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PROBING FCC-ee ENERGY CALIBRATION THROUGH RESONANT DEPOLARISATION AT KARA*

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Abstract

The FCC-ee collider physics programme requires a precise determination of the centre-of-mass energy. The average energies of the two colliding beams can be measured by resonant depolarisation (RDP) of polarised electron and positron bunches. The depolarisation is achieved by an electromagnetic device, e.g., a strip line, excited at a sweeping frequency. Once the excitation frequency is equal to the spin precession frequency, which is directly proportional to the beam energy, the polarisation is lost or reduced. At KARA the resonant frequency is routinely measured via the change of the Touschek lifetime. We report on an RDP beam measurement campaign at the Karlsruhe Research Accelerator (KARA), exploring how this technique could be applied at the FCC-ee. In particular, we examine the sensitivity of the inferred value of beam energy to various parameters, such as the depolariser scan speed, the scan direction, and the beam operation energy.

MOTIVATION

The physics programme of the Future Circular electron-positron Collider (FCC-ee) foresees a precise calibration of the collision energy in its Z-pole and W-pair modes of operation, where, due to the high luminosity, a statistical precision of 4 and a few 100 keV is expected, respectively. The systematic uncertainties should be reduced to a comparable order of magnitude, that is to a relative precision of 10^{-6} [1, 2]. At the Z and W energies of 45.6 GeV and 80 GeV per beam, respectively, the average beam energy can be measured by resonantly depolarising low-intensity, previously polarised pilot bunches, and detecting the loss or change in the polarisation with a laser-based polarimeter [1–3]. Beam-energy measurements based on resonant depolarisation (RDP) were carried out at various previous collider rings, including VEPP-2M [4], VEPP-4M [5, 6], CESR [7], and LEP [8].

The change in polarisation occurs when the slowly varied excitation frequency f_{dep} of the depolariser, modulo an integer multiple of the revolution frequency f_{rev}, coincides with the spin precession frequency $f_{\mathrm{spin}} = f_{\mathrm{rev}} Q_{\mathrm{spin}}$,

$$f_{\mathrm{dep}} = (k \pm Q_{\mathrm{spin}})\, f_{\mathrm{rev}} \quad \text{with} \quad k \in \mathbf{Z} \ , \tag{1}$$

where the spin tune Q_{spin} depends on the average beam energy, or Lorentz factor γ, according to

$$Q_{\mathrm{spin}} = a_e \ \gamma \ , \tag{2}$$

with $a_e = (g_e - 2)/2 = 1.159652... \times 10^{-3}$ the anomalous magnetic moment of the electron (with g_e the g-factor).

The KARA synchrotron at KIT allows us to study some of the systematic errors of the resonant depolarisation measurements planned for the FCC-ee. KARA has a circumference of 110.4 m, and can operate at beam energies between 0.5 and 2.5 GeV. Resonant depolarisation for the purpose of energy calibration was applied earlier at KARA (when this storage ring was still known by the name “ANKA”) [9]. At present, KARA is not equipped with a polarimeter, but the beam depolarisation can be detected through a sudden change in the beam lifetime, and in the associated local beam losses. The reason is that the KARA beam lifetime is dominated by the Touschek effect, and the underlying Möller cross section and resulting local beam losses depend on the degree of beam polarisation. In a high-energy storage ring, beam polarisation increases the Touschek lifetime, by up to 23% [10, 11].

Details of the KARA storage ring, the measurement preparation, the available diagnostics, control system with automated operation sequences and scanning procedures are presented in a companion paper [12]. Measurements characterising the KARA machine optics were performed during the same time period as the RDP scans. The results are discussed in another contribution to this conference [13]. These could be used as input to future simulation studies of polarisation build up or depolarisation in KARA.

MEASUREMENT AND ANALYSIS SET-UP

Most measurements were performed at a nominal beam energy of 2.5 GeV, where the KARA ring is well set up and corrected with the DBA lattice for the KIT light source user operation. Figure 1 presents a typical scan result, where the depolariser frequency is swept from 1.705 to 1.735 MHz over 650 s and we observe the change in the local loss rate. The depolarising frequency, f_{dep}, at which the loss rate changes gives the spin tune via Eq. (1), so that f_{dep} can be converted to an equivalent beam energy E using Eq. (2). For the example of Fig. 1, f_{dep} is 1.7139 MHz, with an equivalent beam energy of roughly 2.48 GeV.

The scan quality also depends on the initial polarisation level. While Fig. 1 was obtained after waiting for 20 min at 2.5 GeV, Fig. 2 shows an example with only 10 min waiting

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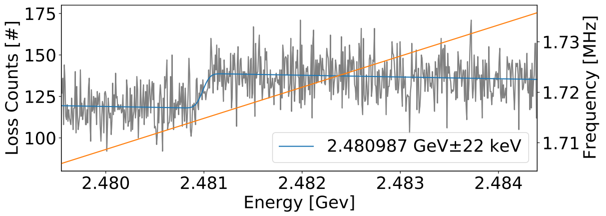

Figure 1: Typical depolarising scan result at KARA. Measured local beam losses versus the energy corresponding to the depolariser frequency. The waiting time for self-polarisation prior to the scan was 20 min. The stored beam current of about 35 mA was distributed over 30 bunches.

time prior to the RDP scan. The theoretical exponential polarisation time at this energy is also about 10 minutes. In this case, the changes of beam losses are not sufficiently clear to deduce the beam energy. Therefore, in the following, for all measurements at 2.5 GeV, we allocated 20 minutes for the beam self polarisation before scanning the depolariser frequency. To simplify the plots, we omit plotting the frequency and only show the corresponding beam energy. Furthermore, since initial measurements indicated a beam energy of about 2.48 GeV, we now vary the depolariser frequency only from 1.705 to 1.725 MHz, around this beam energy.

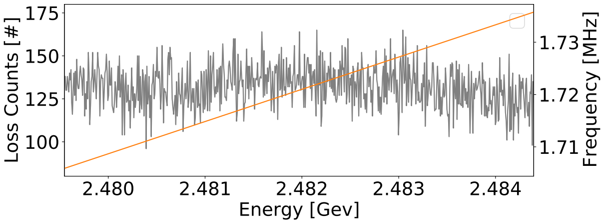

Figure 2: Scan after 10 min waiting time for self polarisation.

The measured loss rates as a function of E are fitted to

$$F(E) = F_0 + (h/2)\ \mathrm{erf}\left((E - E_0)a\right) + bE + cE^2\ , \quad (3)$$

where the fit parameter E_0 corresponds to the centre of the step, and, hence, to the inferred beam energy. For the fitting, we used the Python function *curve_fit*, available from the *scipy* package [14], which implements a nonlinear least-squares method based on the Levenberg-Marquardt algorithm. The parameters a, b, c, h and F_0 are also determined by this fit, including the respective errors. An example fit result is displayed in Fig. 1. We found that fitting noisy raw loss data to a steep step can lead to unrealistically large numerical uncertainties in the location of the step, as is illustrated in Fig. 3 (top). To suppress these numerical uncertainties, we introduced a moving average over 3 successively measured loss-rate data, as is shown in Fig. 3 (bottom). Using this approach a very low fitting error of a few keV could be achieved (10^{-6} relative accuracy). The beam energy was measured to be about 2.481 GeV (that is, 19 MeV lower than the nominal 2.5 GeV). This is close to the historical result from 2004 [9], where the beam energy was inferred to be about 2.478 GeV (or 22 MeV below the nominal value).

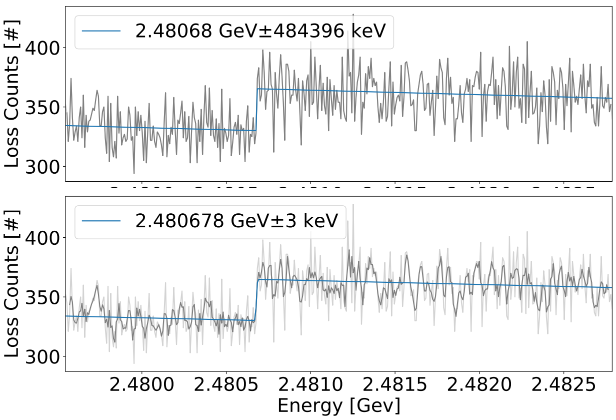

Figure 3: Single scan of local loss rate with fitted step function superimposed and fit result displayed without (top) and with (bottom) a moving average over 3 consecutive data points. For this scan, the depolariser frequency was being slowly increased during 400 s. The beam current, with 30 stored bunches, was approximately 62 mA.

SCAN DIRECTION

The dependence of the result on the scan direction is of interest with regard to systematic errors. We executed measurements where the frequency either increased or decreased, while scanning the same range between 1.705 and 1.725 MHz. Here, we present results for scanning in either directions with a 400 s scan duration. The scan towards lower frequencies, was performed 20 min after the RDP towards higher ones. Loss rates from these two scans are displayed in the top and bottom pictures of Fig. 4, respectively. Notably, the scan towards higher frequencies yields a significantly steeper change of loss counts, than the scan in the other direction. These findings are consistent with FCC simulations [15] for the case of an energy drift. In particular, they suggest a negative beam-energy drift during these scans, as explained in the following. When scanning towards higher frequencies the beam energy is shifting towards the depolarising frequency (on-coming), and, thus, the time required to complete the resonant depolarisation process is shortened compared to sweeping towards lower frequencies. For the latter case, the depolariser frequency is catching-up with the energy drift. Furthermore, we note that the beam energy inferred from the (later) downward scanning is 14 keV lower than for the (earlier) upward scan, which also hints at a negative energy drift.

SCAN VELOCITY AND DIRECTION

To investigate, in detail, the dependence on the scan velocity and direction, an automated measurement campaign was executed. Over one long night of 16 h, numerous scans were carried out and recorded, with a scan range extending from 1705 to 1725 kHz, corresponding to an energy range from 2.4795 to 2.4830 GeV. The scan duration was varied between 100 and 600 s and the frequency scans carried out in both directions. Again beam energies are obtained by the

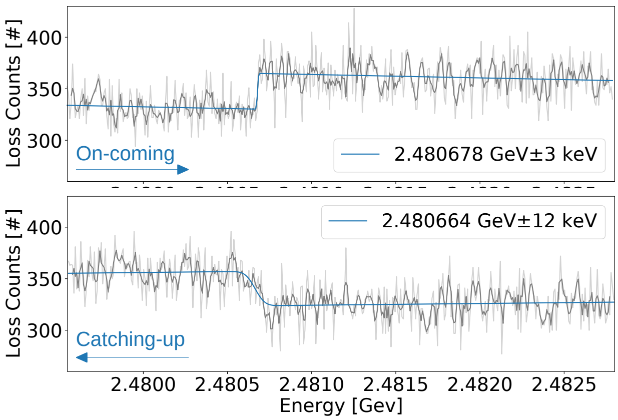

Figure 4: Scan results for increasing (top) and decreasing depolariser frequency (bottom) with the respective fit results shown. The different shape of the fitted function is consistent with a downward drift in beam energy.

same fit, however, now using loss counts from a sliding average over 10 successive data points. All the inferred beam energies are roughly 19 MeV lower than the nominal beam energy of 2.5 GeV, as is summarized in Fig. 5. No clear dependence on either scan duration or direction is visible. We attribute this to an overall drift of the KARA beam energy during the entire 16 h time period, which dominates over, and hides, all other systematic effects and dependencies. Hence, we explored the energy stability over this period.

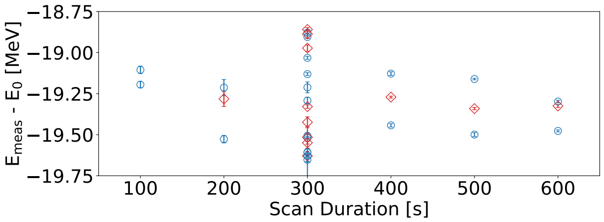

Figure 5: Difference between the measured and nominal beam energy (2.5 GeV) over a 16 h period for various scan velocities and directions. Blue dots and red diamonds refer to, respectively, upward and downward scans. The scatter is due to actual changes in beam energy.

ENERGY DRIFT

After 16 h, the measured beam energy was 0.8 MeV lower than at the start of the measurement. This trend of decreasing beam energy is consistent with all RDP scans in both scanning directions and for scan durations ranging from 100 to 600 s, as is illustrated in Fig. 6. During these scans, the RF frequency was constant. Therefore, a likely source of the observed energy drift is a slow increase in the ring circumference due to warm-up and thermal expansion after restarting the machine operation.

FIRST LOOK AT 2.3 GeV

After completing the energy ramp to 2.5 GeV, we lowered the KARA beam energy to 2.3 GeV, for what was one of the first times KARA operated at this energy. Here, exploratory depolariser-frequency scans showed no clear signature yet of a depolarising resonance. This could be due to the proximity of the fractional spin tune (with $Q_{\mathrm{spin}} = 5.220$ at 2.3 GeV) to the fractional betatron tunes ($Q_x \approx 6.24$ and $Q_y \approx 6.27$), which may enhance betatron-spin resonances and, thus, prevent the build-up of a detectable polarisation level. Also, at 2.3 GeV, the calculated polarisation build-up time is longer, 13.9 min, compared with only 9.4 min at 2.5 GeV. This aspect could be investigated in future experiments by increasing the waiting times before RDP scans. In addition, at 2.3 GeV the ring optics is different and less well corrected, possibly resulting in larger vertical orbit and particle excursions, which could be explored through future orbit and optics measurements at 2.3 GeV.

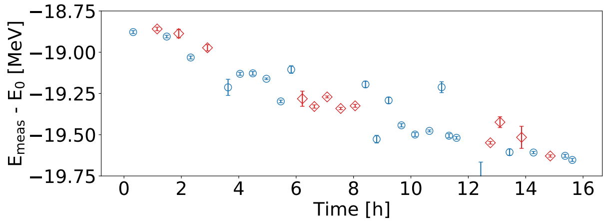

Figure 6: KARA beam energy drift with respect to 2.5 GeV over 16 h evidenced by the RDP scans of various speed and with either scan direction. Blue dots and red diamonds refer to, respectively, upwards and downwards scanning direction.

CONCLUSIONS

At 2.5 GeV, KARA allows clear resonant depolarisation measurements. The “instantaneous” beam energy, obtained by scanning over a few 100 s, is determined with a 10^{-6} fitting precision. In principle, this precision is adequate to explore systematic effects in the RDP energy calibration method proposed for the FCC-ee. The KARA measurements reported here already demonstrated the importance of performing RDP scans in both directions. However, they also revealed a significant drift in the KARA beam energy of 0.8 MeV over 16 h, which, at present, obscures other possible systematic dependencies of relevance for the FCC-ee. Additionally, the measured beam energy is systematically lower than the nominal energy, by approximately 19 MeV, independently of scanning velocity and direction. In exploratory first studies at 2.3 GeV, no clear sign of polarisation, or depolarisation, has yet been seen. Both these points call for further investigations. Simulation tools developed for the FCC-ee could be benchmarked against the KARA measurements at 2.3 and 2.5 GeV.

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