CROSSING OF DEPOLARIZING RESONANCES IN CIRCULAR ELECTRON ACCELERATORS*

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Abstract

In flat electron storage rings, only the vertical component of the beam polarization is preserved. During acceleration, the crossing of several depolarizing resonances may cause severe beam depolarization. Even in case of fast ramping speeds of up to 4 GeV/s, first order effects like imperfection and intrinsic resonances have to be compensated by dedicated measures. At the accelerator facility ELSA, schemes like fast tune jumping and harmonic orbit correction are successfully applied on the fast energy ramp up to 2.4 GeV. Characteristics of the setup as well as the optimization efforts to improve the resonance compensation will be reported in detail.

MOTIVATION

Currently, experiments using ultrarelativistic polarized electrons become more and more important to explore the fundamental physics in the femtoscopic scales. Offering multi-GeV electrons with a high degree of polarization for those experiments is still a demanding task for designing and operating accelerators.

In circular accelerators, the particles pass the magnetic element lattice periodically and thus occuring depolarizing resonances do not only have to be taken into account but they also have to be corrected for.

Polarized electrons in circular accelerators can be obtained by storing electrons and waiting for self polarization according to Sokolov and Ternov. The synchrotron light emission can cause spin flips, in which the flip towards spin-up state is preferred. In case of equilibrium a mean degree of polarization of max. 92.4 % can be obtained. As just one in approx. 10^{10} emitted photons causes a spin flip, the self polarization time for lower GeV-range electrons typically exeeds several hours depending on the bending radius. The more efficient way is to generate a polarized ensemble of electrons in a dedicated source and to further accelerate it using cavities till the particles reach the desired energy.

In a flat ring and according to the Thomas-BMT equation, the spin tune $a\gamma(t)$ is given by the particle energy. Correspondingly, the spin precession frequency $a\gamma(t)f_0$ varies in time depending on the gyromagnetic anomaly a, the commonly linear increase of the Lorentz factor $\gamma(t)$ and the revolution frequency f_0. If the spin precesses in the vertical plane in phase with arising horizontal magnetic fields, the condition for a depolarizing resonance is fulfilled[1]. For multi-GeV ramping accelerators, different resonances have to be crossed during the energy increase.

In circular accelerators, horizontal fields arise either due to a disturbed vertical closed orbit or due to betatron oscillations caused by the vertical focussing and can thus not be avoided in general.

For heavier particles like protons, it is possible to intentionally excite said resonances during energy ramping in order to achieve a complete reversal of polarization. For electrons, the stochastic emission of synchrotron light effects all six dimensions of phase space by two means. On one hand, the stochastic motion leads to a diffusion in phase space and a resulting diffusion of the spin motion. On the other hand, the particles oscillate longitudinally around the design particle in a non-analytical way. Both effects make an intended polarization reversal less efficient for electrons.

At the electron stretcher facility ELSA, efforts were made to offer ultrarelativistic polarized electrons [1]. Therefore, it takes several measures which will be presented in the following. Figure 1 gives an overview of the accelerator part of the facility.

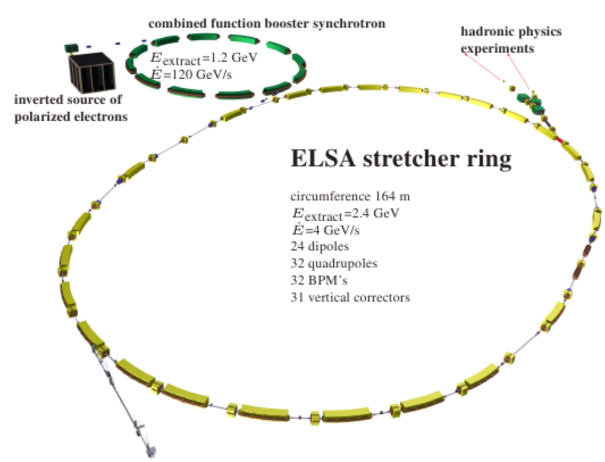

Figure 1: ELSA overview. Shown are the main parameters and components of the ELSA facility with regard to polarized operation performance.

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[1] This phenomenon is similar to the well known Rabi oscillation in atomic physics.

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CONSERVATION OF POLARIZATION IN THE ELSA STRETCHER RING

The initial degree of polarization in the stretcher ring is approx. 72 % at an energy of $E_{\text{in}} = 1.2$ GeV. It is certain that, the faster the velocity of the energy ramp, the shorter the occuring depolarizing resonances can exert their influence. Moreover, after the ramping phase (lasting 0.3 s with an end energy of $E_{\text{in}} = 2.4$ GeV) and without corrections, the degree of polarization is reduced to lower than 40 %. This clarifies why in addition to aiming for the energy ramp to be as fast as possible, corrections are essential. By use of correction methods, the vertical polarization can be conserved to a great extent and an final degree of approx. 65 % is achieved. Due to the fast energy ramp, only first order effects like integer spin-tune resonance and intrinsic resonance are significant.

Using Møller polarimetry at different experimental setups[2], the applied methods were optimized over the course of several years. Namely, these methods are a dynamic correction of the vertical closed orbit, an active correction of integer spin-tune resonances and a correction of the intrinsic resonances via tune jump.

Dynamic Closed Orbit Correction

Inevitable misalignments lead to a disturbed closed orbit in the horizontal as well as in the vertical plane. Even small misalignments in the submillimeter range cause measureable deviations of the closed orbit from the design orbit. Especially, vertical displacements inside the quadrupoles have to be prevented. Otherwise, the acting magnetic fields get horizontal components which might excite depolarizing resonances. In general, the vertical orbit displacements have to be minimized, since larger displacements as well as a transversal beam enlargement lead to higher depolarizing resonance strengths.

In the ELSA stretcher ring, 31 vertical correctors are designated to correct the vertical closed orbit both during the energy ramping phase and during the slow extraction. For technical reasons, the dynamic correction via these correctors is challenging. First, the corrector power supplies have been designed to enable changes of the currents within some milliseconds. The second challenge is an in situ measurement during the fast energy ramp including dynamic effects like e.g. induced eddy currents etc. Furthermore, an algorithm has been developed which uses the so called orbit-response matrix to optimize the position in the beam position monitors (BPM)[3]. The result of both efforts can be measured using the BPMs which are mounted close to each quadrupole. Figure (3) shows traces of all BPMs while correcting for depolarizing resonances. Without applying those corrections a vertical RMS displacement lower than 0.06 mm can be achieved.

[2] Formerly GDH, now Crystal Barrel.

[3] The orbit-response matrix maps the applied corrector currents to the resulting displacement in each BPM. Usually, displacements are minimized by inverting the matrix via singular value decomposition.

Correction of Integer Spin-Tune Resonances

Besides misaligned focussing elements, the yokes of the leading dipoles also can exhibit torsions due to seismic motion or due to temperature gradients. Even if measureable[4] torsions are corrected mechanically, weaker torsions still are present. In polarized operation mode an unknown distribution of horizontal magnetic fields along the orbit remains either caused by torsion of the dipoles, misalignments of the quadrupoles or due to field errors.

At least in case of torsions, unintended horizontal fields periodically act turn by turn. For energies equal to a multiple of 440 MeV, the spin tune is an integer. Under these circumstances, the spins precess in phase with a harmonic of the revolution frequency. Then, the periodically acting horizontal fields do not vanish on average and a depolarizing resonance is excited accordingly.

The driving horizontal field distribution has to be superposed destructively in order to correct for the integer spin-tune resonance. Only those contributions are relevant which are distributed along the orbit according to the spin precession frequency. Therefore, a correction distribution which oscillates $a\gamma = ..., 3, 4, 5, ..$ times along an one-turn-orbit and is $180°$ dephased has to be found. Since the original exciting field distribution is unknown, the correction fields have to be determined empirically by analyzing the relationship between the applied distribution and the corresponding measured degree of polarization.

The sinusoidal field distribution can either be adjusted by defining phase and amplitude or by weighting the sine and cosine part. As sine and cosine are orthogonal, each fraction can be regulated independently. Therefore, this kind of variation is favoured compared to adjusting amplitude and phase. At ELSA, the degree of polarization is iteratively optimized beginning with the sine part of the third integer spin-tune resonance and closing with the cosine part of the fifth resonance. In figure (2) the measured polarization is plotted against the fraction coefficient of the sine and cosine part of the fifth integer resonance.

These corrections manifest themselves in orbit displacements at each specific time belonging to each resonance (see figure 3).

Tune Jump

Another type of first order resonance is called the intrinsic resonance. Even if an ideal lattice is assumed, depolarization occurs due to the single-particle motion. This kind of depolarization strongly depends on the amplitude of the particle's betatron oscillation in the vertical plane. The optical tune is a measure for the number of oscillations. Usually, low order rational numbers have to be prevented in order to avoid optical resonances[5].

At a specific point in time during the energy ramp, the spins

[4] This is done using three precision levels mounted at the edges and in the middle of the yokes.

[5] At ELSA, optical resonances to the order of five are avoided by chosing an vertical tune of $Q_z = 4.431$.

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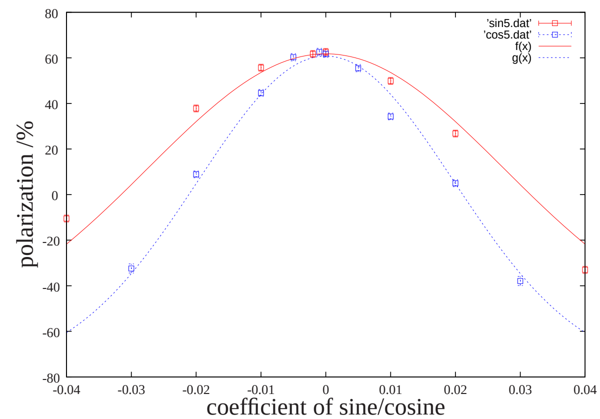

Figure 2: Emperical correction of the fifth integer spin-tune resonance. The measuring points of the sine part are red colored, the blue dots indicates the cosine part.

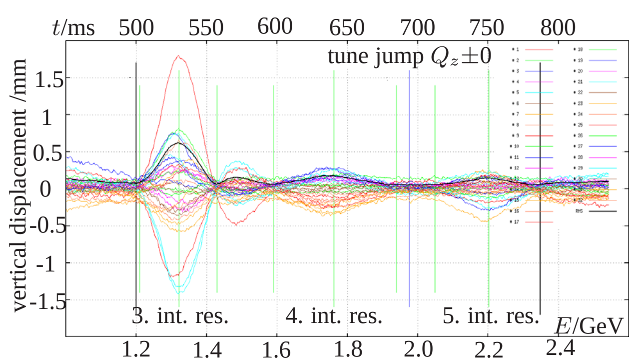

Figure 3: The vertical traces of the beam position monitors are shown (colored for each bpm and in black for RMS) during the energy ramp in the stretcher ring (1.2–2.4 GeV with 4 GeV/s). The correction for the integer resonances causes additional vertical displacements.

precess in phase with a harmonic of the vertical betatron oscillation. In this case, horizontal magnetic fields acts in the rest frame of the electron which also are in phase with the betatron oscillation. Under these circumstances, the non-vanishing horizontal field contributions involve an partially loss of vertical polarization.

Certainly, the resonance strength can be reduced by aiming for small betatron oscillation amplitudes. Yet the more adequate method is to force a change of the vertical tune at the resonance specific time, such that the resonance condition is not fulfilled.

At ELSA, this method is applied by using Panofsky-type tune jump quadrupoles. If this element is actuated at appropriate times, the intrinsic resonances can be crossed almost without loss of vertical polarization. Therefore, the knowledge of each appropriate time is required in order to cross the resonance in an optimal way. The results of an empirical optimization of the time setting is shown in figure 4.

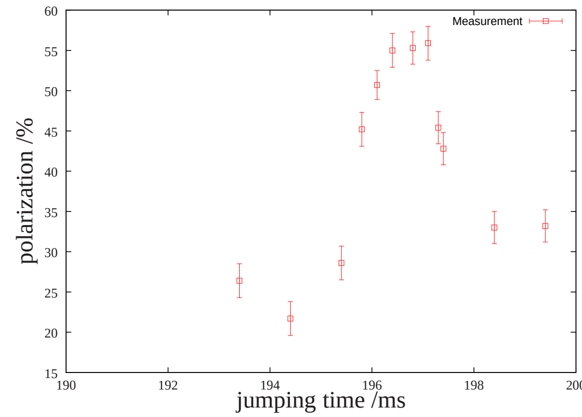

Figure 4: Performance of the tune jump when used at the resonance $a\gamma = 0 + Q_z$. The impact of the apruptly generated quadrupole field is a fast change of the optical tunes. Doing this accurately timed, a higher degree of polarization is preserved.

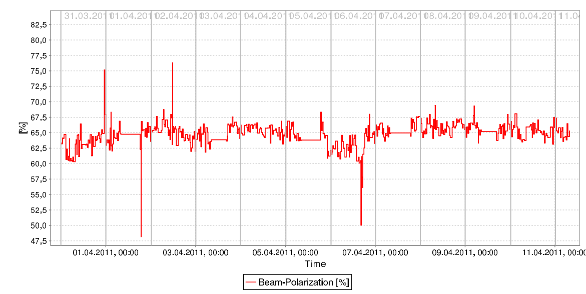

Figure 5: Long-term polarization at the Møller polarimeter (see figure 1) at the final energy.

OUTLOOK

Since more than one decade, polarized beams of electrons in energy range up to 3.2 GeV have been studied and moreover, have been improved to fulfill the demands of each of the consecutive hadronic physics experiments (see figure 5). To overcome depolarizing effects during the increase of the particles energy, serveral different methods are required. These advanced methods are validated by experimental results and have been described theoretically above.

In the future, the correction of the integer spin-tune resonance will be enhanced in particular. The application of new faster and more powerful corrector supplies will affect this method in a positive way. In addition, a new algorithm has been developed taking into account additional displacements in quadrupoles occurring due to applied corrector field distribution [2]. Recently, it became apparent that the above mentioned new algorithm will only be possible by using the new power supplies.

REFERENCES

[1] W. Hillert, "The Bonn Electron Stretcher Accelerator ELSA: Past and Future," Eur. Phys. J. A 28, s01, 139 148 (2006)

[2] O. Boldt, "A new Correction Scheme to Compentsate Depolarizing Integer Resonances at ELSA," PAC, New York (2011)

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