ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO039

OPTIMIZING POLARIZATION WITH AN IMPROVED INTEGER RESONANCE CORRECTION SCHEME AT ELSA*

J. F. Schmidt†, O. Boldt, F. Frommberger, W. Hillert, J.-P. Thiry, ELSA, Bonn, Germany

Abstract

The Electron Stretcher Facility ELSA of Bonn University provides a polarized electron beam of up to 3.2 GeV. In the stretcher ring various depolarizing resonances are crossed during the fast energy ramp of 6 GeV/s. The high polarization degree of up to 70 % can only be conserved by taking several appropriate countermeasures. Concerning integer resonances, additional harmonic horizontal fields are applied by orbit correction magnets around the ring to compensate the resonance driving fields. The correction field has to be adjusted by empirical optimization of polarization.

Recent developments enhance this optimization process, especially at high energies: A new magnet system allows for higher correction amplitudes and shorter rising times. Furthermore, a modified correction scheme was implemented. It takes into account the additional fields of the quadrupole magnets, arising from the orbit response of the correction magnets.

INTRODUCTION

For more than a decade, a polarized electron beam with typically 2.4 GeV has been provided by the Electron Stretcher Facility ELSA at Bonn University (Fig. 1). The polarized electrons gained from an inverted source are accumulated in the stretcher ring via an 1.2 GeV booster synchrotron, then accelerated utilizing a fast energy ramp with up to 6 GeV/s and extracted slowly via resonance extraction. Thereby, a duty factor of more than 80 % is achieved.

This concept requires to preserve the polarization during the whole acceleration process which is hindered by depolarizing resonances. They occur whenever the electron spin precession around the vertical fields of the bending magnets is in phase with any component of the accelerator's horizontal magnetic field distribution. According to the Thomas-BMT equation [1], the spins precess γa times per turn in a flat circular electron accelerator (neglecting longitudinal magnetic fields), where $a = (g_s - 2)/2$ is the gyromagnetic anomaly. $\gamma a =: Q_{\text{spin}}$ is also called the spin tune and increases linearly with beam energy due to the Lorentz factor γ.

Several depolarizing resonances are crossed during the acceleration in the ELSA stretcher ring. Their correction is the major challenge to reach high degrees of polarization. Without any compensation the remaining degree of polarization after extraction at 2.4 GeV is below 40 %. In the past, a polarization of up to 65 % was obtained under consideration of all countermeasures [2].

* Work supported by DFG
† schmidt@physik.uni-bonn.de

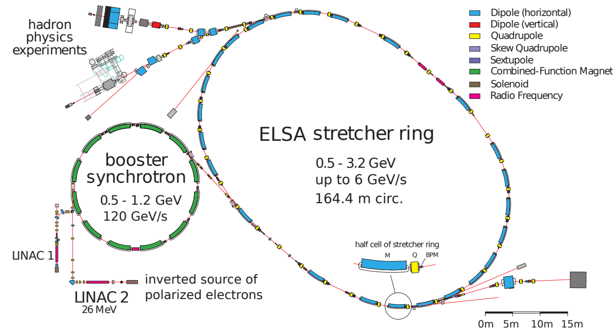

Figure 1: The Electron Stretcher Facility ELSA in Bonn.

HARMONIC CORRECTION OF INTEGER SPIN TUNE RESONANCES

Integer spin tune resonances are one of the two main depolarizing effects[1]. They occur every ∼ 440 MeV when the spin tune γa becomes an integer number. Accordingly, these resonances are driven by those horizontal magnetic fields that act on the beam in the same way each turn. In other words, the resonance $\gamma a = n$ is driven by the field component changing with the nth revolution harmonic around the ring. These are e.g. magnet misalignments as well as quadrupole fields caused by a vertical closed orbit displacement.

Thus, the first measure against integer resonances is a preferably good vertical closed orbit correction during the fast energy ramp (rms of 50 µm [3]). Additionally, the remaining depolarizing field component is superposed destructively with a harmonic field distribution applied with the orbit correction magnets (VC) around the ring as kick

$$\alpha^{\text{VC}}(\theta) = S \cdot \sin(\gamma a \cdot \theta) + C \cdot \cos(\gamma a \cdot \theta) \quad . \tag{1}$$

Here $\theta = \int_0^s 1/R(s')\mathrm{d}s' \in [0, 2\pi]$ is the spin phase advance changing only within the 24 bending magnets (finite curvature $1/R$), where the spins precess around the vertical field. In between there are 24 segments i of constant equidistant spin phase advance $\theta_i = i \cdot 2\pi/24$ with $i \in \{0, 1, \ldots, 23\}$.

This correction procedure is called harmonic correction. The two parameters of the harmonic correction field (S, C) have to be adjusted empirically for each resonance by iteratively optimizing the degree of polarization at the beginning of a beamtime, because the resonance driving misalignments are not known precisely and may change over time. Figure 2 shows an example for such an optimization from March 2014. Here about 25 % polarization were gained from the harmonic correction of $\gamma a = 3, 4, 5$.

Below, recent significant improvements concerning the harmonic correction are presented.

[1] The others are intrinsic resonances, which are driven by the betatron tunes and avoided with tune jumps [2].

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO039

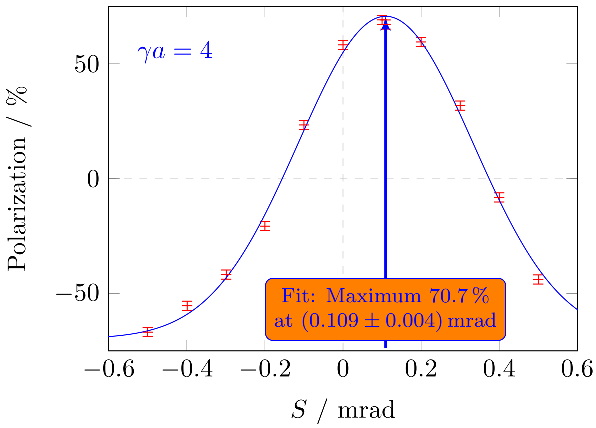

Figure 2: Møller polarimeter measurement from polarization optimization of integer resonance $\gamma a = 4$ in March 2014. It took about 10 min to obtain one polarization value with a statistical error of 2 %. A Gaussian fit is used to determine the maximum.

THE NEW CORRECTION MAGNET SYSTEM

The faster the energy ramp, and thereby the resonance crossing, the smaller is the depolarization. But only acceleration with maximum 4 GeV/s was suitable with the previous correction magnet system due to its limited rising time. This is especially crucial for the harmonic correction, because during a 6 GeV/s energy ramp an integer resonance is crossed approx. every 73 ms and the sequent resonances may require totally different correction fields. Additionally, the maximum field strength of the previous system limited the harmonic correction amplitudes at higher resonances ($\gamma a = 6, 7$) and therefore operation with polarized beam at the maximum energy of 3.2 GeV.

The new correction system includes 30 new vertical steerer magnets driven by new power supplies. Both have been developed in-house. They allow for a field integral of 9.8 mT m and a field reversal time of 20 ms [4]. The first polarization optimization with the new system was performed in March 2014 with a 6 GeV/s energy ramp and yielded an increase of maximum polarization from typically 65 % to (71 ± 2) % at 2.4 GeV.

THE PREVIOUS CORRECTION SCHEME

Naturally, the harmonic correction applied by the vertical correction magnets changes the vertical closed orbit. Thus, the horizontal fields acting on the beam in the quadrupoles also change. That is why the actual change of the resonance driving field distribution $\alpha^{\mathrm{H}}(\theta)$ by the harmonic correction not only consists of the set correction kicks α_m^{VC} according to equation 1, but also implies quadrupole contributions α_j^{Q} caused by the α_m^{VC}:

$$\alpha_i^{\mathrm{H}} := \alpha^{\mathrm{H}}(\theta_i) = \sum_{m \in \mathrm{VC}} \delta_{m,i}^{\mathrm{VC}} \, \alpha_m^{\mathrm{VC}} + \sum_{j \in \mathrm{Q}} \delta_{j,i}^{\mathrm{Q}} \, \alpha_j^{\mathrm{Q}} \quad . \tag{2}$$

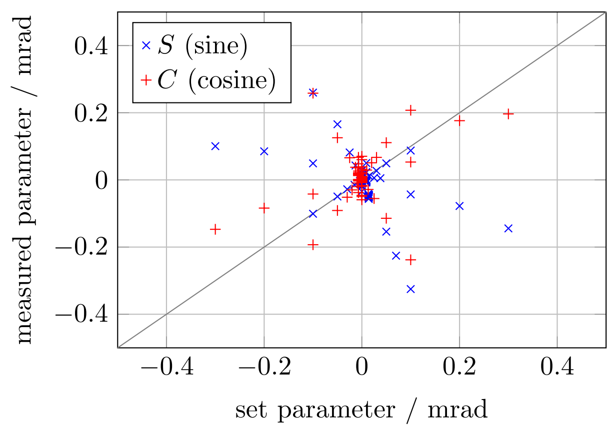

Figure 3: Parameters of the previous harmonic correction scheme for $\gamma a = 3, 4, 5$. They deviate from the set parameters due to the quadrupole contributions caused by the orbit response to the correction fields.

Here the abbreviations $\delta_{m,i}^{\mathrm{VC}}$ and $\delta_{j,i}^{\mathrm{Q}} \in \{0, 1\}$ are used, which are equal 1 if the corrector m or quadrupole j is located within the accelerator segment corresponding to spin phase advance θ_i.

Figure 3 demonstrates the impact on the harmonic field distribution. For different set parameter pairs (S, C) the change of the closed orbit Δz was measured. In each case the total kick distribution $\alpha^{\mathrm{H}}(\theta)$ was calculated and the actual measured parameter pair (S, C) was determined from the corresponding frequency component via a Fast Fourier Transformation. Finally, each measured parameter is plotted against the related set one. The plot shows no significant correlation between the set harmonic correction and the actual resulting field distribution. Though the resulting field changes with (S, C), it is not the desired one. Nevertheless, the empirical polarization optimization is possible with this correction scheme (e.g. Fig. 2), but two problems can occur: First, a part of the parameter space may not be accessible at all, which could inhibit the optimization. Second, the consecutive optimization of both parameters may not result in the global maximum of polarization.

The latter is illustrated by a simulation of the optimization for $\gamma a = 6$ in Fig. 4. It was performed with the in-house developed spin dynamics simulation suite POLE [5], which automatically reads a MAD-X or Elegant lattice and performs a fast spin tracking of the resonance crossing. In this case, the correction kicks described above were inserted in a MAD-X lattice and POLE computed the degree of polarization after the resonance depending on the correction parameters (S, C). The result clearly indicates, that e.g. an optimization in S for fixed C followed by an optimization in C with the found ideal S does not ensure maximum polarization.

THE IMPROVED CORRECTION SCHEME

An improved correction scheme was implemented [6] to achieve a physical accurate behavior of the harmonic

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO039

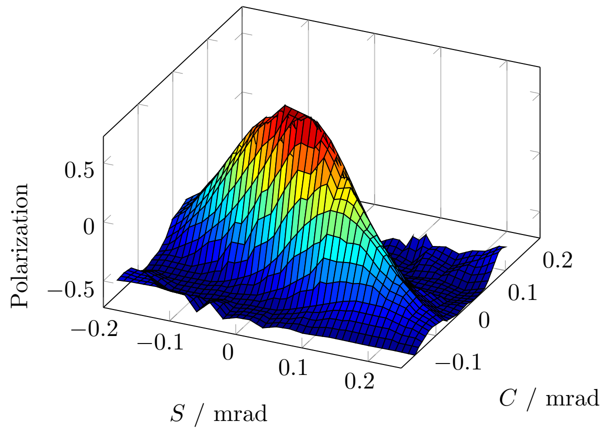

Figure 4: Simulation of the optimization of $\gamma a = 6$ with the previous harmonic correction scheme. The consecutive optimization of both correction parameters may not result in the global maximum of polarization.

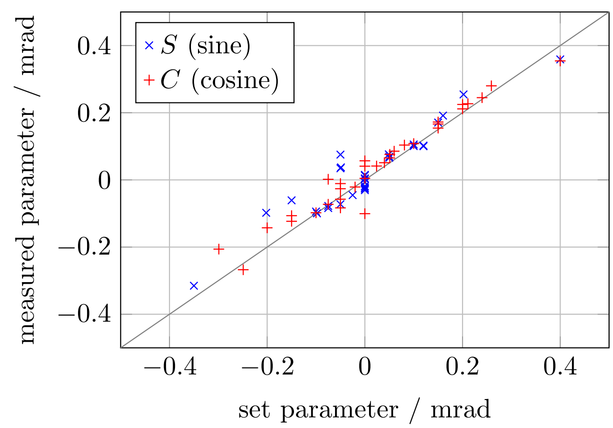

Figure 5: Parameters of the improved harmonic correction scheme for $\gamma a = 3, 4, 5$. They are consistent with the set parameters, because the orbit response is included in the calculation of the correction fields.

correction. It does not apply the harmonic field distribution (equation 1) directly to the correction magnets, but considers the orbit response Δz_j at the quadrupole j to each correction magnet m to determine the correction magnet kicks α_m^{VC} needed for a proper sinusoidal harmonic distribution $\alpha^{\mathrm{H}}(\theta)$. Therefore, the quadrupole kicks are expressed via the orbit response matrix $O_{jm} = \partial z_j / \partial \alpha_m^{\mathrm{VC}}$, which is also used for the orbit correction, as $\alpha_j^{\mathrm{Q}} = l_j k_j \cdot \vec{O}_j \cdot \vec{\alpha}^{\mathrm{VC}}$. Now the so called harmonic correction matrix $\mathcal{H}$ can be defined to write the total kick caused by each correction magnet m in each segment i as a matrix equation.

$$\mathcal{H}_{im} := \delta_{m,i}^{\mathrm{VC}} + \sum_{j \in \mathrm{Q}} \delta_{j,i}^{\mathrm{Q}} \, l_j \, k_j \, O_{jm} \tag{3}$$

with quadrupole lengths l_j and strengths k_j. Using this definition, equation 2 can be expressed as

$$\vec{\alpha}^{\mathrm{HC}} = \mathcal{H} \, \vec{\alpha}^{\mathrm{VC}} \quad \Rightarrow \quad \vec{\alpha}^{\mathrm{VC}} = \mathcal{H}^{-1} \, \vec{\alpha}^{\mathrm{HC}} \quad . \tag{4}$$

$\mathcal{H}$ only depends on the orbit response and the accelerator lattice and optics. Finally, $\mathcal{H}^{-1}$ is determined numerically using a matrix inversion via single value decomposition.

Figure 5 shows the analysis of the actual parameters for the improved correction scheme analog to Fig. 3. In contrast to the previous scheme, the harmonic field distribution is in good agreement with the set parameters.

The maximum kick for a single correction magnet with the previous scheme is the amplitude ($\sqrt{S^2 + C^2}$) of the set harmonic distribution. With the improved scheme the individual kicks can be significantly larger. For instance, at $\gamma a = 4$ the average kick is about the maximum of the previous scheme and about 40 % of the kicks are even higher. This is another reason why the new correction magnet system is essential for the improved harmonic correction scheme, which is thus now available for systematic experimental studies. Polarization optimization with the improved scheme will be conducted soon.

CONCLUSION

Recent hardware and software upgrades significantly enhance polarization optimization via the harmonic correction of integer spin tune resonances at ELSA. The subsequent improvements for both providing a polarized beam for experiments and studying polarization in circular accelerators are currently investigated experimentally.

The new corrector magnet system is an important step towards a polarized beam at the maximum energy of 3.2 GeV and ensures in time application of all desired correction fields. The improved correction scheme allows for accurate adjustment of harmonic field distributions in the accelerator, which is equivalent to direct control of individual resonances. For instance, it paves the way to a longitudinally polarized beam, which can be achieved if the beam is extracted exactly on an integer resonance and the precession is guided by the adjustable harmonic field distribution [7].

REFERENCES

[1] V. Bargmann and L. Michel and V.L. Telegdi, Phys. Rev. Lett. 2.10 (1959) 435.

[2] W. Hillert, et al. “Crossing of Depolarizing Resonances in Circular Electron Accelerators”, IPAC2011, San Sebastián.

[3] J.-P. Thiry et al., “Dynamic Closed Orbit Correction During the Fast Energy Ramp of ELSA”, IPAC2012, New Orleans.

[4] J.-P. Thiry et al., “High Bandwidth Closed Orbit Control for an Fast Ramping Electron Accelerator”, IPAC2014, Dresden, TUPRO040, These Proceedings.

[5] J. F. Schmidt et al., “Simulating Spin Dynamics and Depolarization using POLE”, IPAC2013, Shanghai.

[6] O. Boldt et al., “A new Correction Scheme to compensate Depolarizing Integer Resonances at ELSA”, PAC2011, New York.

[7] O. Boldt et al., “How to achieve Longitudinally Polarized Electrons using Integer Spin Tune Resonances”, IPAC2012, New Orleans.