Developing and testing beam diagnostics for FCC-ee

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2) CERN

on behalf of the FCC & FCCIS BI teams

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FCC key deliverables: prototypes by 2025

**FCC-ee complete arc half-cell mock up**
including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces.

**key beam diagnostics elements**
bunch-by-bunch turn-by-turn **longitudinal charge density profiles** based on electro-optical spectral decoding (beam tests at KIT/KARA);
**ultra-low emittance measurement** (X-ray interferometer tests at SuperKEKB, ALBA);
**beam-loss monitors** (IJCLab/KEK?);
**beamstrahlung monitor** (KEK);
**polarimeter** ; **luminometer**
Sincere thanks to all who have contributed!

Particular thanks go to

• T. Mitsuhashi (KEK)
• U. Iriso (ALBA)
• S. Mazzoni (CERN)
• I. Chaikovska (IJCLab/IN2P3-CNRS)
• A. Santamaria, E. Bründermann (KIT)
Beam diagnostics for the FCC-ee

- A first conceptual design of the FCC-ee BI has been performed for the CDR
- No feasibility issues
- Long list of technological challenges ahead of us
- Benefitting from the R&D for low-emittance ring / linear colliders / FEL communities

→ T. Lefevre, FCCW 2019, 27 June 2019, Brussels
→ T. Lefevre, FCCW 2020, 12 November 2020
FCC-ee Layout

Collider rings
C ≈ 97.8 km

Main Booster Ring (BR)
C ≈ 97.8 km, 20-182.5 GeV

Pre-Booster Ring (PBR)
C ≈ 6.9 km (SPS), 6 – 20 GeV

e⁺e⁻ S-band Linac (2.8 GHz RF)
L = 222 m, 6 GeV

e⁺ Damping Ring (DR)
C ≈ 97.8 km, 1.54 GeV
FCC-ee beam parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>Z</th>
<th>WW</th>
<th>H (ZH)</th>
<th>ttbar</th>
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<tbody>
<tr>
<td>beam energy [GeV]</td>
<td>45</td>
<td>80</td>
<td>120</td>
<td>182.5</td>
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<tr>
<td>beam current [mA]</td>
<td>1390</td>
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<td>29</td>
<td>5.4</td>
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<td>no. bunches/beam</td>
<td>16640</td>
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<td>393</td>
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<tr>
<td>bunch intensity $[10^{11}]$</td>
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</tr>
<tr>
<td>bunch length with SR / BS [mm]</td>
<td>3.5 / 12.1</td>
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- High beam intensity and large dynamic range
FCC-ee beam parameters

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- High beam intensity and large dynamic range
- **Small Emittances**
FCC-ee specifics

• **High luminosity regions**
  • High radiation level close IP’s

• **High beam intensity**
  • Wakefield effects inducing heat load

• **High SR power in the arcs** would produce high X-ray dose requiring
  • Shielding (design dependent on beam energy, i.e. SR critical energy)
  • Radiation hard electronic design

BPM & BLM: radiation hard electronic design

— 6000 BPMs —
up to 400 W dissipated
→ active cooling
BEAM-LOSS MONITORING
Beam loss monitoring

- Large energy stored in both Main and Booster beams
  - BLM in the arcs should not be sensitive to X-ray
  - Identifying beam losses from all different beam lines may not be trivial
    - Main rings: Detectors sensitive to beam propagation
    - Main vs booster ring: Possibly having quadrupoles at different locations?

- Optical BLM system based on Cherenkov fibres
  - High directivity
  - Only measures charged particles

Many experimental investigations initiated within Linear collider study

- RF studies (Breakdown and Dark current): M. Kastriotou et al., “A versatile beam loss monitoring system for CLIC”, IPAC, Busan, Korea, 2016, pp. 266
A Fiber Beam Loss Monitor (FBLM)

- Optical fiber attached to the vacuum chamber.
- Electromagnetic shower generated when the main beam hits the vacuum chamber or any obstacle.
- Cherenkov radiation produced in the optical fiber by the electromagnetic shower.
- The fiber ends are coupled to the PMTs.
- Cherenkov light converted to an electrical signal containing the information about the position and intensity of the beam losses.

Requirements for the fibers:
- High photon yield (large core fibers)
- No scintillation in the fiber (long decay time => worse BL position resolution)
- High optical transmission
- Radiation hardness.

Courtesy I. Chaikovska (IJCLab/IN2P3-CNRS)
The FBLM system has been installed at PHIL and its functionality has been proven.

The measured position accuracy allows resolving the beam losses occurring as close as 30 – 40 cm with the 25 m fiber along the vacuum chamber.
ULTRA-LOW EMITTANCE MEASUREMENT

transverse beam size and profile
Beam Size: Prototype X-ray interferometer at KEK

Vacuum Chamber and Linear Stage - received

Plan to install the full system on an X-ray beam line at SuperKEKB in next spring shutdown

T. Mitsuhashi (KEK)
Beam Size: Heterodyne Near Field Speckles

FCC-Collaboration between CERN, Univ. Of Milano and ALBA

**GOAL:** Alternative way to measure the beam size

- Procedure: analyze the interference of the photon beam with Silica nanospheres suspended in water
- From this interference pattern (called speckles), we obtain the photon beam coherence, and from it, we derive the beam size

![Speckle pattern with water](image1)

![Speckle pattern with colloids](image2)


![Water and Silica capillaries](image3)

Courtesy U. Iriso (ALBA)
Test of Heterodyne Near Field Speckles at ALBA

Many lessons learned, setup and signal visibly improved over the years

Raw Power Spectrum

V profile

Oct 2018

Sept 2020

Courtesy U. Iriso (ALBA)
LONGITUDINAL CHARGE DENSITY PROFILES

bunch length, shape, and structures
Bunch length: dielectric buttons at CLEAR

Detection performed at 30 and 60 GHz using Schottky diodes

Using Dielectric buttons producing Cherenkov Diffraction radiation as a source of radiation

Measured Bunch length using RF spectrometry

Bunch by bunch resolution possible

Senes et al, “A dielectric beam position monitor for short bunches of charged particles”, to be submitted
Bunch-by-bunch longitudinal profiles

FCC-ee bunch profiles are strongly affected by beamstrahlung in collision

high-throughput electro-optical single-shot diagnostics developed at KIT

Near-field electro-optical spectral decoding

high-throughput electro-optical single-shot diagnostics with MHz rep. rates (EU XFEL, light sources)

L. Rota et al., *NIM A*, 936, pp. 10-13, 2019
Pulse diagnostics, e.g., for THz signals

- **KAPTURE readout electronics for fast sensors**
  - Picosecond sampling system
  - Up to 1 GHz trigger rate
  - Up to 8 sampling points per detector pulse
  - Readout by PCIe up to 64 Gb/s continuously
  - Real-time data elaboration by GPUs

- **Scalable, multi-purpose, e.g.**
  - Modular setup
  - Simultaneous readout of multiple sensors
  - Online pulse-shape reconstruction

**KAPTURE working principle**

- Detector signal
- Real-time sampling
- Amplitude (mV)
- Time
- Rep. rate: from 550 ps to 5 ns

M. Caselle et al., *JINST* 072P_1116 (2016)
The full picture…. at 2.7 MHz

**KARA test facility**
- Circumference: 110.4 m
- Energy range: 0.5 - 2.5 GeV
- Revolution frequency: 2.715 MHz
- RMS bunch length: 45 ps (for 2.5 GeV) down to a few ps (for 1.3 GeV)

M. Brosi et al., IPAC19, https://doi.org/10.18429/JACoW-IPAC2019-WEPTS015
Photonic time-stretch recording of long. profile

Serge Bielawski et al., *Scientific Reports, 9*(1):10391, 2019
**Photonic time-stretch recording of long. profile**

Serge Bielawski et al., *Scientific Reports*, 9(1):10391, 2019
Phase space interpretation of bunch profile measurements

Phase space interpretation of bunch profile measurements

*INOVES Simulation:*

- Short unstructured bunch
- Micro-structures appear + increase of bunch size
- Micro-structures disappear

Phase space reconstruction, ...

...validation with simulations, ...

...and application to beam measurements

a Experimental data

\[ \Delta t (\text{ps}) \]

\[ \Delta t (\text{ps}) \]

signal (arb. units)

mean bunch profile

18.20 18.70
19.20 19.70 20.20

\[ t (\text{ms}) \]

The dynamic cycle is reproduced by subsequent measurements

b Dynamic cycle of the micro-structures

- unstructured
- rapid formation of micro-structures with complex dynamical evolution
- fading

@ 40 % subtraction

Turn-by-turn dynamics during the microbunching instability

Demonstration at KARA test facility

- reconstruction time for complete phase space image: 61 µs
- „Randon morphing“ between independent measurement

AI: fast detection - fast feedback?

Vision: Controlling instabilities in autonomous accelerators

Andrea Santamaria Garcia, et al. (KIT)
Conclusion and next steps

- A first conceptual design of the FCC-ee BI has been performed for the CDR
- No feasibility issues
- Long list of technological challenges ahead of us
- Benefitting from the R&D done in low-emittance ring / linear colliders / FEL communities.
- Next step is to launch the FCC-ee specific R&D work to provide a realistic suite of beam diagnostic with a more precise cost estimation
Thank you for your attention.