OVERVIEW OF THE FCC-ee BEAM INSTRUMENTATION R&D

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Abstract

We present an overview of the FCC-ee beam instrumentation needs and the corresponding main challenges. We will review the different R&D activities being currently pursued, including beam position and loss monitoring, transverse and longitudinal monitoring systems as well as polarimetry and luminosity monitoring.

INTRODUCTION

The Future Circular Collider (FCC) is a study of novel research infrastructure composed of an electron-positron collider (FCC-ee) [1] followed by a hadron one (FCC-hh) [2] hosted in the same underground facility, following the successful strategy adopted for the LEP-LHC construction. The FCC study was motivated by the 2013 recommendations of the European Strategy for Particle Physics [3] to undertake design studies for accelerator projects with emphasis on proton-proton and electron-positron high-energy frontier machines to stay at the forefront of particle physics.

Following the Conceptual Design Report (CDR) in 2019, CERN is presently finalising a 5-years feasibility study for geological, technical, environmental and administrative aspects of the FCC complex that shall provide a consolidated cost estimate. These and other aspects of the study (physics case, detector concepts, funding model etc.) shall be part of a Feasibility Study Report (FSR) to be published in March 2025.

In this contribution we will present an overview of the Beam Instrumentation (BI) systems that are currently being studied as part of the FSR. The study focuses at present on the FCC-ee machine which overall design maturity is more advanced than the second-stage FCC-hh. We will present a summary of requirements and related measurement techniques and methods, as well as relevant R&D activities.

THE FCC-ee COLLIDER

FCC-ee consists of a 90.7 km collider ring that can host 4 detectors for electron-positron collision experiments. The collider is design to be operated at all times in collision mode with top-up injection from a booster ring hosted inside the main ring tunnel, in turn fed by a 20 GeV electron and positron injection complex. The FCC-ee is meant to study the electro-weak sector with beam energies ranging from 45 to 182 GeV (see Table 1). The beam current is determined by the requirement to keep the power dissipated by Synchrotron Radiation (SR) at 50 MW.

FCC-ee represents a formidable challenge for BI due to unprecedented operating conditions. The size of the machine, radiation levels and heat load during operation, several-keV-level critical wavelength of SR make it a harsh environment to guarantee stringent BI requirements as well as maintainability. We will here review the development status of the main BI systems for FCC-ee main ring.

Table 1: Some FCC-ee Parameters Relevant to BI Systems

Parameter	Z	WW	H	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
# bunches	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
RMS bunch length [mm]	5.6	3.5	3.4	1.8
bunch spacing [ns]	25	25	25	25

BEAM POSITION MEASUREMENT

The FCC-ee requires approximately 10’000 BPMs throughout the accelerator complex. The collider arc BPMs are required to have submicron orbit resolution, turn by turn resolution in the order of microns, and an accuracy of 20 µm. The requirements for the BPMs around the interaction regions are even more challenging, with 1 µm IP BPM accuracy requested. The BPMs also need to be reliable, radiation tolerant and have a small impedance.

Initial estimates of impedance budget for the BPMs used a design scaled from DAΦNE, and estimated a total loss factor of 40.1 V C^{-1} [1]. More recent simulations of a simple 8 mm radius button in CST, as shown in Fig. 1, have demonstrated that the arc BPM contribution to the wakeloss could be an order of magnitude lower. These simulations also suggest that the signal amplitude would be sufficient from an 8 mm pickup. Further simulations are ongoing to optimise the design and take into account the winglets of the FCC-ee beam pipe.

Measurements of pickup response to an electron beam were recently taken using the eBPMs already installed at the AWAKE accelerator at CERN. These were bench-marked

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against CST simulations. Further analysis of these measurements will allow more accurate predictions of the FCC-ee BPM performance.

Studies are also being undertaken to determine how to directly integrate the BPM into the vacuum chamber using cold-spray additive manufacturing [4]. Direct integration would aid in the alignment of the BPM pickups. The first cold-spray BPM prototypes have been successfully manufactured, but further optimisation and manufacturing process studies are required.

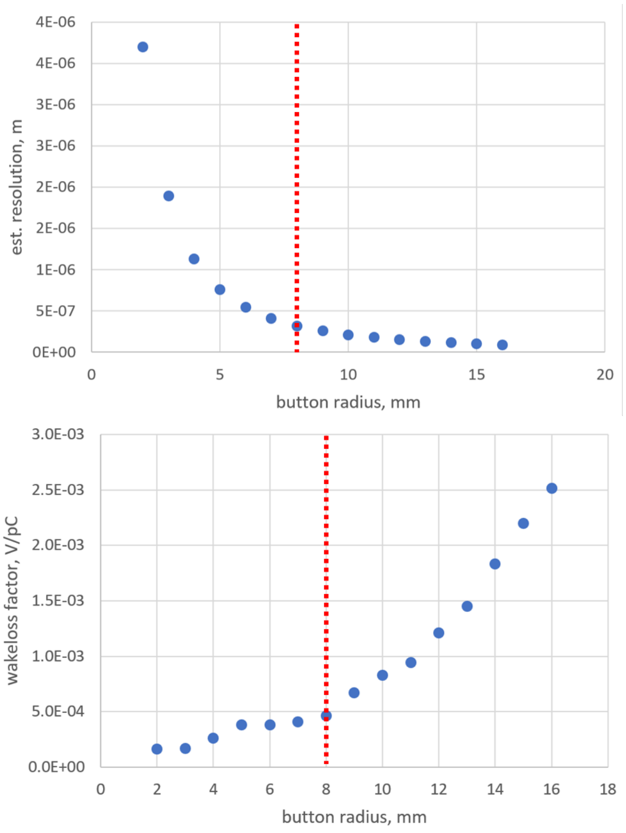

Figure 1: Simulation of resolution (top) and wakeloss (bottom) as a function of the button radius. The button design is scaled from DAΦNE. Red dashed line marks a proposed compromise between resolution and impedance.

TRANSVERSE PROFILE MEASUREMENT

The transverse diagnostics systems will be necessary to achieve the design emittance during the machine commissioning and then monitor the emittance evolution in physics production.

The precision target for the relative emittance monitoring is set at 2% while the desired absolute accuracy is 10%. These specifications align with the capabilities of diagnostics systems in previous large colliders, like LEP and LHC. Beam profiles should preferably be measured near each interaction point (IP), providing redundancy with four systems per beam. The basic requirement for all systems is to measure the average beam emittance at a frequency of at least 1 Hz, with at least one instrument per beam capable of bunch-by-bunch measurements.

SR-based techniques are the most suitable options for FCCee. Pinhole cameras, due to their simplicity and robustness, are ideal candidates for continuous emittance monitoring and can meet the bunch-by-bunch requirement when coupled to a fast-gated detector. The region downstream of the Interaction Points (IP) is currently considered the most suitable location for the diagnostics source. The larger betatron functions in this area, compared to the arcs, provide more favourable conditions for beam size measurements, especially for the challenging small vertical emittances. The machine layout and optics in this region are illustrated in Fig. 2. The BS-type dipoles are promising candidates providing a SR source with critical energy within the useful range of 10-100 keV across all operation modes. The strong BG-type magnets located just downstream can further separate the particle beam from the SR photon fan, which can then be intercepted at a longitudinal distance of the order of 100 meters from the source. The current machine optics allow for beam sizes larger than 20 µm in both planes at this location, well within the capabilities of standard diagnostics used in present-day light source facilities. Additionally, the proximity to access points is advantageous for the operation and maintenance of the instrumentation. In parallel to pinhole diagnostics, a Speckle-based Beam Size Monitor (SpBSM) exploiting the speckle patterns generated by specific nanocomposite materials [5] is being studied to reach few-µm beam measurement in the hard X-ray wavelength range. Thanks to its compact setup, the SpBSM can coexist on the same extraction line of the pinhole camera diagnostics. The current focus of the SpBSM is the realization of high-Z, metallic nanostructured solid targets capable of gen-

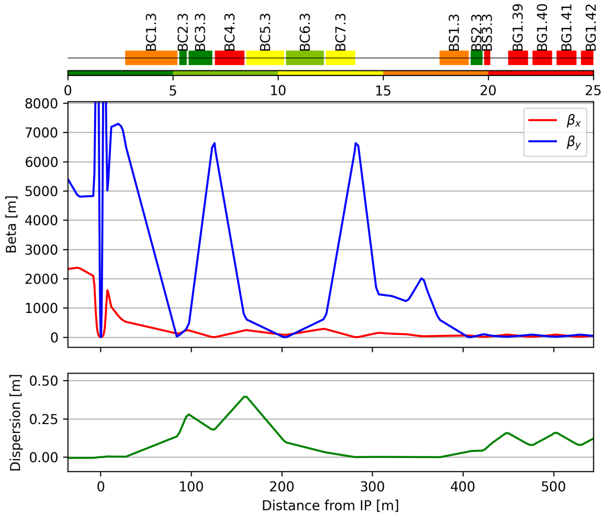

Figure 2: Machine optics downstream of the IP, for the Z mode of the V24 GHC model version. The layout of the bending magnets is reported at the top. The color of each dipole matches its photon critical energy, in keV, to represent the strength of the magnet.

erating a detectable speckle signal for photon energies up to ≈ 100 keV. The SpBSM will be tested at ALBA at the new FE21 beamline starting from the second half of 2025. Operations will require using a specifically designed multilayer monochromator (see TUP57, this conference). The beamline is also equipped with a pinhole camera for direct comparison and cross calibration, thus effectively representing a scaled version of an FCC-ee type photon extraction line.

POLARIMETRY

The beam energy will need to be known with a stringent 10 keV accuracy. Capitalising on the LEP experience, resonant depolarisation (RDP) scans performed on pilot bunches has been identified as the technique of choice for the measurement of centre of mass energy at the Z, W and ZH modes [6], while at $t\bar{t}$ the polarisation of the pilot bunches cannot be maintained over long periods since the beam energy spread is overlapping with depolarisation resonances. Both counter-rotating beams will be equipped with at least one polarimeter instrument in order to perform RDP. Measurements would be performed every 10-15 minutes selecting one bunch out of the pilots train. These frequent RDP measurements are essential to guard against any residual energy drifts from uncorrected tide effects or other mechanisms of energy change in the machine.

The baseline RDP method of operation consists in sweeping an electromagnetic depolarising signal applied to the selected bunch by dedicated kickers while monitoring the pattern of inverse Compton scattering of laser light crossing the beam. Through a bending dipole and a separation drift chamber, both Compton photons and electrons can be separated from the circulating beam and monitored through a sensor device. Figure 3 shows simulation results of the Compton scattering pattern of electrons at the Z pole energy. The fitting of this data would eventually provide the average polarisation state of the targeted bunch with sufficient statistical precision (1% in a second). In addition to energy calibration, polarimeters must be able to provide a precise knowledge of the polarisation state of the colliding bunches. Both transverse and longitudinal polarisation levels need to be measured with high precision (order of 10^{-5}), this is to insure absence of bias in the expected physics cross sections at the experiments level.

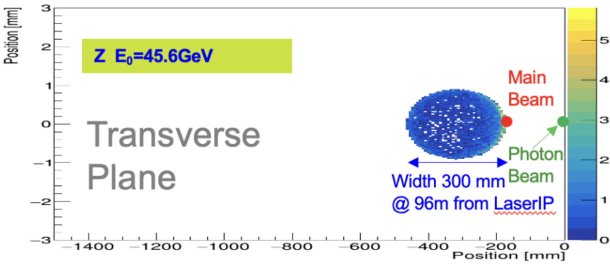

Figure 3: Distribution of scattered electrons at the exit of separation chamber 96 metres from the laser - beam interaction point.

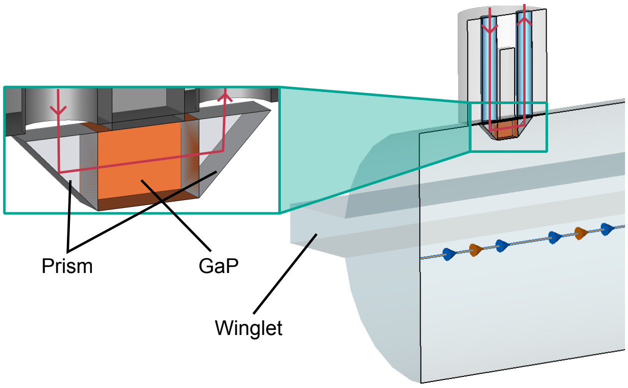

Figure 4: Concept for an EO bunch length monitor for FCC-ee [14].

LONGITUDINAL PROFILE MEASUREMENT

The RMS length of FCC-ee bunches will need to be measured with typical few- % resolution to monitor colliding bunch blow-up due to beam beam (beamstrahlung) effects [7]. Such measurement shall be performed over the entire bunch train within the longitudinal damping time (≈ 1100 turns for the Z case). In addition, the profile of newly injected bunches will need to be measured to ensure temporal overlap of top-up injection. Accuracy of longitudinal measured quantities is still being assessed.

Electro-optical spectral decoding (EOSD) is presently being studied at Karlsruhe Institute of Technology for a potential application in FCC-ee. EOSD allows single-shot measurements of the bunch profile with sub-picosecond resolution at a repetition rate in the MHz range. A notable example is the EO bunch profile monitor in operation at the synchrotron light source and research accelerator KARA at KIT in Karlsruhe, Germany, which performs turn-by-turn, single-shot bunch profile measurements at a repetition rate of 2.7 MHz [8–10]. Based on this setup, simulations has been established to investigate its performance under FCC-ee conditions [11, 12] that present significant challenges for EOSD measurements, especially the long bunches during Z operation with σ = 15.4 mm and the generally high bunch charge [13, 14]. Figure 4 illustrates a concept to address these issues by attaching the crystal to the top of the vacuum chamber, at a significant distance to the beam, with two prisms on its sides. This design allows for the measurement of long bunches with high charge while minimizing beam impedance.

To validate this design, a prototype was constructed and tested at the CLEAR facility at CERN in early 2024. The successful test demonstrated the proof-of-principle for the revised concept. The measurement results are being prepared for publication. Further studies are required to optimize the thermal management of the EO pick-up system under very high repetition rate and energies. Nevertheless, the conducted studies indicate that overall an EOSD system for bunch length measurements at FCC-ee is feasible.

Cherenkov Diffraction Radiation

Cherenkov Diffraction Radiation is under investigation as a potential signal source for bunch length and longitudinal profile measurements at FCC-ee. Characterisation of the incoherent part of the spectrum is ongoing at the ATF2 beamline at KEK, but proves to be difficult due to contributions from the bunch halo [15]. The coherent part of the spectrum has been characterised in both the time and frequency domain using electro-optical read-out systems, extending up to several tens of GHz [16]. The agreement between numerical simulations and experimental measurements allows, for the first time, to design targeted Cherenkov diffraction radiators for coherent emission [17]. Utilizing radiators that were not fully optimized for a fast signal response, a temporal response of less than 10 ps (1σ) has already been demonstrated [18].

CONCLUSION

We have presented the status of development of the main BI systems for the FCC-ee main ring. The continuous advancement of the FCC-ee systems design (optics, RF, magnets) allows to better define requirements for BI and therefore to identify techniques and methods. Still, at present some key diagnostics systems (a notable example is beam loss monitoring) are largely undefined.

Challenges posed by the beam parameters will need to be addressed by BI together with other accelerator systems teams. Radiation levels, at present prohibitive for the safe operation of electronics in the arc tunnels, will require a trade-off between shielding efficiency and development of radiation hard electronics. Also the stringent (20 µm) prealignment of elements onto the arc-half cell girder will require the coherent effort of BI, vacuum, magnets, mechanical design and alignment and metrology teams. Ideas and concepts to overcome these and other technical obstacles will be needed to prove that FCC-ee is a feasible and cost-effective high energy physics infrastructure.

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