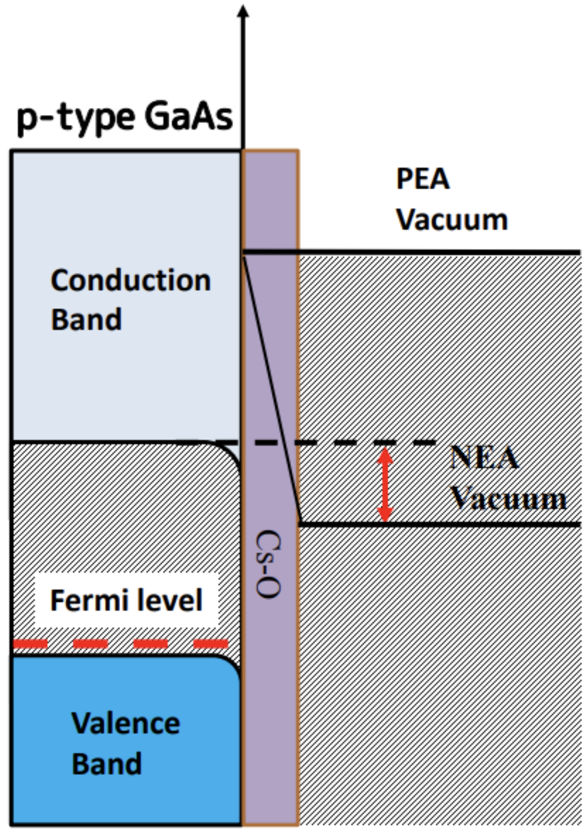

Figure 4: The NEA film mechanism. A thin surface film applied to the GaAs base reduces the band gap and imparts energy to generated electrons, enabling more efficient acceleration.

PROPOSED UPGRADES

To facilitate the inclusion of a polarized electron beam in SuperKEKB, all upgrades under consideration are intended to minimize disruption of the existing beamline.

Beam Source and Transport

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% [8], 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, as shown in Fig. 4.

While this technique has been in use in the past, cathode lifetimes are notably short. To ameliorate this issue, a DC gun can be used instead of an RF gun; such a backup system exists already at KEK and can be utilized without significant trouble.

A beam buncher can also be employed to produce bunches of 4 nC, in line with SuperKEKB's standard.

Simulations have shown that vertical beam polarization can be achieved with the use of a Wien filter at the source point, and that polarization at the source can be maintained through the SuperKEKB linac to the Main Ring injector.

Spin Preservation in the Main Ring

In the 3 km Main Storage Ring (MR), the beam would need to be circulated with a vertical polarization vector with a rotation to (from) longitudinal polarization before (after) collisions at the IP. Spin-polarization vectors in this scheme are shown graphically in Fig. 5.

Challenges inherent to this problem include the preservation of a vertical spin vector around the MR; precise rotation of polarization vectors to that needed for collision; minimal disturbance of the existing beam lattice; and satisfying spin-matching conditions enough to avoid negatively affecting the polarization lifetime.

KEK has prepared an optical model of the beam lattice for use in simulation software, and simulations have demonstrated that this can be achieved in a number of ways which require minimal changes to the existing beam lattice. One such option is the inclusion of superconducting combined di/quadrupole magnets between 100 and 150 m before and after the IP; alternately, rotator magnets could be installed in drift sections of the ring to achieve the same effect.

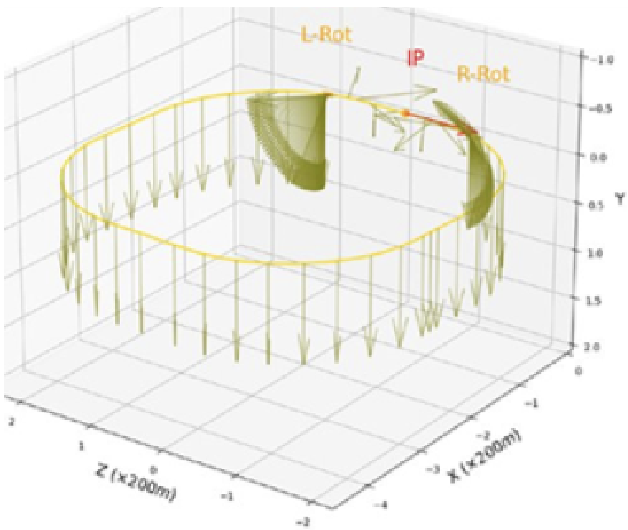

Figure 5: Simulated spin vectors in the proposed rotation scheme for the main storage ring. Electron spins are maintained vertically throughout the majority of the ring and rotated to (from) the horizontal before (after) collisions.

Polarimetry

Polarimetry with high precision and short integration time is needed to measure the beam polarization state and relate it to physics measurements taken in Belle II.

A Compton polarimeter can be deployed for this purpose, and can be used continuously as it is non-destructive. In this scheme, the beam electrons are incident on polarized laser light, and a fraction of them undergo Compton scattering. The asymmetry between electron and photon polarizations aligned parallel and antiparallel is well known and can be used to measure the beam polarization; backscatter electrons can also be used for a largely independent polarization measurement.

A Compton Polarimetry system for use in SuperKEKB, shown in Fig. 6 is under development [9] based on that used by the QWeak Collaboration, which carried out the most precise polarization measurement to date [10].

PROPOSED TIMELINE FOR UPGRADES

The current KEK Roadmap for the near future provides two long shutdowns for Belle II, during which time planned maintenance and upgrades may be carried out. The first of these is slated to occur in 2022, to be focused mainly on replacement of sensitive physics detectors near the Belle II Interaction Point (IP). The next planned long shutdown will occur in 2026. Because of the time involved in R&D for the components necessary for a polarized beam and the necessity to carefully plan changes to the beamline, including the possibility of changing magnets, the 2026 shutdown is considered the more realistic possibility.

Figure 6: Compton polarimeter demonstrator under development at the University of Manitoba.

CONCLUSION

The inclusion of a polarized electron beam at SuperKEKB provides an opportunity to make unique measurements of weak neutral vector currents in a parameter space complementary to existing experiments and at unprecedented precision.

A working group has been assembled with members of the SuperKEKB accelerator team as well as Belle II researchers, and has identified key challenges in upgrading to a spin-polarized beam. The working group is actively working on surmounting the technical challenges involved in beam generation and transport, spin preservation and rotation and polarimetry measurement necessary for producing a useful spin-polarized beam.

Work is currently ongoing in the development of robust spin-polarized cathodes and magnet design, and first-order simulations have shown that electron spin can be preserved through the injector linac, beam transport lines, and main ring, and that spin rotation to horizontal configuration is possible with minimal changes to the existing SuperKEKB lattice.

REFERENCES

[1] K. Akai *et al.*, "SuperKEKB collider", Nucl. Instrum. Methods Phys. Res. A, 907 (2018) 188–199.

[2] SuperKEKB Design Report. `https://kds.kek.jp/indico/event/15914/`

[3] 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.

[4] J.M. Roney, "Precision electroweak physics with polarized beams at SuperKEKB", in Proc. Lepton Photon 2019.

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

[6] 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).

[7] H. Davoudiasl, H. S. Lee and W. J. Marciano, "Low Q^2 weak mixing angle measurements and rare Higgs decays", Phys.Rev. D, 92, no. 5, 055005 (2015).

[8] X.G. Jin, B. Ozdol, M. Yamamoto, A. Mano, N. Yamamoto, and Y. Takeda, "Effect of crystal quality on performance of spin-polarized photocathode", Appl. Phys. Lett., 105, 203509 (2014).

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

[10] D. Androic *et al.*, "Precision Measurement of the Weak Charge of the Proton", Nature **557**, 207–211 (2018).