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PROSPECTS FOR OPTICS MEASUREMENTS IN FCC-ee

J. Keintzel*, R. Tomás and F. Zimmermann, 1211 CERN, Geneva 23, Switzerland

Abstract

Within the framework of the Future Circular Collider Feasibility Study, the design of the electron-positron collider FCC-ee is optimised, as a possible future double collider ring, currently foreseen to start operation during the 2040s. With close to 100 km of circumference and strong synchrotron radiation damping at highest beam energy, adequate beam measurements are needed to control the optics at the desired level. Various possible techniques to measure the optics in FCC-ee are explored, including the option of turn-by-turn measurements in combination with an AC-dipole.

INTRODUCTION AND MOTIVATION

The future circular lepton collider, FCC-ee, is a synchrotron with 91 km circumference, which requires a new tunnel in the Lake Geneva basin and which will be connected to the existing CERN accelerator complex [1,2]. With a possible commissioning date around 2045, FCC-ee would allow for a smooth continuation of frontier particle-physics research after the end of the High Luminosity Large Hadron Collider (HL-LHC) program [3], expected around 2040.

The FCC-ee is designed for high precision physics experiments on the Z- pole, WW-threshold, HZ-production peak and for $t\bar{t}$ quark production, corresponding to beam energies of 45.6, 80, 120 and 182.5 GeV, respectively, with collisions in up to four interaction regions [4]. Although the beams are injected at collision energy (top-up injection), energy losses from e.g. synchrotron radiation (SR) need to be compensated. This is achieved through superconducting radiofrequency cavities. The combination of energy losses and localized RF sections leads to variations of the beam energies and the center-of-mass energies around the machine (further details in [5]). At the lower energy stages it is envisaged to measure the average beam energy by resonant depolarization of a few hundred transversely polarized low-intensity (10^{10}) pilot bunches. Once sufficient polarization ($\approx$10 %) is achieved with wigglers, they are switched off and all nominal bunches (2.5×10^{11}) will be injected and brought to collision. Since misalignment and optics errors can limit the achievable polarization and can drastically limit the performance, they need to be controlled. In addition to precise alignments of elements and girders [6], beam-based measurements need to be performed to identify alignment and optics errors, to then apply dedicated corrections. One crucial design challenge is developing suitable and reliable measurement techniques, adapted to the FCC-ee. We study here the merits and limitation of various optics measurement techniques for the FCC-ee, and highlight pertinent experiences from existing storage rings facilities. Complementary beam tests for other design challenges are reported in [7].

BEAM POSITION MONITORS

Crucial devices for optics measurements are Beam Position Monitors (BPMs), which record the center-of-charge of particle beams. In storage rings such as the LHC, SuperKEKB or ESRF they are typically installed next to each quadrupole magnet. This approach is presently assumed in various optics tuning studies [8] and requires about 1800 BPMs for the FCC-ee. One of the most common types are so-called button BPMs. The alignment of their electrodes varies, for example, in the LHC they are aligned on the transverse axis. Due to strong emitted SR in SuperKEKB, the buttons are rotated by 45° in the transverse plane [10]. BPMs can be used to measure the centroid orbit in each turn for Turn-by-Turn (TbT) measurements, or by recording the average orbit over several turns, or both simultaneously. The BPM resolution depends on the chosen recording setting and also on the beam current. It is typically higher for recording the average orbit of high beam currents.

K-MODULATION

The average β-function in a quadrupole can be measured by the change of its strength and its effect on the transverse tune $Q_{x,y}$, assuming the working point is far away from strong resonances and the tune change is small. This method is typically applied to the final focus quadrupoles, allowing to propagate the measured values to the interaction point, and has successfully been used in various machines including the LHC [11] and SuperKEKB [12]. The main limitation is the accuracy of the tune measurement and fluctuations of the power supplies for the magnetic elements.

ORBIT RESPONSE MATRIX

For an Orbit Response Matrix (ORM) measurement approach, dipole kickers distort the beam orbit one after the other and the response is measured at BPMs. The required time for ORM increases with the size of a storage ring and is hence expected to be time consuming for the FCC-ee. Since the average is taken over several turns, the BPM resolution is good and e.g. for SuperKEKB in the order of a few µm [13]. However, presently the maximum orbit is limited to 10 to

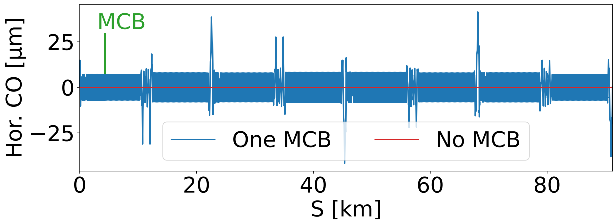

Figure 1: Horizontal closed orbit with one activated dipole kicker (MCB) (blue) and without (red) for the $t\bar{t}$-lattice.

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* jacqueline.keintzel@cern.ch

20 µm to avoid distortions from the final focus quadrupoles and sextupoles [9]. Especially at the top beam energy of 182.5 GeV, with SR losses per revolution are 10 GeV, the damping of the amplitude and its effect on the orbit should be included, and detailed studies are required to conclude on the feasibility and limitations of ORM for FCC. An example of a closed orbit with one dipole kicker is shown in Fig. 1 for the tapered $t\bar{t}$-lattice using MAD-X.

TURN-BY-TURN

Compared to ORM, TbT measurements are acquired faster, once suitable conditions are established, and are thus also envisaged to be used for the FCC-ee. Since the orbit is recorded in each turn, the BPM resolution is typically poorer and up to 100 µm to 200 µm for single bunch measurements in LHC [14] or SuperKEKB [15]. An excellent resolution of about 10 µm is achieved by using 330 bunches in ESRF [16]. In addition to resolution, non-linearities [17] or calibration errors [18] can spoil the measurements.

To perform TbT measurements the beam needs to be excited, where various techniques are possible. Contrarily to hadron storage rings, for leptons a single kick applied to a particle beam is a non-destructive method since strong SR damps the amplitude until the equilibrium emittance is reached. Single kicks are applied with a fast dipole kicker magnet, which is, ideally capable of applying a diagonal kick, i.e. simultaneously horizontally and vertically. The damping is faster for increasing energy and the horizontal and vertical damping times are approximately 0.710 s and 0.012 s, respectively at the Z- and $t\bar{t}$-mode [2]. With a revolution frequency of 3288 Hz this corresponds to 2335 and 41 turns. Single particle tracking for both energies is performed in Strategic Accelerator Design (SAD) using the latest 4-IP-lattice V22 [19], including radiation damping and is shown in Fig. 2. The EPS flag, which is inversely proportional to the number of slices, is set to 0.01 [20] in the final focus and the interaction region sextupoles. The initial kick is 10 times the horizontal and vertical rms beam size, σ_x, σ_y, applied at the interaction point. At the shown location in the regular arc cell $\beta_{x,y} = 16, 90$ m. The transverse emittances are $\epsilon_{x,y} = 71$ nm, 1.4 pm for the Z-lattice, and 1.5 nm, 3.0 pm for the $t\bar{t}$-lattice, and the β-functions at the IPs are $\beta^*_{x,y} = 100, 0.8$ mm and $\beta^*_{x,y} = 1000, 1.6$ mm, respectively. It has to be noted that perfect magnet tapering is assumed, which means that the magnet strength decreases according to the lost energy to restore the closed orbit [20]. Additionally to SR the amplitude of a particle bunch is affected by other contributions such as the head-tail effect [21] or decoherence from linear [22] and second-order chromaticity [23] and amplitude detuning [22].

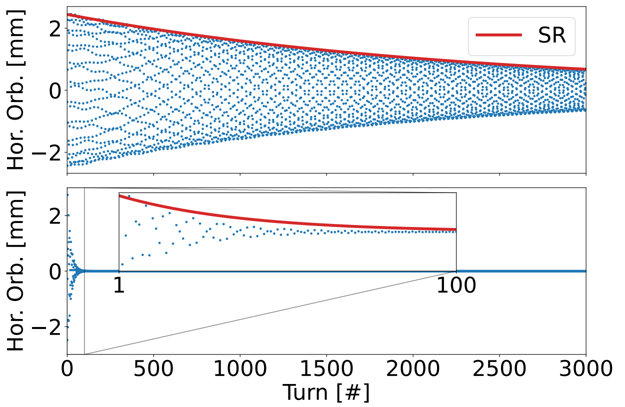

Figure 2: Damping of horizontal orbit for single particle tracking in SAD after applying a kick corresponding to $10\sigma_x$ for the Z- (top) and the $t\bar{t}$-lattice (bottom).

Recent TbT measurements for a single low intensity bunch in SuperKEKB revealed a faster damping than expected from SR [15], whereby the additional damping is mainly attributed to decoherence from amplitude detuning [15]. Decoherence for lepton storage rings has presently been investigated in [15], which also includes a new procedure to correctly measure amplitude detuning in presence of strong SR damping, and thus directly applicable for the FCC-ee.

While the damping is sufficiently slow for single kick excitation at the Z-pole, at top energy of 182.5 GeV, however, the orbit is damped too fast and thus a continuous excitation must be used. For example, in SuperKEKB a continuous excitation is achieved using the transverse feedback system together with an amplification. For this a reference oscillator generates a sine wave. At the betatron frequency the phase difference between the exciter and the transverse motion is 90° and the oscillator locks this frequency, (phase lock loop [24]) and thus this system is designed to excite exactly at the natural tune. In SuperKEKB one limitation is the available amplification, which leads in typically rather low amplitudes, about 10 times lower compared to single kicks [15].

Another technique to achieve a continuous excitation is using an AC-dipole [25], which drives the beam at a tune (Q_u^{ac}) different from the natural tune, and thus, introduces systematic effects which require dedicated compensation methods [26]. The change of orbit, where u denotes one of the transverse coordinates x or y, due to an AC-dipole over turn N is approximated by [27]

$$u(s,N) = \frac{BL}{4\pi\, B\rho\, \delta_u} \sqrt{\beta_u(s)\beta_{u,0}} \times \qquad (1)$$

$$\cos\left(2\pi Q_u^{\mathrm{ac}} N + \phi_u(s) + \phi_{u,0}\right) , \qquad (2)$$

with the amplitude of the oscillating magnetic field B, the AC-dipole length L, the magnetic rigidity $B\rho$, the difference between the driven and the natural tune δ_u, the amplitude functions at an observation point and the AC-dipole β_u and β_0, and the phase advance at the observation point and the location of the AC-dipole, ϕ_u and $\phi_{u,0}$, respectively. δ_u is typically chosen to be close ($|\delta_u| < 0.02$) to the natural tune. It has to be noted that in lepton storage rings, driving the beam exactly at the natural tune with an AC-dipole could also be envisaged since SR naturally damps the emittance after the measurement.

In measurements the raw data is cleaned using algorithms based on Singular Value Decomposition (SVD), keeping only a certain number of modes. Afterwards, a Fourier transformation is performed on the cleaned orbit which gives, among others, the phases between the BPMs, the tunes and the amplitudes at each BPM. Examples of such codes are SUSSIX [28] or HARPY [29,30], where the latter is used for the following studies. Together with models the output of the harmonics analysis is then used to retrieve optics parameters such as the phase advance or the β-function, for example using [31, 32].

To evaluate the impact of BPM noise on optics measurements, a random Gaussian distributed noise with a rms of up to 100 µm is included to the TbT single particle tracking data for the Z-lattice. The initial kick of $6\sigma_x$ and $6\sigma_y$ is applied at IP1 and the orbit is recorded for 500 turns at about 360 virtual BPMs, located next to quadrupoles. Single kicks are simulated by including SR damping, while a constant excitation at the natural tune is simulated by switching it off. As a figure-of-merit the rms phase advance error with respect to the error free model, $\sigma(\mu_{x,y}) = \mathrm{rms}(\mu^{\mathrm{err}}_{x,y} - \mu^{\mathrm{mdl}}_{x,y})$, is used and which is shown in Fig. 3. With increasing BPM noise $\sigma(\mu_x)$ and $\sigma(\mu_y)$ increase linearly, whereby including radiation damping marginally impacts the result. It can be seen in the same figure that the vertical plane is about 20 times more disturbed by the same random noise. This is assumed to be from stronger vertical sextupoles and smaller vertical beam sizes. For example a random BPM noise of 10 µm without radiation yields a horizontal and vertical phase advance error of, respectively, $0.27 \times 10^{-3}(2\pi)$ and $5.29 \times 10^{-3}(2\pi)$. Since only about 500 turns are used, using more turns could reduce the error, as shown for SuperKEKB in [15] and for LHC in [33]. For comparison, using approximately 500 turns for TbT measurements in the LHC yields a rms phase advance error below $4 \times 10^{-3}(2\pi)$, which decreases below $10^{-3}(2\pi)$ by using 6600 turns [33].

Scans of the initial kick amplitude are performed for both transverse planes ranging from $2\sigma_{x,y}$ to $14\sigma_{x,y}$, without and with Gaussian distributed BPM noise. SR damping is switched off. If no BPM noise is considered the relative errors with respect to the model increase with increasing driving amplitude, as shown in Fig. 4. However, by including a BPM noise of 10 µm $\sigma(\mu_x)$ and $\sigma(\mu_y)$ first decrease with increasing oscillation amplitude, since the excitation of the kick is greater than the noise. In this example the minimum horizontal and vertical errors of, respectively, $0.24 \times 10^{-3}(2\pi)$ and $5.28 \times 10^{-3}(2\pi)$ are achieved with $4\sigma_{x,y}$. The necessary kick is equivalent for both planes in units of the respective beam size, however, in absolute units the vertical kick is 3 orders of magnitude smaller. Increasing the driving amplitude further increases the relative error, since non-linearities, here caused by sextupoles only, are enhanced. With a larger BPM noise of 100 µm without radiation damping kicks of $12\sigma_{x,y}$ would be required [34], which would introduce large amplitude detuning [34]. However, with 100 µm BPM noise and radiation damping the optimum is found at $6\sigma_{x,y}$ [34], which suggests that the best kick strength depends if single kicks or constant excitation is performed.

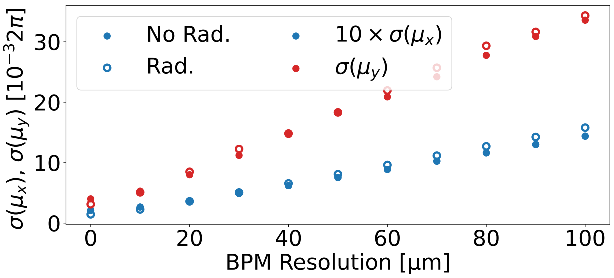

Figure 3: Impact of BPM resolution on horizontal (blue) and vertical (red) rms phase advance error at Z-pole for single kicks (No Rad.) and continuous excitation at the natural tune (Rad.) at $6\sigma_{x,y}$ using 500 turns for optics measurements.

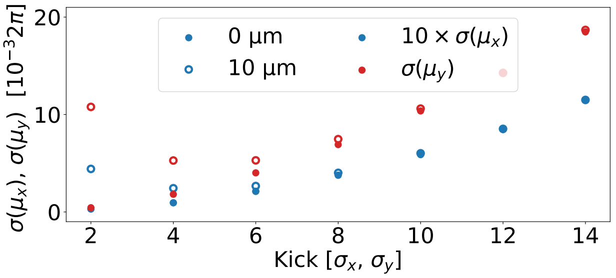

Figure 4: Horizontal (blue) and vertical (red) rms phase advance error over constant excitation strengths without (points) and with (circles) 10 µm BPM noise.

SUMMARY AND OUTLOOK

Performing optics measurements for the FCC-ee is one of the key challenges in its design. Due to its unprecedented size and the strong synchrotron radiation damping at $t\bar{t}$ running, the applicability of existing methods needs to be re-evaluated, including K-modulation, ORM techniques and TbT measurements. First TbT measurement are simulated using SAD for the Z- and $t\bar{t}$-lattices without IR solenoids. It is found that the rms phase advance error with respect to the ideal model increases linearly with the BPM noise. In addition, the amplitude of the excitation needs to be sufficiently large to overcome the effect of the BPM noise. However, large amplitudes enhance nonlinearities and may thereby compromise the accuracy of the measurement. For example, with a random BPM noise of 10 µm and optimum excitation amplitude the horizontal and vertical rms phase advance error is, respectively, $0.24 \times 10^{-3}(2\pi)$ and $5.28 \times 10^{-3}(2\pi)$. In future studies several other optics and misalignment errors will be included and their impact on the measurement quality evaluated. Also the excitation with an AC-dipole will be studied in detail. Complementarily, the impact of synchrotron radiation on the ORM measurements must be studied, and its analysis refined to take this into account.

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