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CERN'S BEAM INSTRUMENTATION R&D STUDY FOR FCC-ee

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Abstract

The Future Circular Collider (FCC) study is investigating the feasibility of CERN's future accelerator project encompassing technical, administrative and financial aspects. As part of the study, Beam Instrumentation (BI) is a key technical infrastructure that will have to face unprecedented challenges. In the case of the electron-positron FCC-ee, these are represented, among others, by the size of the accelerator, the amount of radiation produced along the ring and in machine-detector interaction region, the presence of the top-up booster and collider ring in the same tunnel. In this contribution we will present the current FCC-ee BI study and discuss its status and perspectives.

INTRODUCTION

Following the recommendations of the 2013 Update of the European Strategy for Particle Physics, in 2014 CERN launched the Future Circular Collider (FCC) study aiming for the design of a post-LHC accelerator. A conceptual design report was published in 2019 for a hadron (FCC-hh) and a lepton (FCC-ee) collider [1], the latter is subject of this study, as a ~90 km circumference accelerator tunnel holding the booster and the two main rings. In 2021 a five-year feasibility study was launched to identify R&D requirements to provide all elements necessary for a decision on the continuation of the project in 2026-27.

Beam Instrumentation (BI) represents a key subsystem for FCC-ee that faces unprecedented challenges given its size and complexity. Table 1 lists some of the FCC-ee beam parameters which are particularly relevant for BI, with the values highlighted in redpresenting the biggest challenges. The scope of an extended BI R&D study would be in fact so vast that only critical items have been selected for this first feasibility study. These include the measurement of transverse and longitudinal beam profiles in the main ring and the beam position in the main ring arc and in the interaction regions (IRs).

BEAM POSITION MEASUREMENT

The two main rings and the booster ring together will need a total of approximately 7000 beam position monitors (BPM), distributed along the ~90 km FCC-ee tunnel. All of the BPM pickups will be of button-style, skewed ("rotated") by ~45° to insure the button electrodes stay out of the synchrotron light fan. Figure 1 gives an idea of the BPM pickup cross-section for the main ring BPMs, which in most cases will be rigidly assembled and aligned, mechanically and electrically, to the quadrupole magnets.

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Table 1: FCC-ee Beam Parameters Relevant to Beam Instrumentation

parameter (4 IPs, t_{rev} = 304 µs)	**value**
circumference [km]	91.18
beam energy,min./max. [GeV]	45 / **182.5**
beam current, max./min. [mA]	1280 / **5**
number of bunches, max./min.	10000 / **40**
bunch spacing [ns]	25
bunch intensity [10^{11}]	2.43
min. H geometric emittance [nm]	0.71
min. V geometric emittance [pm]	1.42
min. H rms IP spot size [µm]	8
min. V rms IP spot size [nm]	34
min./max. rms bunch length [mm]	**1.95 / 14.5**

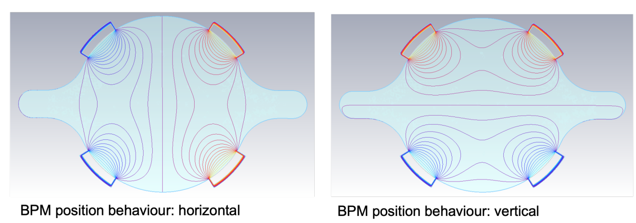

Figure 1: Lines of constant beam displacement of a FCC-ee main ring button BPM, horizontal (left), vertical (right).

BPM R&D

The R&D for the FCC-ee BPM systems is focused on design, integration and alignment of the button-style BPM pickup for the arc and interaction regions (IR) of the main rings. The BPM system, with the button pickups as signal source, has to meet several challenging requirements, e.g. a resolution of 10 µm (turn-by-turn) and <1 µm (orbit mode) with the relative accuracy and the alignment tolerances in the same regime. A bunch-by-bunch measurement capability is required, the nominal FCC-ee bunch spacing is given as 25 ns. The BPMs also will serve in different feedback applications, thus the layout, segmentation and cabling to minimize the latency of the BPM data need to be studied.

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To tune and optimize the luminosity in the interaction points (IP), BPMs will be symmetrically located on each side of the IP. One BPM in the combined beam vacuum chamber at the luminosity calorimeter will serve the IP feedback system, the other 3 . . . 5 BPMs are located in the IR cryostat with the beams in separate chambers and mounted next to the two segmented superconducting quadrupoles. These IR BPM pickups, and their signal cabling need to be very reliable, as their locations will be unreachable after the final assembly. Many details and the requirements are still in discussion.

Another focus of the BPM pickup R&D is related to the minimisation of the beam coupling impedance, i.e. unwanted wakefields. Preliminary studies have been performed [2, 3], and the longitudinal beam coupling impedance of 4000 BPM pickups with conical button electrodes was compared to other impedance contributing elements, such as the resistive wall (RW), bellows, RF cavities and taper section.

TRANSVERSE BEAM PROFILE MEASUREMENT

Beam profile measurements in rings are normally performed through the analysis of the emitted synchrotron radiation (SR) in an optical imaging system. The very high beam energy of FCC–ee introduces intrinsic source diffraction effects that make the utilisation of imaging quite difficult. This, coupled to the fact that SR peaks in the hard X-rays regime ($\lambda \approx 0.1$ nm) calls for the utilisation of X- ray interferometric techniques [1].

In this context, BI is pursuing R&D activities on the X ray Heterodyne Near Field Speckles (X-HNFS) method. It enables full 2D coherence mapping of X-ray SR, thus providing a 2D beam size measurements technique [4]. Speckles are formed by interfering the weak spherical waves scattered by a nanostructured material with the intense trans-illuminating X-ray beam. Fourier analysis of these random speckle patterns allows direct measurements of the coherence function of the incoming synchrotron light [4–6]. The 2D beam profile is then retrieved by the Fourier transform of the measured 2D spatial coherence, under the conditions of applicability of the Van Cittert and Zernike theorem [7]. The technique has been validated in preliminary measurements at the NCD-SWEET undulator beamline at the ALBA synchrotron light source through a systematic measurement of the horizontal and vertical beam sizes as a function of the machine coupling parameter [4], demonstrating micron-size resolution (see Fig. 2).

As part of this R&D activity, X-HNFS tests will resume in 2023 at the ALBA light source on a newly created extraction line of SR from a dipole. Nanostructured materials for the Xrays target that have the correct scattering properties and can withstand FCCee parameters will be studied.

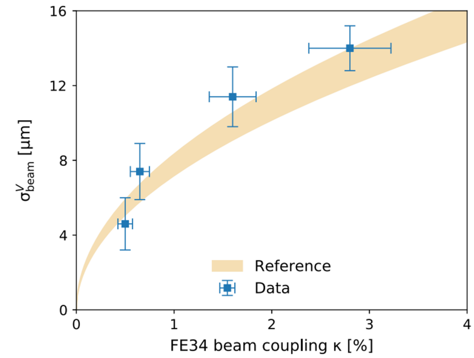

Figure 2: Measured vertical beam size at the NCD-SWEET beamline as a function of the ALBA coupling parameter. Adapted from [4].

LONGITUDINAL BUNCH PROFILE MEASUREMENTS

Bunch length profile measurement system for FCC-ee is needed on a bunch-by-bunch basis to monitor the strength of the beamstrahlung at the IPs, for energy calibration and to ensure correct top-up operation [1]. The design of a bunch-by-bunch, sub-ps resolution, non-invasive longitudinal profile monitor is part of the BI R&D. An electro-optical system is currently being developed at the Karlsruhe Research Accelerator (KARA). In parallel, the characterisation of diffracted Cherenkov Radiation is being studied to evaluate its potential as a alternative source for longitudinal profile monitoring.

Longitudinal Profile Monitoring Using EOSD

Electro-optical spectral decoding (EOSD) is a technique to measure the longitudinal bunch profile in a non-destructible way in a single shot. The KARA electron storage ring at the Karlsruhe Institute of Technology (KIT) has demonstrated, for the first time at an electron storage ring, turn-by-turn bunch profile measurements with EOSD and it has been further developed and optimised since its installation in 2013 [8]. This technique and setup serves as a basis for the development of a bunch length measurement system for FCC-ee.

With the electro-optical (EO) monitor, the longitudinal bunch profile is encoded into the polarisation of a chirped laser pulse via an electro-optical crystal mounted close to the electron orbit in the vacuum chamber. The Coulomb field of the electron bunch changes the birefringence of the crystal, which modulates the polarisation of the laser pulse and, therefore, after passing through two waveplates and a polarising beam splitter, into an intensity modulation. For EOSD, the chirped laser pulse is sent onto a grating and a line camera to measure the spectrum of the laser pulse, which contains the information of the longitudinal bunch profile. At KARA, the KIT-built ultra-fast line array camera KALYPSO is used to allow for turn-by-turn measurements at 2.7 MHz [9].

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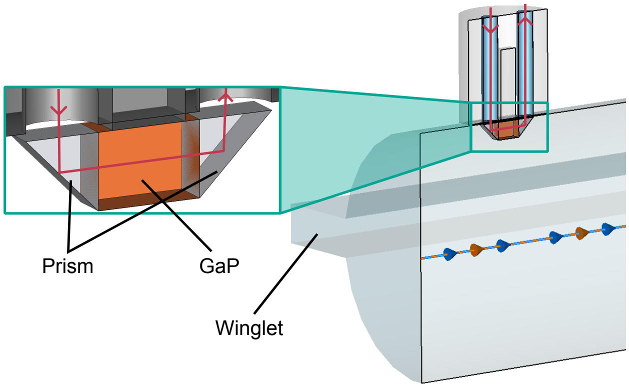

Figure 3: Conceptual design with two prisms attached to the crystal for and EOSD setup for FCC-ee [10].

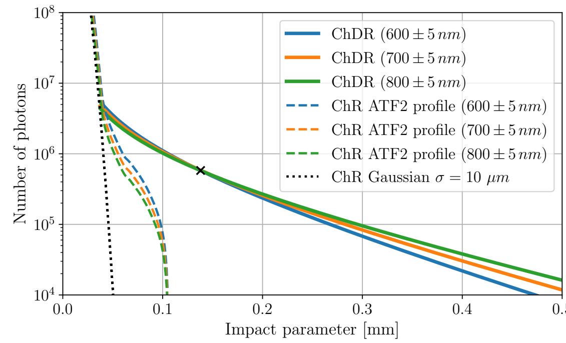

Figure 4: Expected photon yield according to the *non-stationary model*. Solid coloured lines correspond to ChDR at different wavelengths, dashed coloured lines correspond to the photon yield from direct Cherenkov radiation [20].

To reach higher repetition rates, a line camera with higher frame rate is needed, or alternatively multiple setups could be installed. Multi-bunch operation also brings other challenges like crystal heating caused by larger beam current, which is currently being investigated during two-bunch operation with short time spacing [11].

For FCC-ee beam parameters, a simulation has been set up, which revealed two major challenges [12]: The long bunches at FCC-ee during the operation at the Z-boson pole energy (45.6 GeV) and the high charge density in the bunches. In order to adapt to these conditions, a new design idea has been developed [10] as shown in Fig. 3. The new concept uses two prisms to guide the laser through the crystal and it is attached to the edge of the FCC-ee vacuum chamber. With this setup, a similar EOSD signal level than for the KARA setup can be reached. A first prototype for proof-of-principle tests is currently being built.

Incoherent Cherenkov Diffraction Radiation

Cherenkov Diffraction radiation (ChDR) is generated as a charged particle is passing in the vicinity of a dielectric material under the condition that the velocity v of this particle exceeds the speed of light in the given dielectric material. ChDR is emitted at the well-known Cherenkov angle [13] .

The incoherent part of the ChDR spectrum is a promising candidate for measuring bunch length in the FCC-ee. However, two analytical models [14, 15] predict a largely different photon yield [16, 17] with very little experimental data [18]. To assess the potential of incoherent ChDR for FCC-ee, a photon counting experiment is being prepared to measure its photon yield in the visible spectrum.

The ATF2 beamline at KEK [19] is a suitable candidate for these tests, as it provides high particle energy and charge and a small beam size, which allows a beam-crystal distance in the sub-mm range. In Fig. 4, simulation results for one model are shown for ATF2, i. e. a beam energy of 1.2 GeV, 5×10^9 particles per bunch, SiO_2 as dielectric material and a radiator length of $l = 10$ mm.

The coloured solid lines show the expected photon yield from ChDR as well as added contributions from halo particles for three different wavelengths (600, 700 and 800 nm). The black dashed line corresponds to the photon yield from halo particles hitting the radiator itself and therefore emitting direct Cherenkov radiation. This direct Cherenkov radiation has a non-negligible contribution to the expected number of photons. This can be seen in the photon yield for different wavelengths, which changes behaviour at around 0.14 mm distance to the beam center (marker $\times$ in Fig. 4). This change in behaviour stems from the fact that direct Cherenkov radiation increases for shorter wavelengths whereas ChDR decreases for shorter wavelengths. Measuring at different wavelengths therefore provides a possibility to distinguish between direct Cherenkov and ChDR.

SUMMARY AND OUTLOOK

We presented the status of the BI R&D study for the measurement of beam position and longitudinal and transverse profiles for the FCC-ee main ring. It is important to emphasise that, while this addresses the most pressing scientific and technical issues, it is far from covering the full scope of FCC-ee diagnostics. Beam loss is a critical system for the safe operation of the machine that will need to distinguish between losses from the booster and main ring and be insensitive to the SR spectrum. The machine-detector interface regions will also pose significant challenges for the monitoring of beamstrahlung photons, given the extremely high rate and energies. Ultimately, it will be the very size and complexity of the FCC-ee, including the injector complex and booster ring, that will represent an unprecedented challenge to BI systems.

REFERENCES

[1] A. Abada *et al.*,"FCC-ee: The Lepton Collider", *Eur. Phys. J. Spec. Top.*, vol. 228, pp. 261–623, 2019. doi:10.1140/epjst/e2019-900045-4

[2] E. Carideo, D. De Arcangelis, M. Migliorati, D. Quartullo, F. Zimmermann, and M. Zobov, "Transverse and Longitudinal Single Bunch Instabilities in FCC-ee", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 3153–3156. doi:10.18429/JACoW-IPAC2021-WEPAB225

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPL088

[3] M. Migliorati, C. Antuono, E.~Carideo, Y.~Zhang, and M. Zobov, "Impedance Modelling and Collective Effects in the Future Circular $e^+ e^-$ Collider with 4 IPs". doi:10.48500/arXiv.2204.04616

[4] M. Siano *et al.*, "Two-dimensional electron beam size measurements with X-ray heterodyne near field speckles", *Phys. Rev. Accel. Beams*, vol. 25, p. 052801, 2022. doi:10.1103/PhysRevAccelBeams.25.052801

[5] M. Alaimo *et al.*, "Probing the transverse coherence of an undulator X-ray beam using Brownian particles", *Phys. Rev. Lett.*, vol. 103, p. 194805, 2009. doi:10.1103/PhysRevLett.103.194805

[6] M. Siano *et al.*, "Characterizing temporal coherence of visible synchrotron radiation with heterodyne near field speckles", *Phys. Rev. Accel. Beams*, vol. 20, p. 110702, 2017. doi:10.1103/PhysRevAccelBeams.20.110702

[7] J. W. Goodman, *Statistical Optics*, John Wiley & Sons, Inc., New York, 2000.

[8] N. Hiller, "Electro-optical bunch length measurements at the ANKA storage ring", Ph.D. thesis, Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany, 2013. doi:10.5445/IR/1000041159

[9] M. M. Patil *et al.*, "Ultra-Fast Line-Camera KALYPSO for fs-Laser-Based Electron Beam Diagnostics", in *Proc. IBIC'21*, Pohang, Korea, Sep. 2021, pp. 1–6. doi:10.18429/JACoW-IBIC2021-MOOB01

[10] M. Reißig *et al.*, "Status of a Monitor Design for Single-Shot Electro-Optical Bunch Profile Measurements at FCC-ee", in *Proc. IBIC'22*, Kraków, Poland, Sep. 2022, pp. 455–459. doi:10.18429/JACoW-IBIC2022-WEP26

[11] M. Reißig *et al.*, "First two-bunch measurements using the electro-optical near-field monitor at KARA", presented at IPAC'23, Venice, Italy, May 2023, paper THPL121 this conference.

[12] M. Reißig *et al.* , "Development of an Electro-Optical Longitudinal Bunch Profile Monitor at KARA Towards a Beam Diagnostics Tool for FCC-ee", in *Proc. IPAC'22*, Bangkok, Thailand, 12-17 June 2022, pp. 296–299. doi:10.18429/JACoW-IPAC2022-MOPOPT025

[13] I. Frank and I. Tamm, "Coherent visible radiation of fast electrons passing through matter", *Compt. Rend. Acad. Sci. URSS*, vol. 14, p. 109, 1937.

[14] R. Ulrich, "Zur Cerenkov-Strahlung von Elektronen dicht über einem Dielektrikum", *Zeitschrift fur Physik*, vol. 194, pp. 180–192, 1966. doi:10.1007/BF01326045

[15] A. Potylitsyn and S. Gogolev, "Radiation Losses of the Relativistic Charge Moving Near a Dielectric Radiator", *Russ. Phys. J.*, vol. 62, pp. 2187–2193, 2020. doi:10.1007/s11182-020-01965-0

[16] M. Wendt *et al.* "Beam Instrumentation Challenges for FCC-ee", in *Proc. eeFACT2022*, Frascati, Italy, Sep. 2022. doi:10.18429/JACoW-eeFACT2022-WEZAS0203

[17] K. Łasocha *et al.*, "Experimental Verification of Several Theoretical Models for ChDR Description", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2420–2423. doi:10.18429/JACoW-IPAC2022-THOYGD1

[18] Kieffer *et al.* "Direct Observation of Incoherent Cherenkov Diffraction Radiation in the Visible Range", *Phys. Rev. Lett.*, vol. 121, p. 54802, 2018. doi:10.1103/PhysRevLett.121.054802

[19] A. Aryshev *et al.*, "ATF report 2020", CERN, Geneva, Switzerland, CERN-ACC-2020-0029, 2020.

[20] R. Yang *et al.*, "Evaluation of beam halo from beam-gas scattering at the KEK Accelerator Test Facility", *Phys. Rev. Accel. Beams*, vol. 21, p. 021001, 2018. doi:10.1103/PhysRevAccelBeams.21.051001