

BENCHMARKING THE XSUITE CODE WITH BEAM POLARIZATION DATA OF THE LARGE ELECTRON POSITRON COLLIDER

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Abstract

The 26.7 km long Large Electron Positron collider (LEP) was operated at CERN between 1989 and 2000. The most precise measurements of the Z boson mass and width were made possible thanks to high precision energy calibration of the LEP beams with resonant depolarization. Transversely polarized beams had to be established at LEP to achieve this goal, providing a rich legacy of data on polarized beams at beam energies around 45 GeV. The beam dynamics simulation package Xsuite was recently enhanced to track polarized beams and to evaluate the equilibrium polarization of beams and related quantities. Xsuite code benchmarking with LEP results on transverse polarization and resonant depolarization will be presented in this contribution.

INTRODUCTION

High precision measurements of the Z boson mass and width and of the W boson mass are important pieces of the 91 km circumference Future Circular Collider (FCC-ee) physics program. The goal of this program is to reduce by at least a factor of ten the uncertainties in the beam energy compared to the LEP results [1]. The precision measurement of the beam energies at FCC-ee will rely on resonant depolarization of transversely polarized beams, based on the LEP experience [2, 3].

The Xsuite accelerator simulation framework [4] was enhanced with spin modeling capabilities [5], allowing six-dimensional tracking of particle trajectories together with their spin motion. The module includes integration of the Thomas–BMT equation and a linearized computation of the invariant spin field (ISF). Radiative spin effects are incorporated through the Sokolov–Ternov mechanism and its generalizations, allowing the evaluation of equilibrium polarization and of its buildup times.

This contribution complements the benchmarking of the Xsuite polarization module with LEP polarization and resonant depolarization data collected during the years of LEP operation around the Z boson resonance, mainly in the beam energy range of 44.5 to 46.5 GeV.

SOLENOID COMPENSATION

Each of the four large LEP detectors had solenoids with integrated fields ranging from 2.6 Tm to 10.08 Tm. The betatron coupling induced by those solenoids was compensated by skew-quadrupoles installed in the long straight sections. The spin resonances introduced by the solenoids were not compensated for by this scheme, leading to very low or no

transverse polarization at all. The spin correction schema relied instead on orbit bumps installed in the arcs around each experimental IP [6]. The correction relied on vertical double pi-bumps in the arc on either side of every solenoid to minimize the spurious dispersion generated by the large bumps, with peak amplitudes of ≈ 6 mm for the ALEPH solenoid as shown in Fig. 1. The evolution of the polarization vector through this bump is shown in Fig. 2.

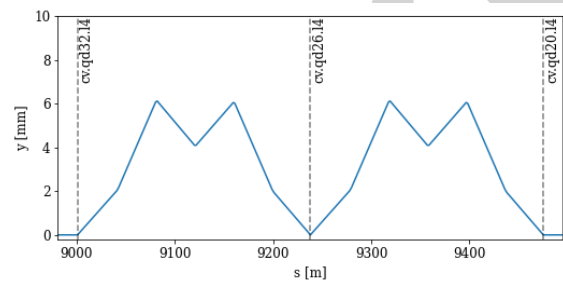


Figure 1: Double pi-bump used to compensate the solenoid of the ALEPH detector. This bump is placed on the left side of the IP, a symmetric bump is placed on the right side.

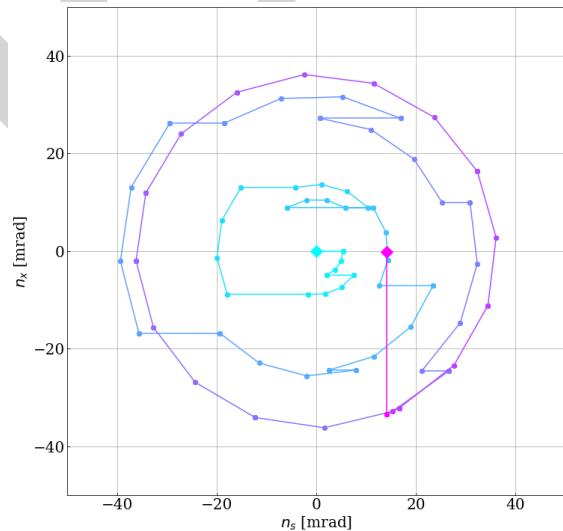


Figure 2: Evolution of the polarization vector projection in the horizontal plane (s-x) through the bump shown in Fig. 1 and half of a solenoid. The polarization vector is initially vertical (cyan rectangle at (0,0)), it ends at the purple rectangle.

The predicted equilibrium vertical polarization with and without solenoid compensation is shown in Fig. 3, in good agreement with the LEP results [2]. With solenoids switched on, the transverse polarization never exceeded a few percent in the absence of the compensation bumps.

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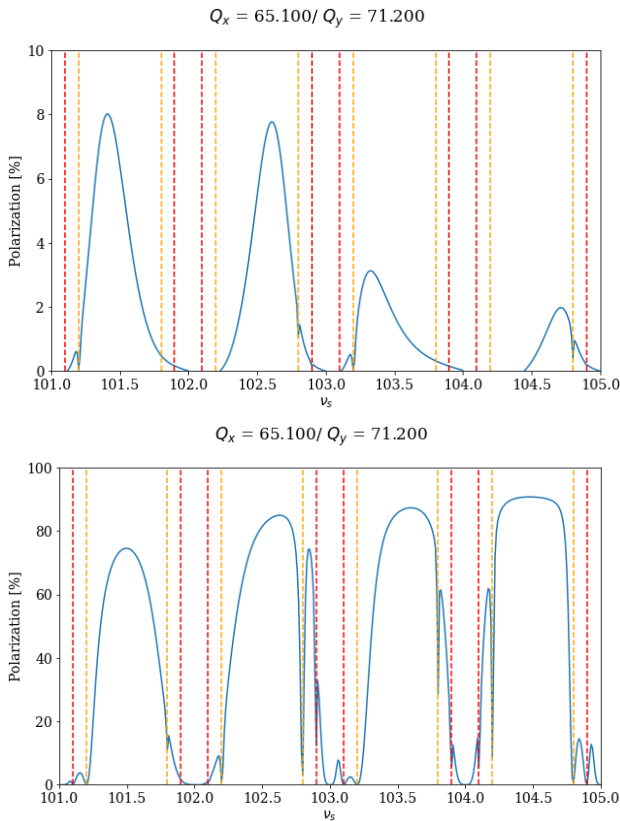


Figure 3: Equilibrium vertical polarization without (top) and with (bottom) compensation of the LEP solenoids with the vertical orbit bumps. The vertical dashed lines indicate the positions of the $n \pm Q_{x,y}$ spin resonances.

RESONANT DEPOLARIZATION

The LEP beam energy was measured with high accuracy using resonant depolarization (RDP) of transversely polarized beams [1, 3]. A RF kicker with a maximum transverse deflection of $1.3 \mu\text{rad}$ and a varying excitation frequency were used to rotate the polarization away from the vertical direction. For a kicker frequency close to the fractional spin tune, the beam may be depolarized, or the polarization may even flip sign [7]. With a single kick, the beam performs a forced vertical betatron oscillation which can enhance the deflection provided by the RF kicker [8]. For LEP the enhancement was in the range 3-6 depending on the optics variant.

The RDP process was simulated for LEP in Xsuite with typical frequency scan parameters: frequency range of 0.002 (in tune units) for a sweep duration of 12 seconds ($\approx 135'000$ machine turns). A simulated scan is presented in Fig. 4 for a synchrotron tune of $Q_s = 0.0625$ typical for LEP energy calibration.

A fine scan of the RDP resonance was performed in 1993 [3] with tune scan ranges reduced by a factor four, but with the same frequency scan speed. This experiment was reconstructed with Xsuite and the simulations match the original data very well as can be seen in Fig. 5. Only the

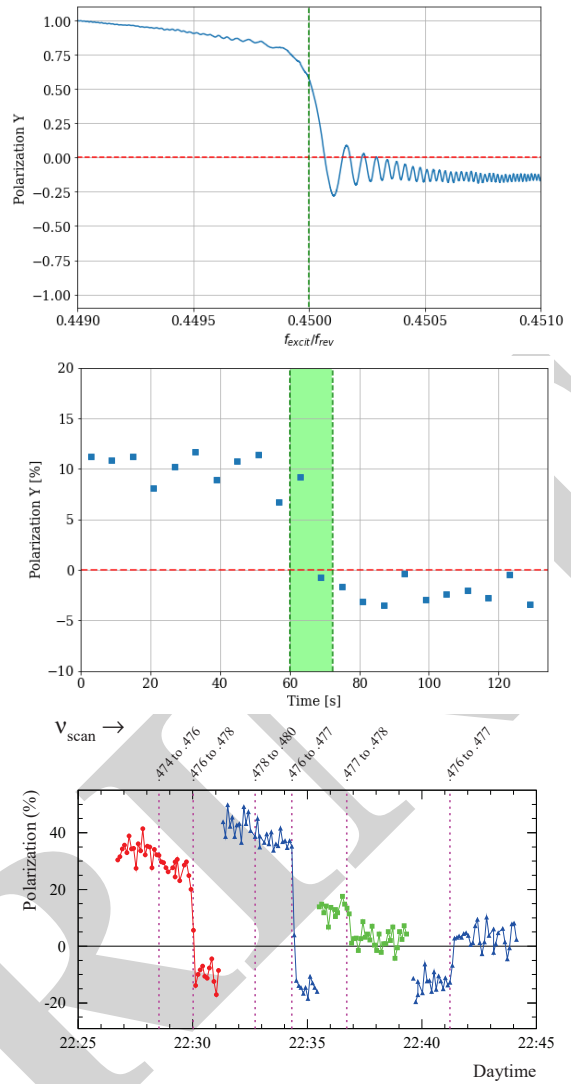


Figure 4: A simulation of a standard LEP RDP scan is presented in the top plot with polarization evolution as a function of the exciter frequency turn after turn. On the middle plot, this raw data is convoluted with LEP measurement conditions: one data point every 6 seconds and the typical measurement error. In addition ten simulated measurements were added before and after the scan which covers the points in the green vertical band. On the bottom plot, a typical LEP RDP scan sequence is presented for comparison.

kicker strength had to be increased from 1.3 to $1.5 \mu\text{rad}$ to match the final polarization of the central point.

SPIN TUNE SYSTEMATIC SHIFTS

Controlling systematic errors is an important aspect of high precision energy calibration [1,3]. An irreducible uncertainty arises from imperfections that break the relationship between the closed orbit spin tune ν_0 and $a\gamma$, leading to an offset δ_ν :

$$\nu_0 = a\gamma + \delta_\nu \quad (1)$$

Vertical orbit deviations or solenoidal fields for example lead to non-zero δ_ν due to the non-commutation of interleaved

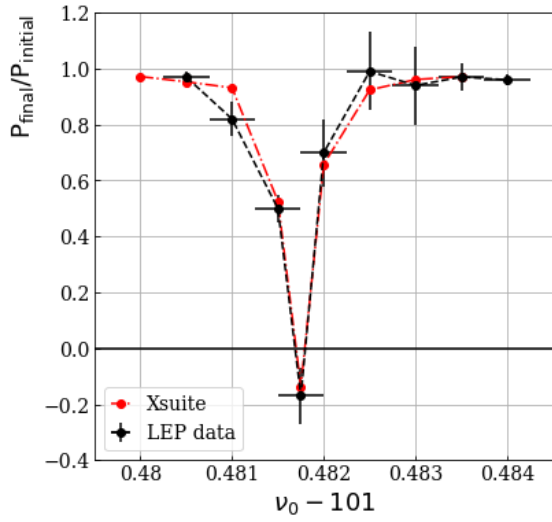


Figure 5: Fine scan of the RDP resonance with smaller tune scan ranges. The LEP data from 1993 [3] is compared to a Xsuite simulation of the same scan.

rotations around the three different axes. The impact of vertical orbit offsets on δ_ν was studied in detail for LEP1 [3].

A LEP optics used for energy calibration during the LEP2 era with 60° horizontal and vertical phase advance was used to benchmark Xsuite against the LEP results. A RMS quadrupole misalignment of 0.35 mm in horizontal and 0.18 mm in vertical was applied together with a 0.3 mm RMS BPM misalignment. The orbits were corrected to 0.6 mm in horizontal and 0.35 mm in the vertical plane. The shift δ_ν was evaluated from the difference between the spin tune obtained by particle tracking and an FFT of the horizontal polarization and the average energy shift from Xsuite. The resulting errors are presented in Fig. 6 together with the estimates made at the time of LEP operation [3].

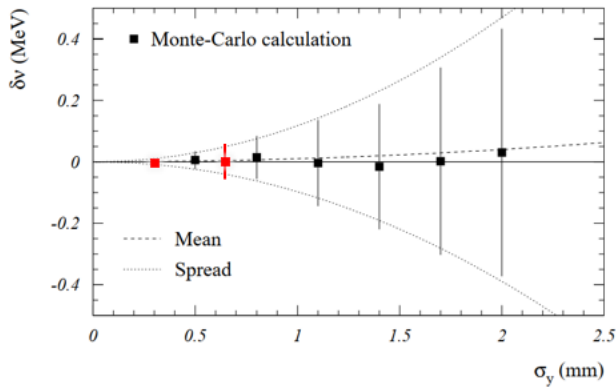


Figure 6: Systematic error on the closed orbit spin tune δ_ν as a function of the vertical orbit rms. Simulations performed during LEP operation [3] are compared to Xsuite results (red points).

The impact on the spin tune value of the solenoids and of their compensation bumps was computed as a function of the closed orbit spin tune ν_0 with Xsuite. The results are presented in Fig. 7 for the four LEP solenoids with and

without the compensation bumps. The Xsuite results are in very good agreement with an estimate based on the rotations tracked independently along the closed orbit. For solenoids alone, the shift generally vanishes at half-integer spin tune values except close to 103.5 and 104.5 due to the presence of the systematic resonance for $a\gamma$ equal to 104. It is worth noting the residual shift present even when the solenoids are compensated. The shift amounts roughly to 2×10^{-5} in tune units or 88 keV in beam energy. This shift has not been considered for the beam energy errors of the LEP Z boson mass and width measurements. The shift is within the error of 100 keV assigned to spin tune shifts [1, 3] and amounts roughly to 10% of the total LEP beam energy uncertainty.

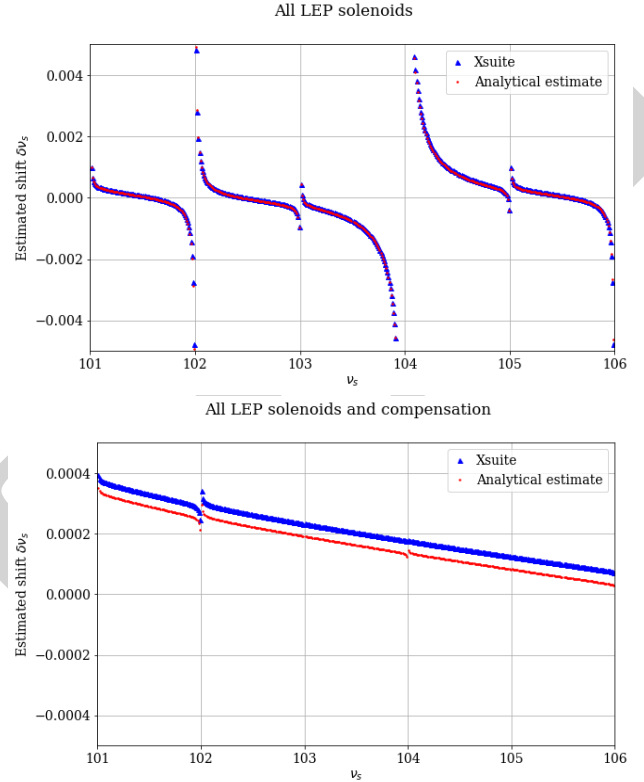


Figure 7: Systematic shift of the closed orbit spin tune due to the four LEP solenoids (top) and due to the four solenoids and their compensation (bottom). The Xsuite result is compared to an independent analytic estimate using the spin rotation matrices.

SUMMARY

LEP transverse polarization and resonant depolarization results have been compared with Xsuite simulations based on the LEP machine sequences and the LEP optics strength files. The simulation results are in very good agreement with the historic LEP data, providing a convincing benchmarking of the polarization module that is implemented in Xsuite.

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