SciPost Phys. Proc. 17, 012 (2025)

Chiral Belle: e-Beam polarization upgrade of SuperKEKB

J. Michael Roney,
on behalf of the Belle II/SuperKEKB e- Polarization Upgrade Working Group

University of Victoria, Victoria, Canada

mroney@uvic.ca

The 17th International Workshop on
Tau Lepton Physics (TAU2023)
Louisville, USA, 4-8 December 2023
doi:10.21468/SciPostPhysProc.17

Abstract

Recent R&D work associated with upgrading the SuperKEKB e^+e^- collider with polarized electron beams is presented. The Chiral Belle physics program enables a set of unique precision measurements using the Belle II detector. It includes a set of measurements of $\sin^2\theta_W$ via separate left-right asymmetry (A_{LR}) measurements in annihilations to pairs of electrons, muons, taus, charm and b-quarks that yield precisions matching or exceeding those of the current world averages from measurements at the Z^0-pole, but at 10GeV, thereby also probing the running of the couplings. Chiral Belle will also probe for new physics via the highest precision measurements of neutral current universality ratios and precision measurements of tau lepton properties, including the tau magnetic moment. After summarizing the physics goals, developments related to provision of the polarized source, the new components of the accelerator lattice that rotate the electron spin from transverse to longitudinal at the interaction point, and polarimetry of the electron beam will be reported.

Received 2024-07-04
Accepted 2024-12-04
Published 2025-07-23
doi:10.21468/SciPostPhysProc.17.012

1 Introduction

With the SuperKEKB e^+e^- collider upgraded to reach a luminosity of $6 \times 10^{35}\ cm^{-2}s^{-1}$, Belle II's datasets will be sufficiently large that a new and unique program of precision physics at a center-of-mass energy of 10.58 GeV is enabled by further upgrading SuperKEKB to have polarized electron beams stored in its High Energy Ring (HER).

The physics potential of the proposed 'Chiral Belle' program and corresponding hardware upgrade requirements needed to achieve those physics goals, which were introduced in the Snowmass White Paper on upgrading SuperKEKB with a polarized electron beam [1], are summarized. Data with polarized beam is also to be used for Belle II's current unpolarized physics program. Consequently the plan is to introduce and run with polarized beam while Belle II accumulates its 50 ab^{-1} sample and substantially exceed the original physics deliverables of Belle II/SuperKEKB after making a modest investment in the polarization upgrade program.

2 Physics goals

By upgrading SuperKEKB to have polarized electron beams, unique and high-impact sensitivities to new physics via precision neutral current measurements at 10 GeV are enabled. For example, a determination of the weak mixing angle from measuring the parity violating left-right asymmetries, $A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$, will yield values of $\sin^2\theta_W$ having a precision comparable to the current world-average Z^0-pole value, but at 10.58 GeV. In this way, Chiral Belle will be uniquely sensitive to the presence of beyond-the-Standard Model parity violating bosons with masses below the Z^0 that are predicted in some Dark Sector models. These measurements of the neutral current vector couplings will be performed separately for all three charged leptons and b- and c-quarks, and as they are made at 10 GeV, they provide unique probes the running of neutral current vector couplings of 1st, 2nd and 3rd generation fermions with high precision. Chiral Belle will also be the only facility to precisely measure neutral current for charm and beauty quarks and all three charged leptons at energies below the Z^0 pole. The ratios of neutral current vector couplings between pairs of fermions will also be measured with unprecedentedly high precision, benefiting from the cancellation of the beam polarization systematic uncertainties. For example the b-to-c quark coupling ratio will be measured 14 times more precisely than current world averages. Since these measurements are precisely predicted in the Standard Model, deviations in any of them would be a sign of New Physics beyond the Standard Model. There are no other experiments planned that would probe the Standard Model in this way and which such high precision.

The production of τ's in $e^+e^- \to \tau^+\tau^-$ events at 10 GeV with polarized beams will also enable a measurement of the Pauli form-factor, $F_2(q^2)$, of the τ at 10 GeV and thereby provide the only means to probe the third-generation $g-2$ at an interesting precision. With Belle II having a 40 ab^{-1} sample of polarized beam data, a measurement at the 10^{-5} level is possible, which represents a 1% precision on the "Schwinger term" of the anomalous magnetic moment. This is more than 100 times more precise than current limits on the tau $g-2$. No other running or experiment planned to run before the 2040's is able to reach this level of precision.

The Chiral Belle physics program extends to include precision measurements of the τ electric dipole moment, QCD hadronization studies, and high precision measurements of the τ Michel parameters. Having polarized electron beams also gives rise to improved sensitivities of lepton flavor violation searches in τ decays.

If SuperKEKB is further upgraded to extremely high luminosity in the longer term, then the tau anomalous magnetic moment measurement can reach the $\mathcal{O}(10^{-6})$ level. This would be at the level equivalent to that of the muon $g-2$ anomaly scaled by $(m_\tau/m_\mu)^2$ motivated in Minimal Flavor Violation scenarios. Achieving $\mathcal{O}(10^{-6})$ will require substantially more statistics than the base plan of collecting 40 ab^{-1} of polarized-beam data and also requires improved measurements of m_τ and $m_{\Upsilon(1S)}$ in addition to additional theoretical work [2].

3 Polarization upgrade requirements

Accessing this novel precision-frontier window on New Physics will require completion of planned upgrades to increase SuperKEKB luminosity to its design target of $6 \times 10^{35} cm^{-2} s^{-1}$ as well as the addition of three hardware upgrades related to implementing the beam polarization:

1) a low-emittance polarized source that injects vertically (i.e. transversely) polarized electrons into SuperKEKB with two data sets with opposite polarization states: one with spin up and the other with spin down - the stable spin-states in the dipole fields of the HER synchrotron;

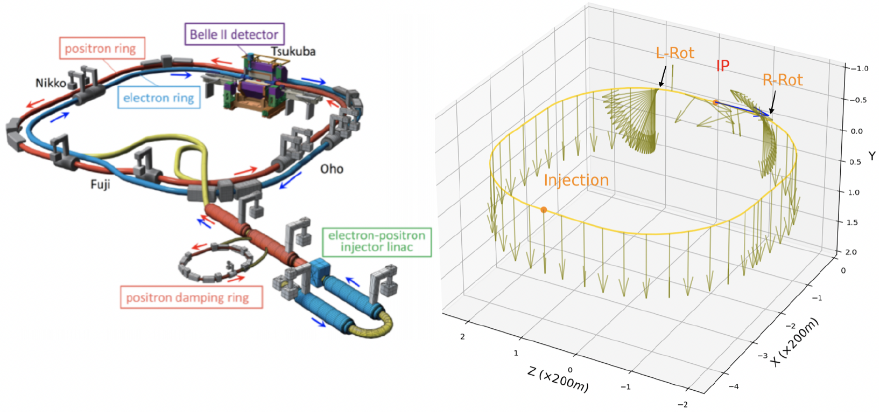

Figure 1: The spin motion of the electron in the HER with the spin rotators installed. Figure adapted from [1].

2) two sets of spin rotator magnets in SuperKEKB's HER, with the first set rotating the spin of the beam electrons from transverse to longitudinal before the interaction point (IP), where the Belle II detector is located, and the second set rotating the spin back to transverse after the IP, as depicted in Figure 1; and

3) a Compton polarimeter located between the first spin rotator and the IP to provide real-time measurements of the beam polarization. Belle II will also precisely measure the beam polarization at the IP by analysing the spin-dependent kinematics of particles produced in the decay of τ leptons produced in an $e^+e^- \to \tau^+\tau^-$ data set - details are provided in the submission by Caleb Miller to these Proceedings. Since it is measured at the IP, this technique gives Chiral Belle a unique way of controlling systematic uncertainties on the beam polarization.

R&D on the polarized source has many synergies with the polarized source development for the Electron Ion Collider project at Brookhaven National Lab. As with polarized sources used in the SLC, SLAC-E158 and QWeak experiments, the helicity of the electrons is to be changed by controlling the circular polarization of the source laser illuminating a GaAs photocathode. In Chiral Belle the polarization for different bunch trains can be flipped from one polarization state to the other by changing the polarization state of the laser illuminating the source photocathode. The operational strategy for flipping the polarization state in the SuperKEKB electron ring will be designed to minimize overall systematic uncertainties in the final left-right asymmetry measurements. The electrons stored in the HER will be vertically polarized, except near the IP, see Figure 1. Since at the source the electrons are emitted from the photocathode in a longitudinally polarized state, the spin must be rotated to transverse using a Wien filter immediately after photocathode to inject transversely polarized electrons into the linac supplying the HER beam. Using BMAD software [3], spin tracking studies from the source, through the linac and injector lattice, show that the transverse polarization state of the electrons will be preserved when injected into the HER. Multi-particle long term tracking studies using BMAD demonstrate that the electrons injected with transverse polarization will maintain their polarization in the HER, with a transverse polarization lifetime of many hours.

An important goal of Chiral Belle is to provide a spin rotator solution in the SuperKEKB HER that is "transparent" to the rest of the HER lattice - that is, the rest of the HER lattice is not impacted by the spin rotators so that the SuperKEKB high luminosity is fully maintained. The solution that has been developed minimizes disruptions to the existing lattice and also easily permits the possible operation of the HER without any spin rotator magnet fields. This solution, proposed by Uli Wienands (Argonne National Laboratory), employs compact combined function magnets consisting of a dipole, a solenoid and a system of six skew-quadrupole fields,

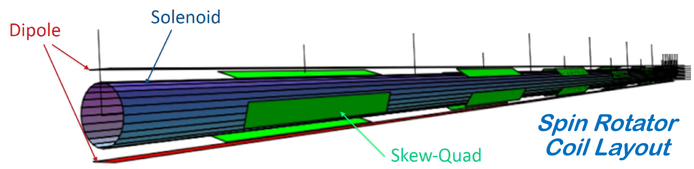

Figure 2: Wienands concept for a compact combined function spin rotator with overlaid dipole, solenoid and skew-quadrupole superconducting coil fields. Figure adapted from [1].

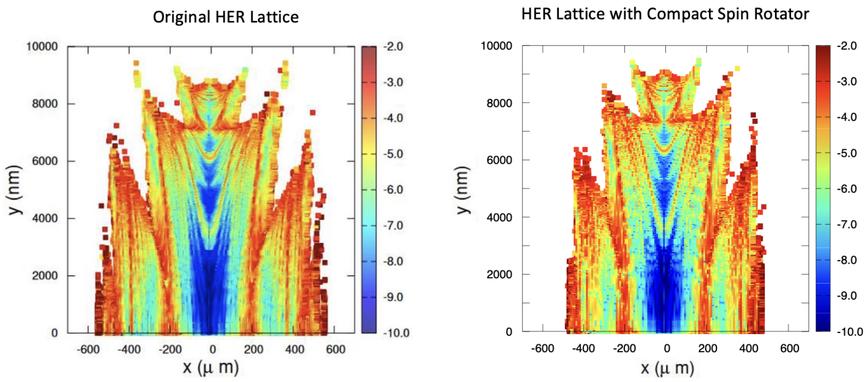

Figure 3: Output of Frequency Map Analysis for (left) the current High Energy Ring (HER) lattice and (right) for the HER lattice with four compact combined function spin rotator magnets installed. These show that spin rotators can be implemented in a manner that is transparent to the rest of the lattice, which have been further confirmed with long term tracking studies, as described in the text. These FMA plots were provided by (left) D. Zhou [KEK] and (right) N. Tessema [Univ. of Victoria]).

see Figure 2. It would be implemented in the HER using four compact combined function magnets, two before the IPP and two after the IP. These four combined function magnets would physically replace existing dipole magnets in the HER. The success of this solution is demonstrated with Frequency Map Analysis dynamic aperture studies that indicate that stable beams can be maintain with the spin rotators in place with little change to the dynamic aperture of the lattice, as can be seen in Figure 3. Multi-particle long term tracking studies, which include radiation damping and radiation fluctuations/quantum excitation effects, explore non-linear features of beam lifetime and polarization lifetime. Such studies have been performed and demonstrate that sufficiently long beam and polarization lifetimes can be achieved with the spin rotators in place and confirm the viability of this particular spin rotator concept.

As described in reference [4], a Compton polarimeter can be installed at a location that minimizes any disruptions to the existing lattice. The Compton polarimeter described in [4] can achieve polarization measurements with systematic uncertainties at the 0.5% level. Unique to the Chiral Belle program is the additional means of measuring the beam polarization at the IP using τ pair events with a relative systematic uncertainty of 0.4%, as described in [5] and reported in the submission by Caleb Miller to these Proceedings. They describe the technique and evaluation of the statistical and systematic uncertainties using PEP-II e^+e^- collision data collected with the BaBar detector at the $\Upsilon(4S)$ center-of-mass energy.

4 Next steps

A Conceptual Design Report on the SuperKEKB Beam Polarization Upgrade Project is being prepared and work is proceeding on the R&D of the hardware components, including prototypes. These will converge on the Technical Design with cost estimates. To set the scale on the capital costs for the polarization upgrade, they are expected to be substantially less than half of the annual power costs of operating the SuperKEKB accelerator. It is also be expected that a significant fraction of those capital costs will be provided by non-Japanese groups on Belle II.

A proposal for a near-term measurement of the lifetime of the transverse polarization in the current HER is in preparation. In this proposal, a polarized source will inject transversely polarized electrons and the polarization lifetime measured using the Touschek effect, as was been done in past resonant depolarization measurements. This dedicated experiment of a few days duration will serve to validate the BMAD multi-particle long term tracking studies predicting a long transverse spin lifetime. This Touschek-Polarization Experiment would be conducted at the end of a SuperKEKB running period within the next couple of years.

It is feasible to plan for a polarization upgrade to commence towards the end of this decade using the next SuperKEKB long shutdown and possibly a number of summer shutdowns. This would have the polarization program beginning while SuperKEKB completes its program of delivering 50 ab^{-1} of data to Belle II.

5 Conclusion

The physics program enabled by Chiral Belle is a set of unique precision measurements using the Belle II detector. A set of measurements of $\sin^2\theta_W$ via separate left-right asymmetry (A_{LR}) measurements in annihilations to pairs of electrons, muons, taus, charm and b-quarks will yield precisions matching or exceeding those of the current world averages from measurements. These precision measurements provide unique probes the running of the weak mixing angle and consequently are sensitive to New Physics, such as predicted in some Dark Sector models. The program will also generate the highest precision measurements of neutral current universality ratios and precision measurements of tau lepton properties, including the tau anomalous magnetic moment. The upgrades to SuperKEKB required to get there include: higher luminosity as well as the installation of a polarized source, the replacement of four dipoles with combined function spin rotator magnets, and the installation of a Compton polarimeter. Initial studies have shown that these upgrades are entirely feasible and a detailed Conceptual Design report is in preparation.

References

[1] A. Accardi et al., *Snowmass 2021 white paper on upgrading SuperKEKB with a polarized electron beam: Discovery potential and proposed implementation*, (arXiv preprint) doi:10.48550/arXiv.2205.12847.

[2] A. Crivellin, M. Hoferichter and J. M. Roney, *Toward testing the magnetic moment of the tau at one part per million*, Phys. Rev. D **106**, 093007 (2022), doi:10.1103/PhysRevD.106.093007.

[3] D. Sagan, *Bmad: A relativistic charged particle simulation library*, Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **558**, 356 (2006), doi:10.1016/j.nima.2005.11.001.

[4] D. Charlet, T. Ishibashi, A. Martens, M. Masuzawa, F. Mawas, Y. Peinaud, D. Zhou and F. Zomer, *Conceptual study of a Compton polarimeter for the upgrade of the SuperKEKB collider with a polarized electron beam*, J. Instrum. **18**, P10014 (2023), doi:10.1088/1748-0221/18/10/P10014.

[5] J. P. Lees et al., *Precision e^- beam polarimetry at an e^+e^-B factory using tau-pair events*, Phys. Rev. D **108**, 092001 (2023), doi:10.1103/PhysRevD.108.092001.