BEAM DIAGNOSTICS FOR FCC-ee

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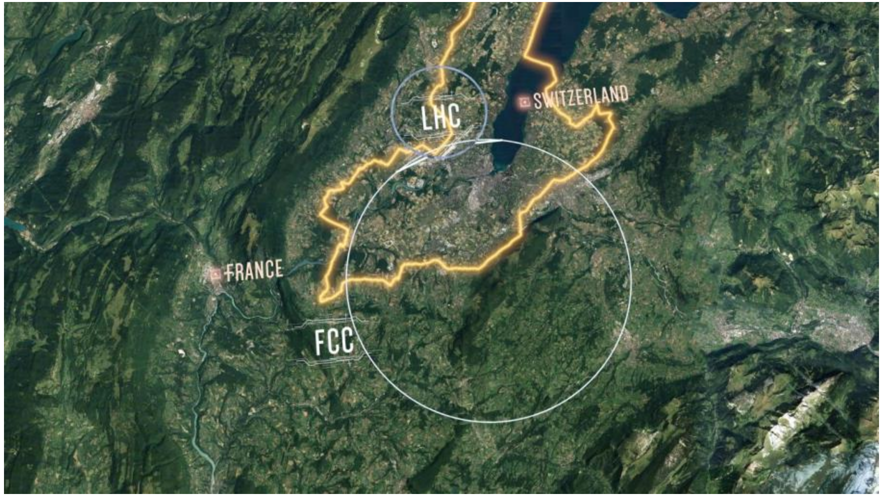

Fig 1: Schematic of the FCC tunnel footprint compared to the LHC. It would be underground, in the area around Geneva. [1]

OVERVIEW OF THE FCC-ee

The FCC-ee: Introduction

- The FCC-ee is a proposed electron-positron collider at the precision frontier of high energy physics, providing an electroweak and Higgs factory.
- It would be 90.7 km in circumference, constructed underground in the Geneva area, where CERN is based.
- The FCC-ee would run at four energies and have four interaction points.
- The same tunnel could be used to house a hadron collider, FCC-hh, after the FCC-ee has finished.

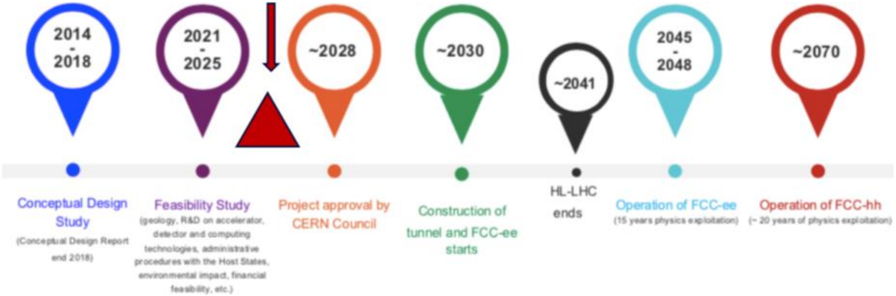

Fig 2: Proposed timeline for the FCC. [2]

Fig 3: Circumference of the FCC superimposed over a map of the Barcelona area.

OVERVIEW OF BEAM INSTRUMENTATION FOR FCC-ee

The FCC-ee: Challenges for BI

- High levels of **synchrotron radiation** in arcs (50 MW per beam) – shielding needed.
- **Large distances** – optical fibres must be used, over 300 km of accelerator to be instrumented.
- Small emittance and small beam size at **interaction point** – challenges measuring beam profile and emittance, strict alignment requirements.
- **Different operating modes** – high beam current in Z pole mode means all devices must have very low coupling impedance to minimise **beam heating**, but function sufficiently at the lowest beam intensities.

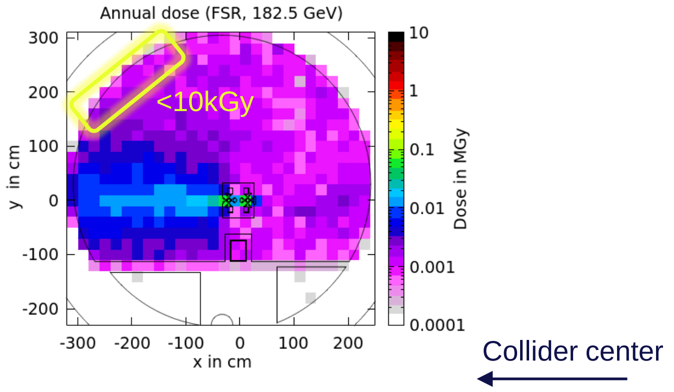

Fig 4: Dose levels in tunnel cross section at quadrupole, with shielding as detailed in the feasibility study report. Courtesy of B. Humann. [3]

Mode	Z	WW	ZH	ttbar
Bunch intensity, 10^{11}	2.14	1.45	1.15	1.55
Bunch charge, nC	34.3	23.2	18.4	24.8
rms bunch length (SR/BS), mm	5.6/15.5	3.5/5.4	3.4/4.7	1.8/2.2
Number of bunches/beam	11200	1780	440	60
Bunch spacing, ns		25		
Beam current, mA	1270	137	26.7	4.9

Table 1: Beam parameters of the different operating modes of the FCC-ee collider. [4]

BI for FCC-ee

Instrument	Main tunnel	Injector + TLs	Total
Position	8855	862	9717
Losses	26544	200	26744
Intensity	15	15	30
Transverse profile	21	35	56
Longitudinal profile	6	14	20
Beamstrahlung monitors	8	0	8
Polarimeter	2	0	2

Table 2: Numbers of different BI systems needed, to be confirmed. [5]

- Large collaboration with regular meetings focusing particularly on devices related to machine protection, devices with large impact on cost (e.g. BPMs) and systems requiring significant R&D.
- Due to large numbers of systems; reliability, automation, and cost optimisation are important considerations.
- No show stoppers identified, but lots more to be done by the collaboration!

Some of the institutions contributing to the FCC BI collaboration.

ARC BPMs FOR FCC-ee

FCC-ee BPM Requirements

- The FCC arc BPMs, and most other FCC BPMs, will use button pickups.
- Shall provide orbit, turn-by-turn and bunch-by-bunch measurements.
- High resolution requirements (see Table. 3).
- Small beam impedance → minimise heating, at the expense of smaller signals and resolution.
- Need to be reliable, rad tolerant electronics.
- Within cost budget.
- Need to fulfil requirements at all operational modes and will also be used in commissioning.

BPM Parameter	Requirement
Orbit resolution	0.1 μm
TxT resolution	1 μm
Arc BPM accuracy	20 μm
CDR est. loss factor, 4000 BPMs	40.1 V/pC
Min bunch spacing	25 ns

Table 3: Requirements for FCCee arc BPMs.

Different modes of FCC-ee

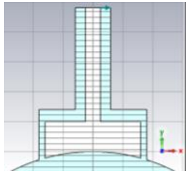

Fig. 5: BPM model used in CST

- A simplified 8 mm radius pickup was modelled in CST.
- This was simulated at the most extreme FCC-ee beam parameters: during injection for ZH mode and at 105% nominal charge before collisions at ZZ and ttbar mode.
- Difference of factor 18 between raw peak to peak.

Mode	ZH injection	Z, 105% nom.	$t\bar{t}$, 105% nom.
Raw peak to peak, V	62	1100	2200
Convoluted peak to peak, V	0.034	1.1	0.76
Est. res., m (only thermal noise)	6.90×10^{-6}	2.13×10^{-7}	3.09×10^{-7}
Wakeloss factor V/pC	1.06×10^{-3}	3.99×10^{-3}	1.75×10^{-5}

Table 4: Summary of CST results for extreme cases

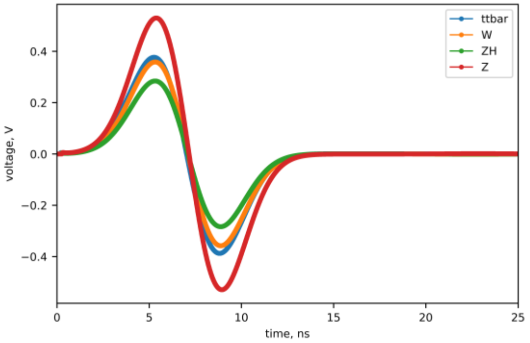

Fig 6: Signals from CST simulation of all 4 modes before collisions (SR), convoluted by a 75 GHz filter.

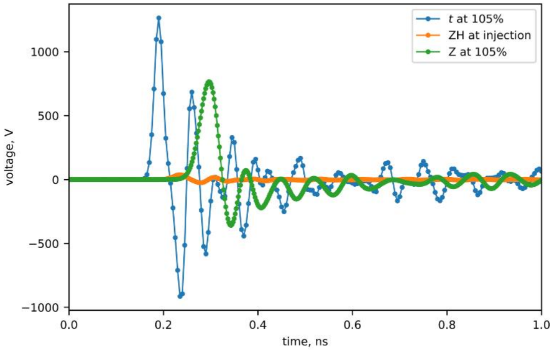

Fig 7: Initial part of raw signals in CST for the extreme beams.

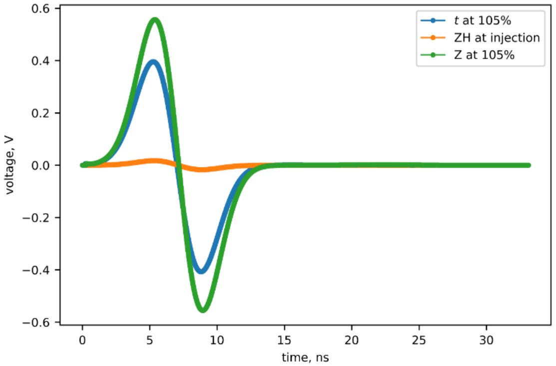

Fig 8: Signals convoluted by a 75 GHz filter.

Including Beam Pipe Winglets

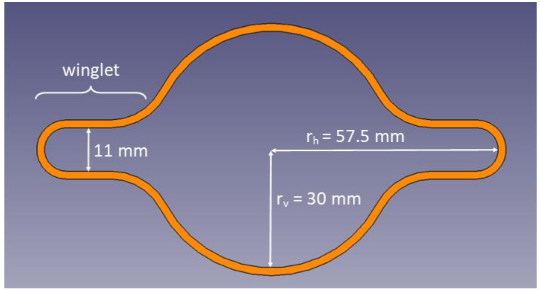

Fig 9: FCC-ee beam pipe cross section

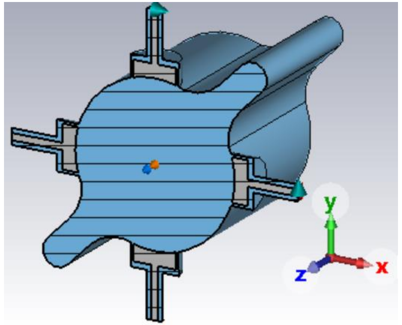

Fig 10: BPM model used in CST, skewed for ease of modelling.

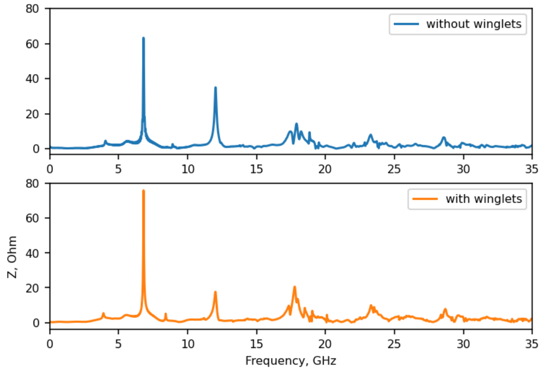

Fig 11: Wake impedance with and without winglets

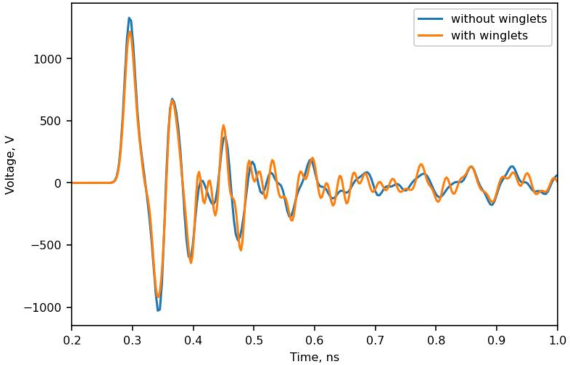

Fig 12: Voltage signal with and without winglets

- The FCC-ee beampipe has winglets to absorb synchrotron radiation.
- Simulating a simplified BPM in a beampipe with and without winglets showed that the winglets make a difference to the amplitudes of the resonances in the impedance, so should be included in future simulations.

EXPLORING GEOMETRICAL PARAMETER SPACE

Curved vs Flat Pickups

- Whether the pickup is flat, or curved to be flush with the beam pipe makes very little difference to either the voltage or impedance signal in this simulation.
- Smaller pickup radii will be considered, but not larger. With a smaller radius, the difference made by the curvature will be even less.
- Since flat pickups are easier to manufacture and align, future designs for FCC-ee will all have flat pickups.

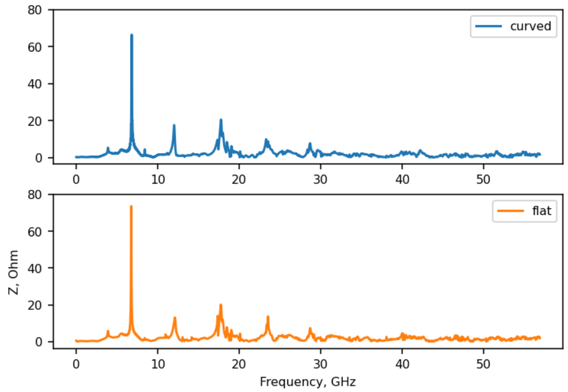

Fig 13: Wake impedance for curved and flat pickups

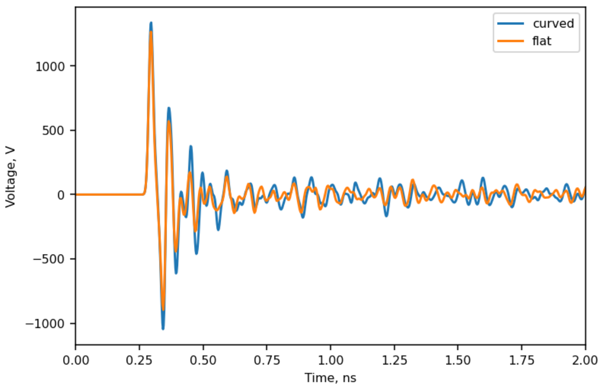

Fig 14: Voltage signal for curved and flat pickups

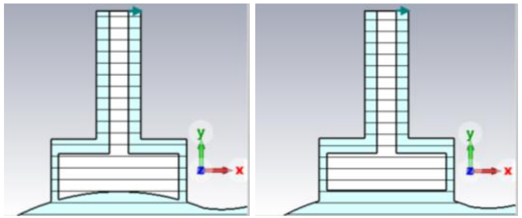

Fig 15: CST model of curved and flush pickups.

Varying Geometric Parameters of a Flat Pickup

- Wake-loss factor increases with both pickup radius and gap size. Back gap and height have negligible effect.

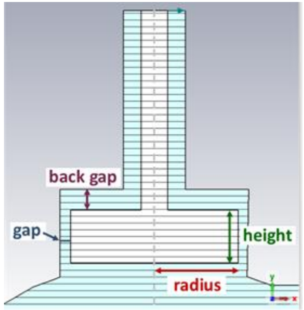

Fig 16: Simplified flat pickup with geometric parameters labelled.

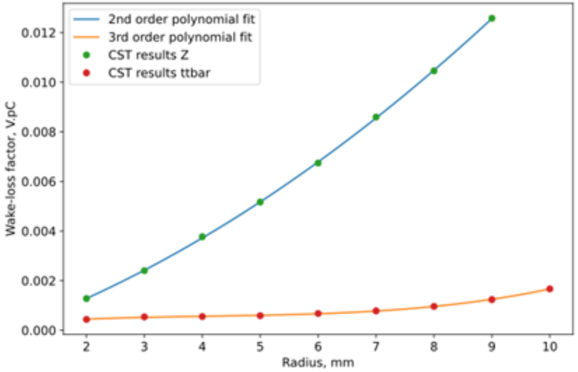

Fig 17: Wake-loss factor calculated within CST vs radius of the pickup

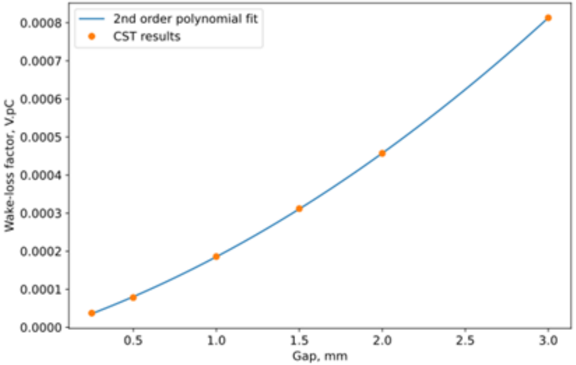

Fig 18: Wake-loss factor calculated within CST vs pickup gap, Z (BS) mode.

Varying Geometric Parameters of a Flat Pickup

- The peak to peak voltage signal (and therefore resolution) increases significantly with radius, increases slightly with gap size, and decreases slightly with back gap size. Height has negligible effect. .

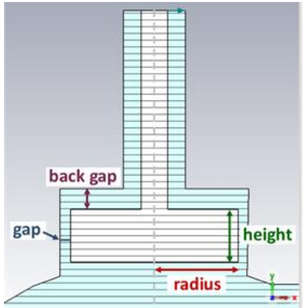

Fig 16: Simplified flat pickup with geometric parameters labelled.

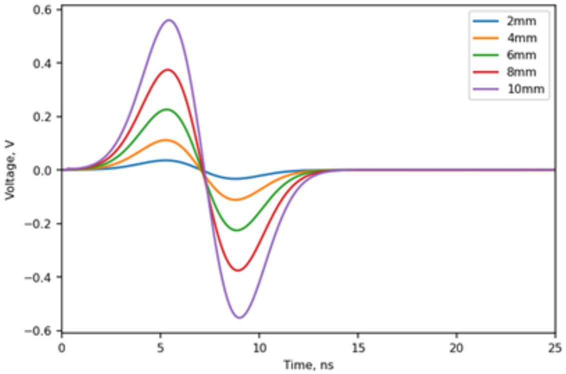

Fig 19: Voltage signal calculated vs time within CST for different pickup radii, ttbar (SR) mode, with a 75 MHz filter applied.

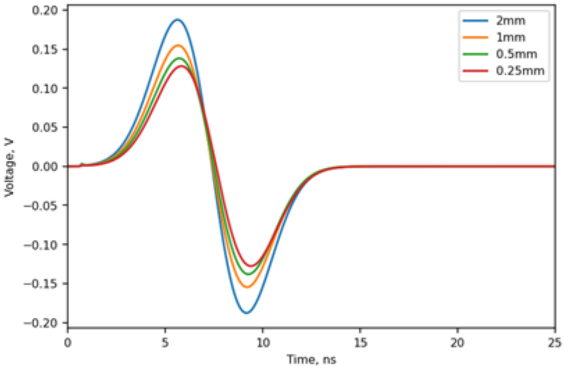

Fig 20: Voltage signal calculated vs time within CST for different pickup gaps, Z (BS) mode, with a 75 MHz filter applied.

Varying Geometric Parameters of a Flat Pickup

- The resonant peak amplitudes in the wake impedance spectrum increase with radius and gap. Increasing the back gap slightly decreases the amplitude of the largest peak. Pickup height has a slight non-linear relation with the amplitudes.

- The resonant peak frequencies in the wake impedance spectrum increase as radius decreases, and increase slightly in frequency as height decreases and back gap decreases. Gap size has negligible impact.

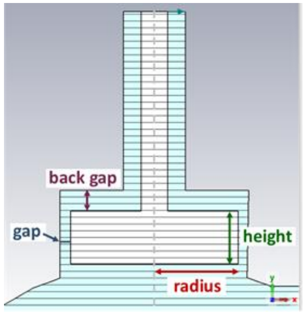

Fig 16: Simplified flat pickup with geometric parameters labelled.

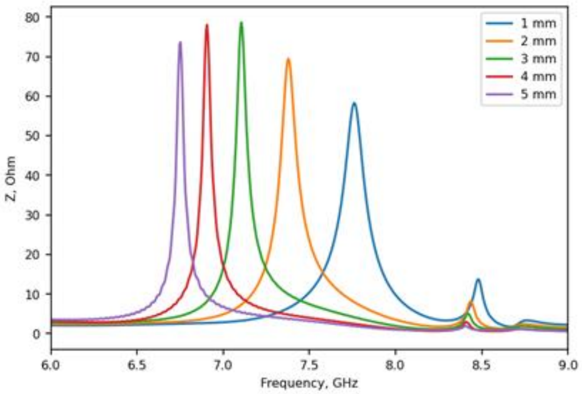

Fig 21: The largest peaks in wake impedance as a function of frequency for different pickup heights, ttbar (SR) mode.

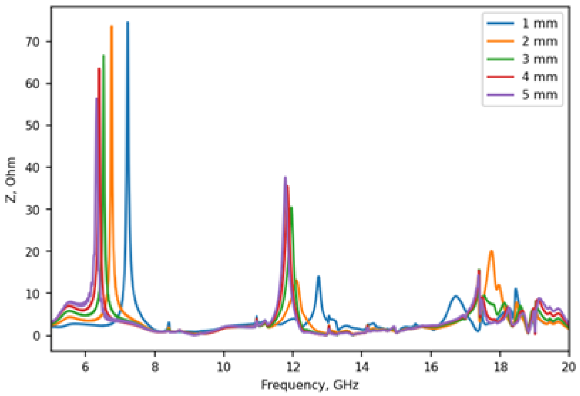

Fig 22: Wake impedance as a function of frequency for different pickup back gaps, ttbar (SR) mode.

Flat, Stepped and Conical Pickups

- Conical, flat and stepped buttons were simulated.
- Conical pickups pushed the resonant peaks in the impedance spectrum to higher frequencies compared to a flat pickup, which is beneficial due to the beam spectrum having a lower amplitude at higher frequencies.
- Stepped buttons had no advantage.

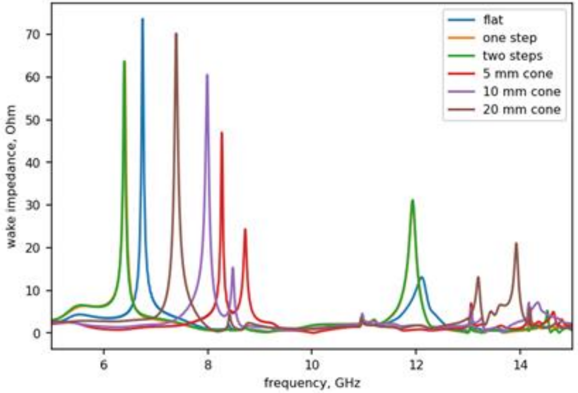

Fig 23: The largest resonance peaks in the wake impedance frequency spectrum for different pickup geometries, simulated in CST with the ttbar (SR) mode.

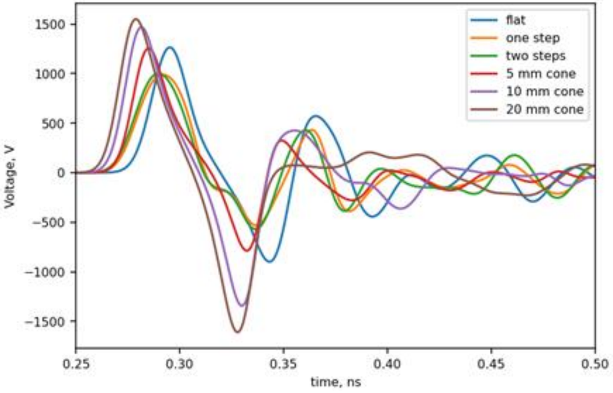

Fig 24: The initial voltage signal for different pickup geometries, simulated in CST with the ttbar (SR) mode.

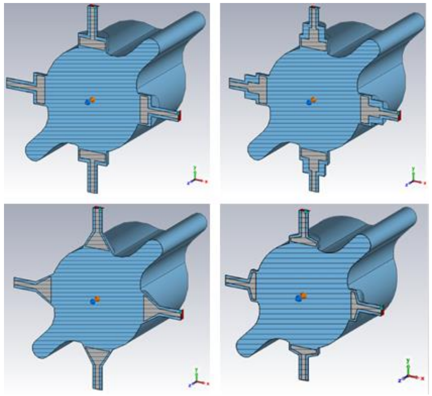

Fig 25: Cross-sections of some of the geometric models used in CST. From top left clockwise they are flat, stepped, conical and trapezoid.

Trapezoid Pickups

- Trapezoid pickups had a effect similar to conical pickups, whilst being easier to manufacture.
- CST results comparing a 1 mm tall flat button and a trapezoid button with a 1 mm parallel section and 1 mm cone are shown in Figs. 15-16.
- The trapezoid has a beneficial effect on the impedance and a similar voltage signal to the flat button.

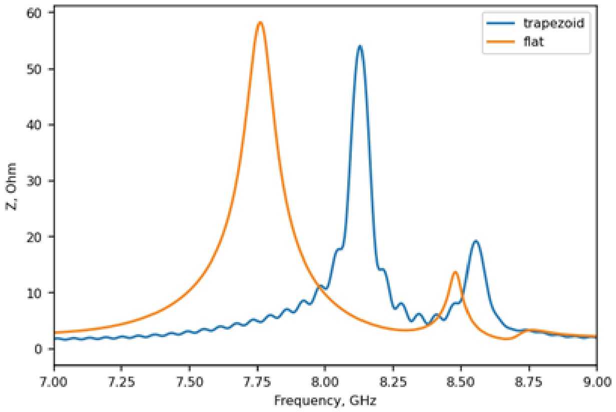

Fig 26: The largest impedance resonant peaks for a flat and a trapezoid pickup, simulated in CST with the ttbar (SR) mode.

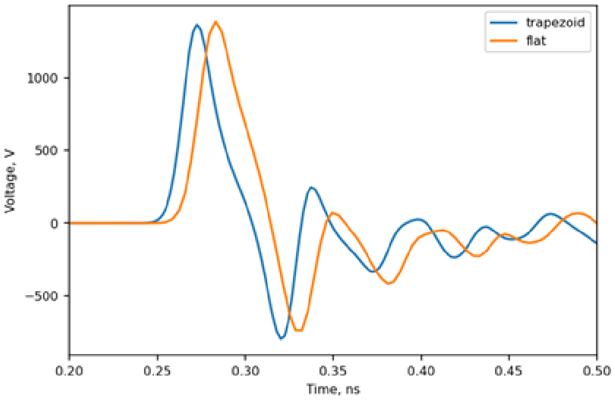

Fig 27: The initial voltage signal over time for a flat and a trapezoid pickup, simulated in CST with the ttbar (SR) mode.

Introducing Non-Ideal Materials

- More realistic material models were included in the simulations.
- The pickup was changed from PEC to steel, and a borosilicate glass vacuum seal held in place by a Kovar pin was added. The seal was based on a design from the AWAKE eBPMs.
- Peak to peak voltage in the ZH (BS) mode after a 75 MHz filter was applied was 0.2 V, suggesting a TxT resolution of 1.6 μm (only thermal noise). A different filter could improve this.
- This allowed for power distribution simulations to be conducted. Beam heating simulations are ongoing.

Power	With seal	Without seal
Total power	71.47 W	65.97 W
Power on 4 buttons	4.28 W	12.01 W
Power on Kovar of 4 buttons	48.38 W	/

Table 5: Summary of initial results from power loss studies using the ZZ (SR) mode, courtesy of Carlo Zannini.

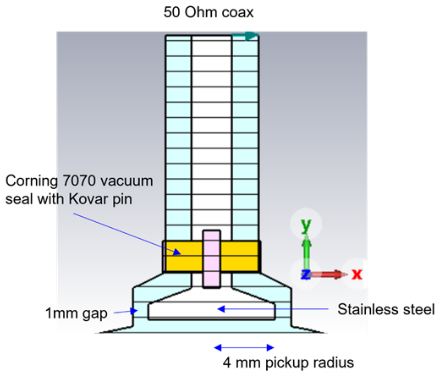

Fig 28: A cross-section of the pickup model used in the first power loss simulations.

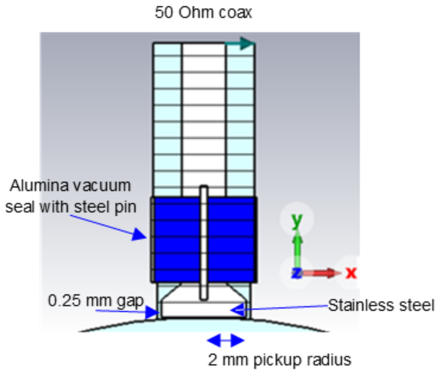

Fig 29: A cross-section of the pickup model currently in power loss simulations.

BENCH-MARKING MEASUREMENTS AT AWAKE

The AWAKE eBPMs in CST

- To benchmark CST results against measurements with beam, an existing BPM at AWAKE was used.

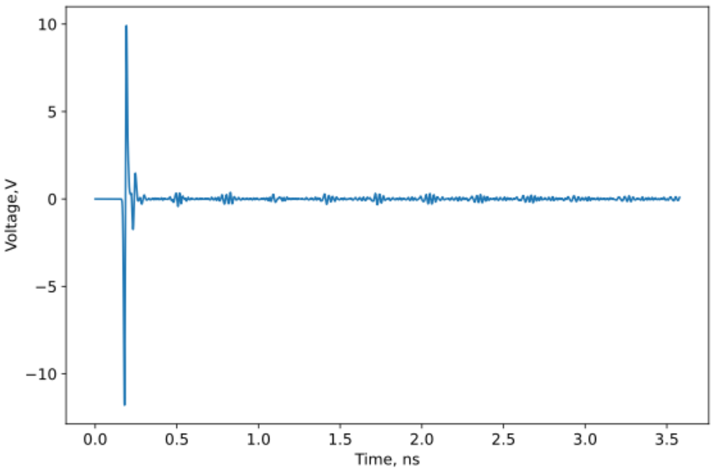

Fig 30: Voltage signal over time for the AWAKE eBPM simulated in CST.

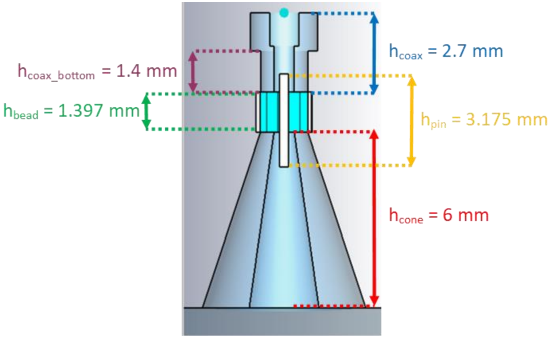

Fig 32: Cross-section of the CST model of the AWAKE eBPM. Model courtesy Bethany Spear.

The AWAKE eBPMs in CST

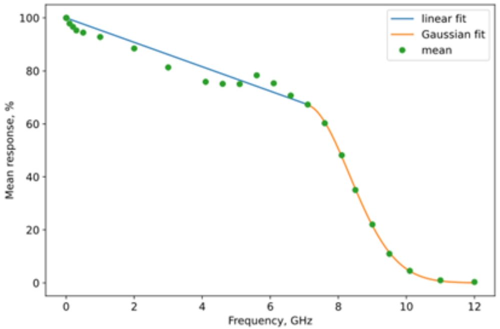

Fig 33: Oscilloscope measured response and model fit to it.

- The cable attenuation and oscilloscope response were applied to the CST voltage results.
- The result is shown in Fig. 21. The peak to peak voltage is similar, but the beam measurements show significantly more ringing.

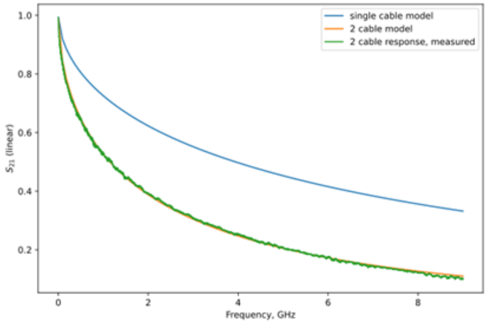

Fig 34: Measurement of cable response and model for half the length of cable.

Data Set	Peak to peak Voltage, V
CST with no compensation	21.69
CST with cable response	0.57
CST with cable and oscilloscope responses	0.21
Measured eBPM at AWAKE	0.26

Table 6: Summary of the CST and AWAKE eBPM benchmarking.

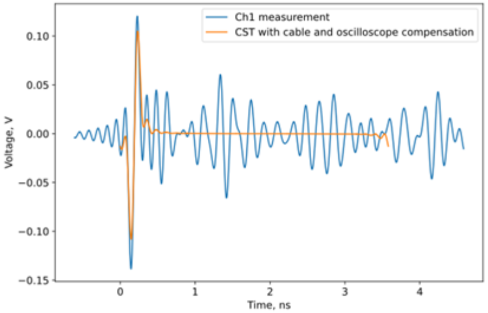

Fig 35: Measured voltage response over time of AWAKE eBPM compared with CST results, compensated for the cable and oscilloscope responses.

Further Benchmarking with PSI and CLEAR

- Broad-Band Pickups (BBPs) developed by N. Vallis at PSI were tested at CLEAR and SwissFEL.
- These measurements will both be compared with CST simulations and will benchmark how simulations compare to measurements at two different electron accelerators.
- LHC BPM pickups have been installed in CLEAR to test with an electron beam for further benchmarking against CST simulations.

1.05 mm radius antenna

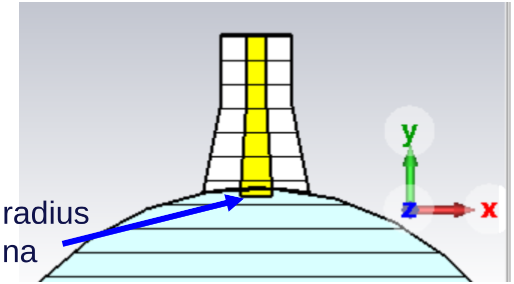

Fig 36: BBP CST model, courtesy N. Vallis.

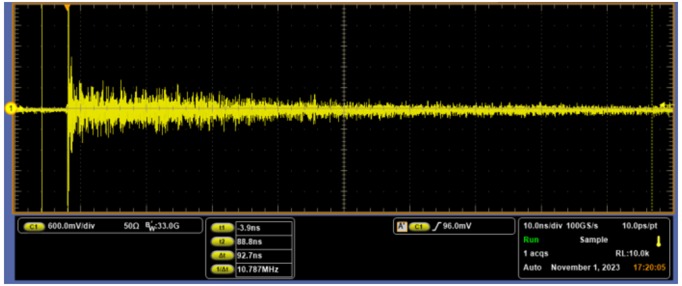

Fig 37: Signal from one of the BBPs on oscilloscope at CLEAR

FUTURE PLANS

Conclusions Future Plans

- A trapezoid button is the most promising geometry for the FCC-ee arc BPMs.
- Further optimisation is needed to reduce power loss to the BPM. This could include making the gap and radius smaller, but care must be taken to ensure resolution is still sufficient at low beam intensities. Alternative materials will also be studied.
- Different filters for the voltage signal will be simulated to determine effect on resolution.
- More exotic pickup geometries could be explored, such as asymmetric pickups.
- Further bench marking will take place using an LHC BPM installed at CLEAR.

Thanks for your attention!

References

[1] CERN's proposed 100-km particle accelerator would run rings around the LHC. [Online]. Available: https://newatlas.com/future-circular-collider-physics/58068/.

[2] FCC Week 2025 (19-23 May 2025): Welcome and Introduction · Indico. [Online]. Available: https://indico.cern.ch/event/1408515/contributions/6491862/.

[3] B. Humann, FCC Week 2025 (19-23 May 2025): Radiation environment in the FCC-ee arcs · Indico.[Online]. Available: https://indico.cern.ch/event/1408515/contributions/6526980/.

[4] B. Auchmann, W. Bartmann, M. Benedikt, et al., "Future Circular Collider Midterm Report," Tech. Rep.,2024.

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