APPLICATIONS OF ELECTRON ENERGY MEASUREMENT BASED ON RESONANT SPIN DEPOLARIZATION AT BESSY II

A. Gora*, T. Olsson, G. Rehm, M. Ries, M.-L. Venzke, Helmholtz-Zentrum Berlin, Germany

Abstract

An electron energy measurement based on resonant spin depolarization has been running permanently at BESSY II for several years. This high-precision energy measurement was set up primarily for users of synchrotron radiation for meteorological applications from the Physikalisch-Technische Bundesanstalt (PTB). Recent investigations have led to a better understanding of the method and the possibility of shortening the measurement time. This allows for new observations and the use of the energy measurement for different applications such as the model-free measurement of the natural chromaticity, the momentum compaction factor or synchrotron sidebands.

INTRODUCTION & MOTIVATION

The PTB is a major user of BESSY II, a 1.7 GeV synchrotron light source operated by the Helmholtz-Zentrum Berlin (HZB) in Berlin, Germany. Since they use synchrotron radiation to determine radiometric units, the electron energy has to be known very precisely [1]. Therefore, an energy measurement based on resonant spin depolarization was established several years ago and has been running continuously during user operation since then [2, 3]. The measurement is based on the principle that electrons self-polarize, described by the Sokolov-Ternov effect [4], and that a polarized beam can be depolarized by exciting it at the spin tune, which is correlated with the beam energy [5]. Depolarizations can be observed experimentally as changes in global lifetime or local loss rates as Touschek scattering depends on the polarization of stored electrons [6].

Recent investigations of the measurement method have led to an optimization of the measurement duration from about 4 h to 10 min, allowing a range of new observations as well as extending the availability of measured electron energy for a new class of experiments.

SIDEBANDS

In addition to the spin tune resonance, which is related to the energy of the electrons, synchrotron sideband resonances can be seen at a distance of multiples of the synchrotron frequency f_s using the resonant spin depolarization method [7]. As the synchrotron frequency at BESSY II in standard user operation at 300 mA is $f_s \approx 5$ kHz, the excitation frequency was swept over a range of up to ±10 kHz around the depolarization frequency of the main resonance to observe the sidebands. Scanning sufficiently slow, three depolarizations could be observed in this interval, as can be seen in Fig. 1. When comparing the sidebands to the main depolarization resonance, the jump in the loss rate was about 3 times smaller, and the slope of the beam loss increase was about 20 times weaker, indicating that the sideband resonances are not as strong and also broader than the main resonance. This means that no sidebands should be visible when scanning faster, which is also the behavior that is observed.

Using the energy measurement analysis to determine the frequency of the sidebands, frequencies of $f_s = (4.9 \pm 0.4)$ kHz were calculated. The frequencies found varied with the scan direction (up or down), which can be explained by the width of the resonance. For up scans, depolarization starts on the left side of a resonance, so lower frequencies are observed, whereas for down scans, depolarization starts on the right side, so higher depolarization frequencies are measured, as can be seen in the examples in Fig. 1. The synchrotron frequency is expected to be centered between the observed depolarization frequencies of an up and down scan, and therefore the calculated frequencies are in good agreement with the expected value.

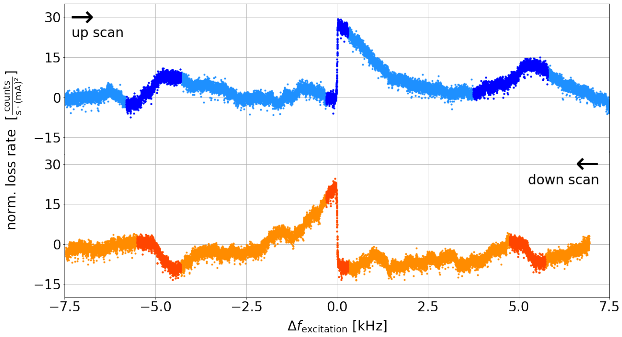

Figure 1: Examples of scans to observe the synchrotron sidebands; The bunch current normalized loss rate (norm. loss rate) $= \frac{\text{loss rate}}{\sum I_{\text{bunch}}^2} - \text{offset}$ is plotted as function of the change in excitation frequency $\Delta f_{\text{excitation}}$ compared to the depolarization frequency of the main resonance. Depolarizations are highlighted in darker colors, arrows indicate the scan direction of the up (top/ blue) and down scan (bottom/ orange).

DIPOLE POWER SUPPLY

The dipole magnets in the BESSY II storage ring are connected in series, but the power supplies can be switched between two different ones. This is done routinely once a year to ensure their functionality and to train the switching process. As shown in Table 1, after the last exchange at the end of October 2024, the same set current was used for the power supply as before the replacement. The energy changed by about $5 \cdot 10^{-4}$, which can be explained by the

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* anny.gora@helmholtz-berlin.de

fact that the internal control loops of the power supplies are not calibrated exactly the same. As the energy before the switch was already low compared to the average energy over the last years of $E_{\mathrm{avg(last\ years)}} = 1.7185\,\mathrm{GeV}$, the new energy was lower than ever observed. To ensure stable conditions for the users, the energy should be brought back to the standard energy $E_{\mathrm{avg(last\ years)}}$ by increasing the current of the power supply by a factor, assuming a linear dependence between energy and dipole current. After this adjustment, the energy was found to be $E_{\mathrm{new}} = 1.7184\,\mathrm{GeV}$. To better control changes caused by the power supplies, a high-precision current measurement of the supplies was set up.

Table 1: Power supply (PS) set value I_{set} and measured energy E before and after dipole PS replacement and a current adjustment; In parentheses the used PS number is noted.

State (PS)	I_{set} **[A]**	E **[GeV]**
Before PS change (1)	614.50	1.7176
After PS change (2)	614.50	1.7168
After current adjustment (2)	615.11	1.7184

ENERGY STABILITY

In order to be able to identify and understand causes of energy changes and increase the electron energy stability, the electron energy has been monitored long-term.

Maintenance Shutdown

At BESSY II, there is a maintenance shutdown every Monday from 7 a.m. to about 1 p.m., followed by machine commissioning and at 7 a.m. on Tuesday user operation starts.

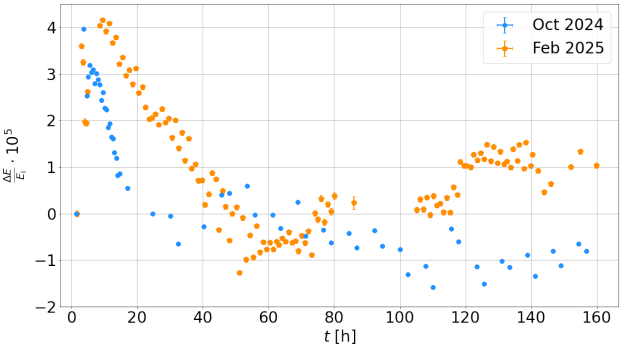

Figure 2: Two examples of the energy drift over one week after a commissioning shutdown; $t = 0\,\mathrm{h}$ refers to the point after the machine restart when the current was above 295 mA for the first time. The energy difference ΔE relative to the first energy measurement after the shutdown E_{i} is plotted.

It was observed that the energy increases quite fast during the first hours and then slowly drifts from a higher to a lower value in the first (36 - 48) h after the maintenance shutdown and machine commissioning. Afterwards, as can be seen in the examples shown in Fig. 2, the energy remains more stable. Since this behavior was observed independently of whether the storage ring magnets had been turned off for several hours during the maintenance shutdown or not, the reason for this drift appears to be in the interaction between the beam and the machine. In addition, it was observed multiple times that the first energy measured after a maintenance shutdown is close to the value the energy reaches after the drift. So far no explanation has been found for this. Based on these observations, it was concluded that measurements requiring high energy stability should only be performed after approximately two days of continuous operation.

Long-term

To get an overview of the long-term energy stability at BESSY II, the energy of the last decade was analyzed, with the exception of the year 2017 when no energy measurements were performed due to hardware problems. Criteria for the analysis included operation in top-up mode with an electron beam current above 290 mA. The measured electron energy from 2014 to 2024 is depicted in Fig. 3. During this period, the electron energy fluctuated between (1.717 and 1.719) GeV, with a standard deviation of 0.022 %. However, when the energies are studied on a weekly basis starting after about 1.5 days of operation, a more stable energy is observed, with an average standard deviation of only 0.0026 % during a week.

The gaps in the energy measurement during the summer months are due to the machine summer shutdown, whereas individual outliers can be explained by steps in the loss rate that are not related to depolarizations, but caused by rapid change in RF frequency, a power outage resulting in incomplete data, or movement of an undulator. As discussed before, jumps in energy from (1.7175 to 1.7185) GeV and vice versa were concluded to be caused by the use of two different power supplies driving the dipoles. In addition to these easily traceable changes in energy, unexpected correlations were discovered between variations in energy and adjustments of steerer magnets. To help identify and correct such changes more quickly, a live online energy measurement and analysis has been set up.

NATURAL CHROMATICITY

The chromaticity ξ is defined by the change in tune ΔQ and relative momentum deviation δ as

$$\xi = \frac{\Delta Q}{\delta} \tag{1}$$

where $\Delta Q = Q - Q_{\mathrm{i}}$, $\delta = \frac{\Delta p}{p_{\mathrm{i}}}$ and $\Delta p = p - p_{\mathrm{i}}$, with i indicating the initial value respectively [8]. In terms of energy E, the momentum deviation δ can also be written as

$$\delta = \frac{1}{\beta_{\mathrm{i}}^2} \cdot \frac{\Delta E}{E_{\mathrm{i}}}, \tag{2}$$

where $\beta_{\mathrm{i}} = \frac{v_{\mathrm{i}}}{c}$ the ratio between the initial velocity v_{i} and the speed of light c. The chromaticity can be divided into natural chromaticity, which describes only the influence of quadrupole magnets, and higher-order influences.

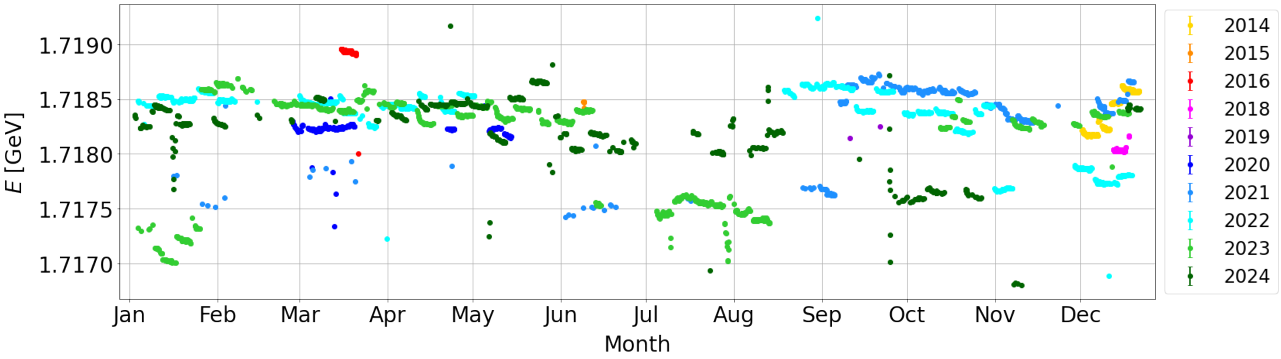

Figure 3: Electron energy stability at BESSY II over the last 10 years, with the exception of 2017 when no measurements were performed due to hardware problems.

In order to determine the natural chromaticity of BESSY II, the energy of the electrons was varied by changing the dipole current while keeping the RF frequency constant, so that the orbit did not change and measuring the tune change and energy for each dipole setting [9]. As shown in Fig. 4, a fit based on Eq. (1) and (2) resulted in natural chromaticities of $\xi_\mathrm{x} = (-44.82 \pm 1.01)$ and $\xi_\mathrm{y} = (-21.79 \pm 0.26)$. Both, the measured horizontal natural chromaticity ξ_x as well as the vertical ξ_y differ by about 8 % from the value found from simulation using pyAT [10] of $\xi_\mathrm{x} = -48.56$ and $\xi_\mathrm{y} = -23.58$. This deviation indicates that the BESSY II model is not yet good enough for this aspect.

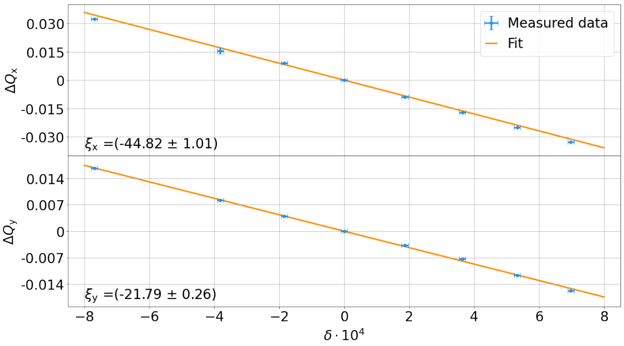

Figure 4: Measured change in horizontal ΔQ_x resp. vertical tune ΔQ_y as function of the momentum deviation δ with a fit to determine the natural chromaticity $\xi_\mathrm{x,y}$.

MOMENTUM COMPACTION FACTOR

The momentum compaction factor α_c (MCF) describes the ratio between the relative change in path length $\frac{\Delta L}{L_\mathrm{i}}$ and the momentum deviation δ [8]:

$$\alpha_\mathrm{c} = \frac{\frac{\Delta L}{L_\mathrm{i}}}{\delta}. \tag{3}$$

Rewriting Eq. (3) gives a formula for the change in RF frequency Δf_RF as a function of the MCF:

$$\Delta f_\mathrm{RF} = \frac{(1-\alpha_\mathrm{c}\gamma_\mathrm{i}^2)\cdot\delta}{\gamma_\mathrm{i}^2-(1-\alpha_\mathrm{c}\gamma_\mathrm{i}^2)\cdot\delta}\cdot f_{\mathrm{RF}_\mathrm{i}}, \tag{4}$$

where γ_i is the Lorentz factor of the initial energy and $\alpha_\mathrm{c}(\delta) = \alpha_{\mathrm{c}_0} + \alpha_{\mathrm{c}_1}\cdot\delta + \alpha_{\mathrm{c}_2}\cdot\delta^2 + \ldots$.
By changing the RF frequency f_RF and measuring the energy, a fit based on Eq. (4) was performed to determine the first orders of the MCF of the BESSY II standard user mode as shown in Fig. 5. The measured values are close to the ones found from simulation in pyAT, indicating a good agreement of the machine and model in the longitudinal plane.

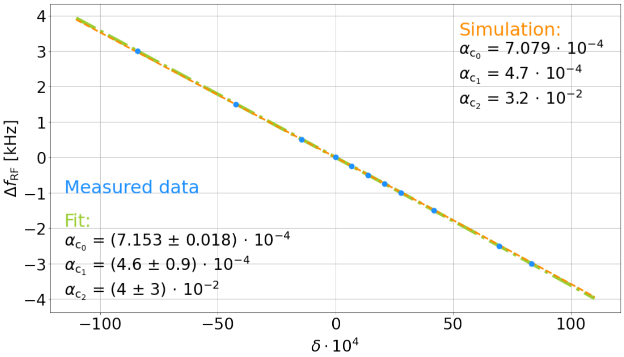

Figure 5: Measured change in RF frequency Δf_RF as function of the momentum deviation δ with a fit to determine the momentum compaction factor $\alpha_\mathrm{c}(\delta)$, together with a presentation of the simulated values.

CONCLUSION & OUTLOOK

The improvement of the energy measurement at BESSY II and better understanding of the method have enabled new observations and measurements, which can contribute to improving the machine model. By combination of the faster measurement and new online analysis, attempts will be made to further optimize the energy stability for user operation. It is also planned to extend and automate the measurement of the momentum compaction factor for higher orders and for other operating modes, such as negative and low MCF.

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