PROGRESS ON OPTICS MEASUREMENTS FOR THE FCC-ee

J. Keintzel[*,1], D.B. Pio[2], R. Tomás[1]
[1]CERN, Geneva, Switzerland
[2]DTU, Lundtofte, Denmark

Abstract

Precise optics measurements will be crucial for commissioning and optimising the Future Circular electron-positron Collider, FCC-ee, across its full energy range. To prepare for this challenge, simulation studies have been performed to evaluate the accuracy and robustness of Turn-by-Turn (TbT) based optics diagnostics applied to the FCC-ee. A central element of this effort is the use of an AC-dipole to generate coherent, controlled beam oscillations suitable for high-quality TbT data analysis. This contribution presents the latest progress in simulated TbT optics measurements, including sensitivity to Beam Position Monitor (BPM) noise. Particular emphasis is placed on exploring the first specifications for BPMs and AC-dipoles for the FCC-ee, accounting for constraints related to synchrotron-radiation damping, excitation strength, and driving frequency. The results provide essential input for defining the optics-measurement strategy, hardware requirements, and correction schemes foreseen for the FCC-ee.

INTRODUCTION

The Future electron-positron Circular Collider (FCC-ee) [1, 2] has been recommended as the highest priority future collider succeeding the High-Luminosity LHC (HL-LHC) [3]. This lepton storage ring collider aims at an exceptionally high luminosity production at collision energies from 91.2 GeV to 365 GeV, corresponding to physics around the Z-pole up to above the $t\bar{t}$-threshold. Achieving its design performance requires an extremely precise beam optics control. In particular, accurate measurements of the β-functions, phase advances and linear coupling are fundamental to apply optics and emittance tuning techniques successfully [4].

Turn-by-Turn (TbT) Beam Position Monitor (BPM) data provide a powerful tool for optics measurements. Traditionally in lepton storage rings, such measurements rely on single kicks applied transversely to the beam. However, with a transverse damping time of 2600 turns to as low as 40 turns, respectively at 45.6 GeV to 182.5 GeV beam energy, the fast decay of free oscillations significantly limits the achievable measurement accuracy (see also Ref. [5]). An AC-dipole is, therefore, an attractive method to excite beams over a longer period at a constant amplitude and has been demonstrated reliable for various past and present machines, see e.g. [6, 7]. Due to strong Synchrotron Radiation (SR) damping for the FCC-ee this technique requires careful review.

In this paper, we investigate the use of AC-dipoles for global optics measurements in the FCC-ee. We study the performance versus excitation strength, and distance to the natural tune, including SR damping and amplitude detuning. Furthermore, we assess the impact of BPM resolution errors on the quality of optics measurements, aiming to set first tolerances. All studies are performed using Xsuite [8] and the LCC optics version 106.2.2, which has recently been selected as baseline [9, 10]. The overall goal is to contribute to define a global optics measurement strategy, tolerances, and to define the optimal parameter space for reliable and precise optics measurements.

THEORY

The transverse motion under AC-dipole excitation is well established in the absence of SR [11–13]. It can be written as

$$x(s,n) = \frac{B_m L}{4\pi B\rho\delta}\sqrt{\beta(s)\beta_0}\cos(2\pi Q_d n - \pi Q + \phi(s))\,, \tag{1}$$

where n is the turn number, β_0 is the β- function at the AC-dipole, Q_d is the driven tune, $\delta = Q_d - Q$ is the difference between the driven and natural tune, and $\beta(s)$ and $\phi(s)$ are the driven optics parameters. In contrast to free betatron oscillations, the AC-dipole generates a coherent driven motion that can be sustained over many turns. This is particularly advantageous in the FCC-ee, where SR leads to rapid damping of free oscillations.

The oscillation amplitude scales inversely with δ. Expressing the motion in units of the beam size, $x(s) = N_\sigma\sqrt{\varepsilon\beta(s)}$, the required kick angle without SR can be estimated as

$$\theta \approx N_\sigma\, 4\pi\delta\sqrt{\varepsilon/\beta_0}\,. \tag{2}$$

The transverse kick is generated by an AC dipole through an oscillating magnetic field which can be expressed in terms of the applied voltage. This scales with the desired excitation amplitude and can be expressed as

$$V \approx N_\sigma \frac{4\pi\delta\, p_0 c}{0.3}\sqrt{\varepsilon/\beta_0}\,. \tag{3}$$

In practice, however, various effects could modify this ideal excitation. Amplitude detuning introduces a dependence of the tune on the amplitude, effectively changing the detuning for large excitations. Additionally, SR damping leads to a time-dependent oscillation amplitude.

IMPLEMENTATION

In the FCC-ee AC-dipoles are already foreseen to be integrated in the dispersion suppressor, used for measurements of the beam energy via resonant depolarization (RDP), as part of the polarization and energy calibration effort [14–16].

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[*] jacqueline.keintzel@cern.ch

For RDP, in total 6 vertical closed orbit bumps, each consisting of 3 kickers are currently being foreseen. While for RDP only vertical excitation is required, we assess here the feasibility to also excite horizontally, which would only require additional horizontal plates. As a first implementation one of those kickers is used as an AC-dipole, where relevant parameters for the Z and $t\bar{t}$ optics at that location are given in Table 1.

Table 1: Optics And Beam Parameters At The Implemented AC-Dipole Location

Parameter	**Z**	**$t\bar{t}$**
Energy [GeV]	45.6	182.5
β_x, β_y at studied AC-dipole [m]	48 / 128	48 / 128
Transverse damping time [turns]	2600	40
Chromaticity Q'_x, Q'_y	12 / 5	1 / 1
Hor. amp. detuning [10^3 m^{-1}]	−1.5	−29.0
Vert. amp. detuning [10^6 m^{-1}]	1.4	17.4

For RDP measurements a maximum deflection of 2.5 µrad per kicker is currently set as a target at Z energy. Using Eqs. (1) to (3) the maximum deflection angle required to obtain a certain excitation N_σ for different δ is calculated, and shown in Fig. 1. Amplitude detuning is included. With a driving tune close to the natural one, deflection angles below 1 µrad are sufficient for 1 to 5 $\sigma_{x,y}$ excitation in both planes and for Z and $t\bar{t}$ energy.

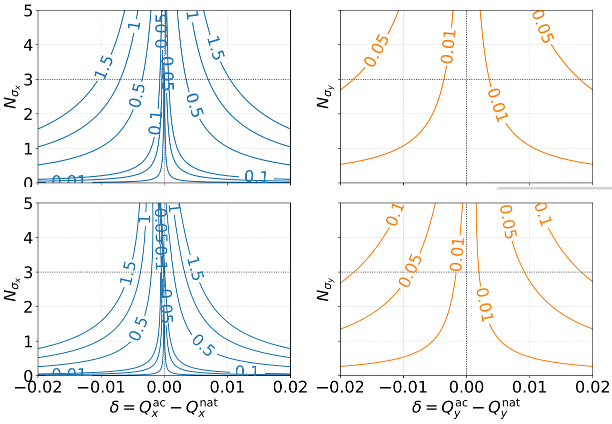

Figure 1: Required horizontal (left) and vertical (right) AC-dipole kicks for Z (top) and $t\bar{t}$ (bottom), given in µrad.

SIMULATED OPTICS MEASUREMENTS

Optics measurements are simulated by using one AC-dipole with a single particle, with an example of the TbT orbit is shown in Fig. 2 for Z energy. The optics is then measured with OMC3 [17] by using only the stable plateau. First studies presented here focus on linear, on-momentum optics measurements. While for hadron storage rings the ramping must be slow enough to avoid emittance growth after the AC-dipole excitation, we note that this parameter has currently not been optimized for the FCC-ee.

To quantify good optics measurements the rms phase advance error between the simulated measurement and the model is used as a figure-of-merit. If SR is included in the tracking, it is also included in the model together with ideal tapering. Previous studies for the GHC lattice suggest that the rms phase advance error in the arcs must be kept below $10^{-3}(2\pi)$. Furthermore, we recall that tuning studies for GHC and LCC assume a phase advance measurements error of $10^{-4}(2\pi)$ for GHC and LCC [4].

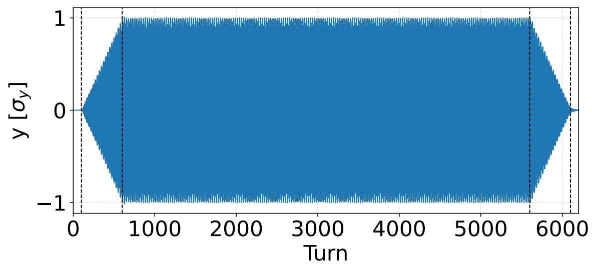

Figure 2: Example of an AC-dipole excitation for Z energy.

The particle is driven either in horizontal or vertical plane with a δ of 0.002 and a plateau of 50 000. SR damping is included. As presented in [18], changing δ or the number of used turns does only contribute marginally to the achieved resolution. At Z energy an rms phase advance error below $10^{-4}(2\pi)$ is achieved for driving with an maximum amplitude of 2 $\sigma_{x,y}$ for both planes, as shown in Fig. 3. Without SR the rms phase advance error is approximately identical to the previous scenario, shown in the same figure. In the absence of measurement noise, the rms phase advance error increases with increasing driving amplitude, stemming from non-linear contributions, such as amplitude detuning. A similar dependence is observed for free kicks [19].

BPM resolution errors are modelled as a random Gaussian noise on the horizontal and vertical TbT orbit truncated at 2.5 σ, where values of 1 µm, 0.5 µm and 0.1 µm rms are used. SR, a plateau of 50 000 turns of δ of 0.002 are used for 30 different random seeds. As before, the rms of the phase advance error is calculated, and here the mean and standard deviation over all seeds is given, as shown in Fig. 4. As expected, the rms phase advance error increases with increasing BPM resolution. Nevertheless, it is found that by driving the beam to low excitation amplitudes and assuming 1 µm TbT resolution a phase advance error of approximately $1 \times 10^{-4}(2\pi)$ is achievable in both planes.

At $t\bar{t}$ energy the particle is driven either in horizontally or vertically with a δ of 0.01 or 0.002 for 50 000 turns including

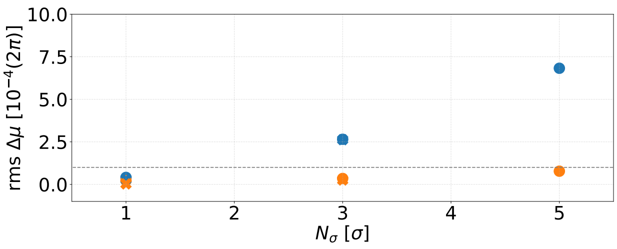

Figure 3: Horizontal (blue) and vertical (orange) rms phase advance error over maximum excitation, with (circles) and without (crosses) SR for Z energy.

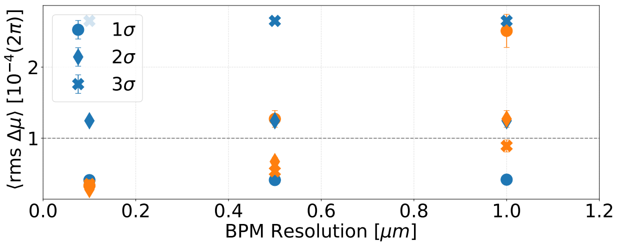

Figure 4: Horizontal (blue) and vertical (orange) rms phase advance error over BPM error for Z energy with SR.

SR. The analytical estimate of Eq. (2) slightly underestimates the required deflection angle at $t\bar{t}$ energy. Tracking simulations indicate a correction factor of about 1.15, applied in the following. The lowest rms phase advance error is, respectively for the horizontal and vertical plane $2 \times 10^{-3}(2\pi)$ and $2.7 \times 10^{-3}(2\pi)$, at an amplitude of only $1\,\sigma$, as seen in top Fig. 5 for $\delta = 0.01$. Simulations with SR for $\delta = 0.002$ show a slightly larger error horizontally. Since the rms phase advance error is significantly larger than at Z energy, possible sources are discussed in the following. Previous work [20] suggests also linear chromaticity as a possible source. However, in here presented studies, it is already roughly 1 in both planes. At the location of the kicker required for RDP horizontal dispersion is 35 cm. Beam excitation at a location with non-zero dispersion can drive synchro-betatron resonances. To test this, another AC-dipole is installed in a long straight section, where dispersion is 0, with $\beta_x = \beta_y$ of 730 m. It reduces the rms vertical phase advance error only to 1.7×10^{-3}, while the horizontal one remains at the same value as before. We note, that implementing AC-dipoles at locations with larger β-functions has the advantage that lower deflection angles would be required. Performing tracking simulations without SR reduces the rms phase advance error to approximately $1 \times 10^{-4}(2\pi)$ for an excitation of $1\,\sigma$ in either of the transverse planes at $\delta = 0.01$, as also shown in Fig. 5. This indicates that the current phase reconstruction method is not yet adapted to driven oscillations with strong damping, which must be investigated.

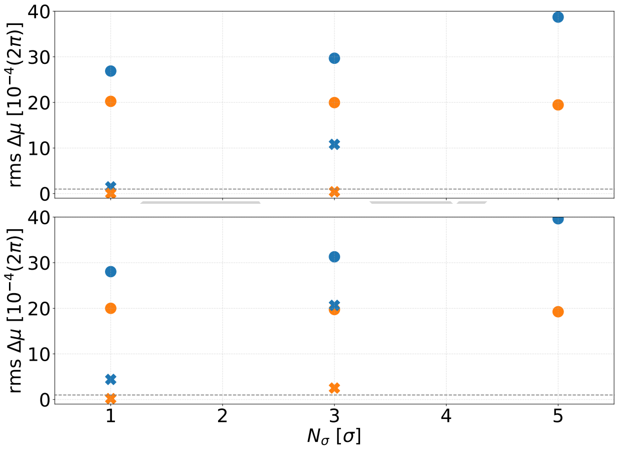

Figure 5: Horizontal (blue) and vertical (orange) rms phase advance error over maximum excitation, with (circles) and without (crosses) SR for $t\bar{t}$ energy, with $\delta = 0.01$ (top) or $\delta = 0.002$ (bottom).

To obtain first insights on the impact of BPM resolution, no SR is included in the following and a δ of 0.01 is used. The same BPM resolution errors are applied as for Z energy. These preliminary studies also suggest that 1 µm in combination with a low excitation could achieve a phase advance error in the order of approximately 1×10^{-4}, shown in Fig. 6.

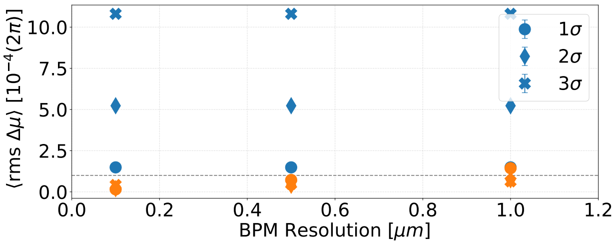

Figure 6: Horizontal (blue) and vertical (orange) rms phase advance error over BPM resolution for $t\bar{t}$ without SR.

PROSPECTS FOR MEASUREMENTS

Optics measurements are foreseen to be performed on a bunch-by-bunch and TbT basis. A key limitation is the achievable BPM resolution, which is inversely proportional to the bunch charge. As shown in [21], it is found that assuming even 0.1 µm could be extremely challenging to measure non-linear optics such as resonance driving terms. First considerations, are presented in [22], and propose to improve optics measurements using a dedicated set-up, e.g. using roughly 20 bunches with 10^{11} particles each, could significantly improve the achievable resolution. From an operational perspective, optics measurements in the FCC-ee must be compatible with machine protection constraints.

SUMMARY AND OUTLOOK

Accurate optics measurements techniques are required in FCC-ee to achieve design performances. Optics measurements using an AC-dipole have been investigated for the FCC-ee using TbT measurement simulations. The integration of AC-dipole functionality into kickers, foreseen for RDP could provide an efficient and attractive solution. These studies demonstrate that, at Z energy, phase advance errors at the level of $1 \times 10^{-4}(2\pi)$ could be achieved with moderate excitation amplitudes, 50 000 turns and a BPM resolution of 1 µm. At $t\bar{t}$ energy, however, significantly larger phase advance errors are observed, challenging the optics tuning. This discrepancy is currently attributed to limitations in the phase reconstruction, in particular due to the strong SR damping. Further investigations are required to properly account for these effects. The present results are based on single-particle simulations and focus on linear, on-momentum optics. Future work must include multi-particle tracking with quantum fluctuations. In addition, the scope of the studies should be extended to a full set of optics observables, including β- functions, dispersion, coupling, and non-linear optics.

REFERENCES

[1] M. Benedikt *et al.*, "Future Circular Collider Feasibility Study Report: Volume 1 Physics, Experiments, Detectors", CERN, Geneva, Switzerland, Rep. CERN-FCC-PHYS-2025-0002, May 2025. doi:10.48550/arXiv.2505.00272

[2] M. Benedikt *et al.*, "Future Circular Collider Feasibility Study Report: Volume 2 Accelerators, Technical Infrastructure and Safety", CERN, Geneva, Switzerland, Tech. Rep. CERN-FCC-ACC-2025-0004, Mar. 2025. doi:10.48550/arXiv.2505.00274

[3] European Strategy Group, "The European Strategy for Particle Physics: 2026 Update – Recommendations by the European Strategy Group", Rep. No. CERN-ESU-2025-002, 2025. doi:10.17181/CERN.423R.S20Z

[4] J. Keintzel *et al.*, "FCC-ee Optics Tuning – Towards the reference design", presented at IPAC'26, Deauville, France, May 2026, paper MOP1039, this conference.

[5] J. Keintzel, R. Tomás García and F. Zimmermann, "Prospects for optics measurements in FCC-ee", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 827-830. doi:10.18429/JACoW-IPAC2022-TUOZSP1

[6] R. Tomás, M. Aiba, A. Franchi and U. Iriso, "Review of linear optics measurement and correction for charged particle accelerators", *Phys. Rev. Accel. Beams*, vol. 20, p. 054801, 2017. doi:10.1103/PhysRevAccelBeams.20.054801

[7] M. G. Minty and F. Zimmermann, *Measurement and Control of Charged Particle Beams*, Springer Verlag, Berlin, Germany, 2003.

[8] G. Iadarola *et al.*, "Xsuite: an integrated beam physics simulation framework", in *Proc. 68th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB'23)*, Geneva, Switzerland, Oct. 2023, pp. 73-80. doi:10.18429/JACoW-HB2023-TUA2I1

[9] S. Kostoglou and G. Roy, Eds., "FCC-ee optics comparison report", CERN, Geneva, Switzerland, 2026, unpublished.

[10] J. Keintzel *et al.*, "Defining the new FCC-ee baseline optics", presented at IPAC'26, Deauville, France, May 2026, paper WEV1001, this conference.

[11] J. Serrano and M. Cattin, "The LHC AC-dipole system: an introduction", CERN, Geneva, Switzerland, Rep. CERN-BE-Note-2010-014, May 2010.

[12] R. Miyamoto, R. Calaga, M. Aiba, R. Tomás and G. Vanbavinckhove, "Measurement of coupling resonance driving terms in the LHC with AC-dipole", in *Proc. IPAC'11*, San Sebastián, Spain, Sep. 2011, pp. 2067-2069.

[13] M. Bai, "Non-destructive beam measurements", in *Proc. EPAC'04*, Lucerne, Switzerland, Jul. 2004, pp. 165–169.

[14] J. Keintzel *et al.*, "FCC-ee energy calibration and polarization – towards the reference design", presented at IPAC'26, Deauville, France, May 2026, paper MOP1037, this conference.

[15] A. Blondel, J. Keintzel, J. Wenninger, G. Wilkinson *et al.*, "Collision-energy calibration and monochromatisation studies at FCC-ee", CERN, Geneva, Switzerland, CERN Tech. Rep., Mar. 2025. doi:10.17181/y6s2j-dhh22

[16] G. Iadarola *et al.*, "Spin tracking and equilibrium polarization computation in Xsuite: implementation and benchmarks", presented at IPAC'26, Deauville, France, May 2026, paper MOP1028, this conference.

[17] OMC Team, "OMC3". doi:10.5281/zenodo.5705625

[18] J. Keintzel, "Optics measurement news", presented at the FCC-ee optics tuning WG meeting, 17 Apr. 2026. https://indico.cern.ch/event/1675106/

[19] L. Malina *et al.*, "Improving the precision of linear optics measurements based on turn-by-turn beam position monitor data after a pulsed excitation in lepton storage rings", *Phys. Rev. Accel. Beams*, vol. 20, p. 082802, 2017. doi:10.1103/PhysRevAccelBeams.20.082802

[20] A. Franchi *et al.*, "AC dipole experience in ESRF", presented at the FCC-ee tuning meeting, 22 Mar. 2022. https://indico.cern.ch/event/1138028

[21] P. J. Hunchak, "Non-linear optics in tuned lattices", presented at the FCC-ee optics tuning WG meeting, 17 Dec. 2025. https://indico.cern.ch/event/1620480/

[22] J. Keintzel, "Polarisation studies", presented at the 1st FCC Beam Instrumentation Workshop, 2022. https://indico.cern.ch/event/1209598/