Design Aspects of the Arc Beam Position Monitors of the FCC-ee

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Abstract

The electron-positron Future Circular Collider (FCC-ee) has challenging requirements for beam instrumentation, including the need for thousands of high-resolution beam position monitors (BPMs) presenting low impedance to the circulating beam. This poster details the requirements for the FCC-ee arc BPMs and presents the simulation results of BPM button pickups with various geometries, modelled with FCC-ee beam parameters. Applying results from benchmarking tests of already available button electrodes at AWAKE, a suggested geometry and expected performance are presented.

Requirements

- Electrostatic button BPMs, one per quadrupole, rigidly fixed.
- Shall provide orbit, turn-by-turn and bunch-by-bunch measurements.
- High resolution requirements (see Table. 1).
- Low beam impedance to minimise beam instability and heating, at the expense of resolution.
- Need to be reliable, have rad tolerant electronics and be within cost budget.

BPM Parameter	Requirement
Orbit resolution	0.1 μm
TxT resolution	< 10 μm
Arc BPM accuracy	20 μm
CDR est. loss factor, 4000 BPMs	40.1 V/pC
Min bunch spacing	25 ns

Table 1: Requirements for FCC-ee arc BPMs.

Varying Parameters of Flat Button

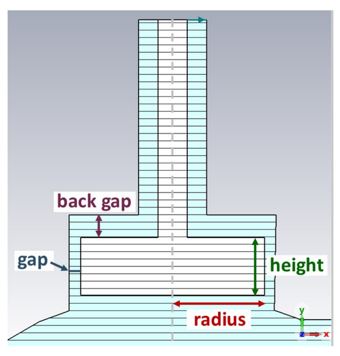

Fig 5: Simplified flat pickup with geometric parameters labelled.

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

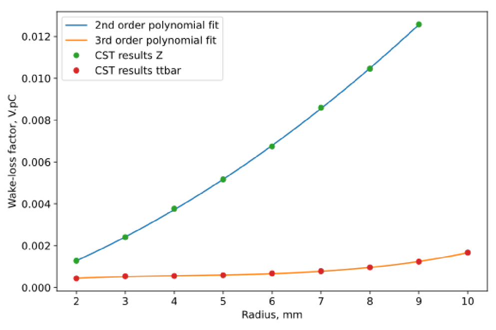

Fig 6: Wake-loss factor calculated within CST vs radius of the pickup

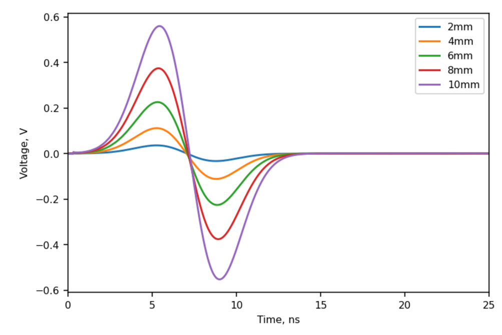

Fig 8: Voltage signal calculated vs time within CST for different pickup radii, ttbar (SR) mode, with a 75 MHz filter applied.

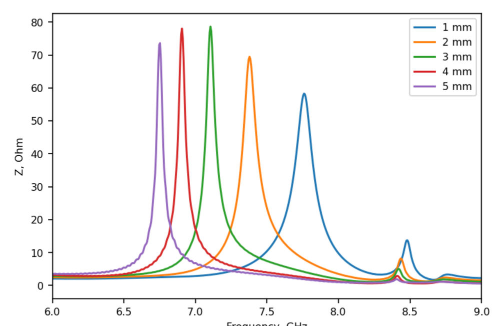

Fig 10: The largest peaks in wake impedance as a function of frequency for different pickup heights, ttbar (SR) mode.

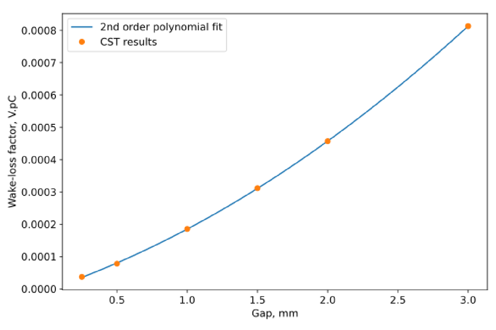

Fig 7: Wake-loss factor calculated within CST vs pickup gap, Z (BS) mode.

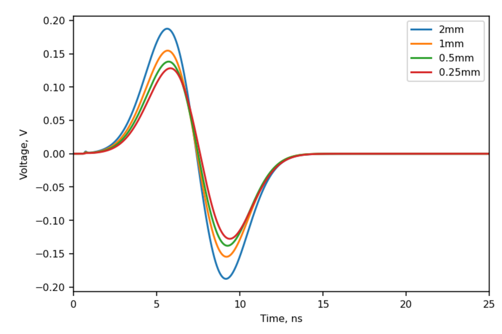

Fig 9: Voltage signal calculated vs time within CST for different pickup gaps, Z (BS) mode, with a 75 MHz filter applied.

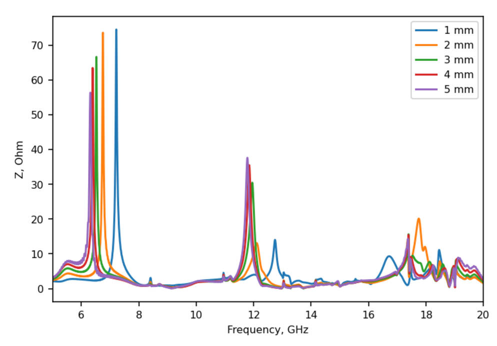

Fig 11: Wake impedance as a function of frequency for different pickup back gaps, ttbar (SR) mode.

Bench-Marking Studies

- Tests of an existing BPM at AWAKE have been used to benchmark CST results against measurements with beam.
- The cable attenuation and oscilloscope response, shown in Figs. 19-20 were applied to the CST voltage results to allow a comparison to be made.
- The result is shown in Fig. 21. The peak to peak voltage is similar, but the beam measurements show significantly more ringing.
- Other benchmarking measurements have been taken at SwissFEL and CLEAR using a broad-band pickup from PSI. Further bench marking is planned using an LHC BPM at CLEAR.

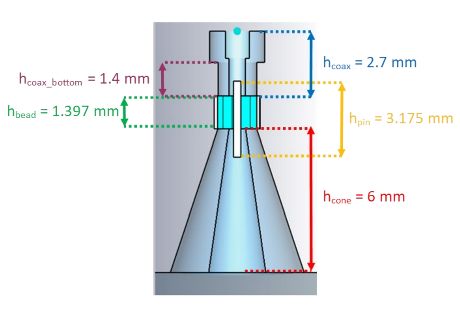

Fig 17: Cross-section of the CST model of the AWAKE eBPM. Model courtesy Bethany Spear.

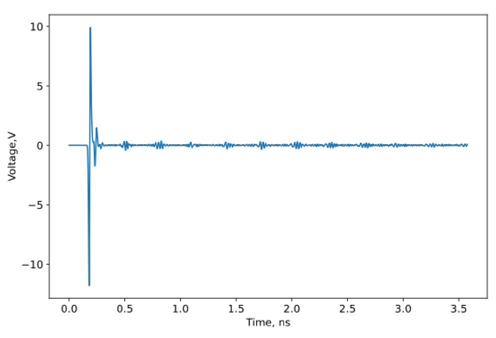

Fig 18: Voltage signal over time for the AWAKE eBPM simulated in CST.

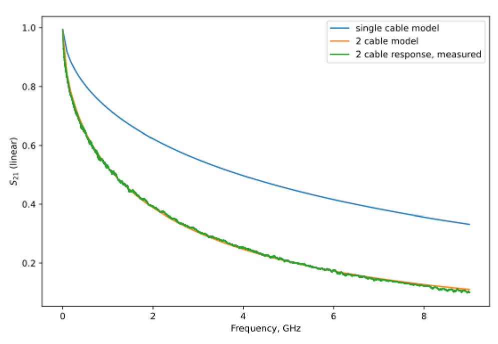

Fig 19: Measurement of cable response and model for half the length of cable.

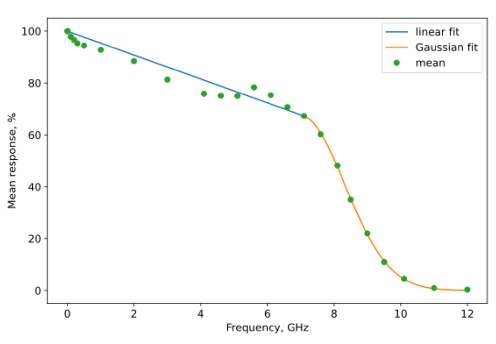

Fig 20: Measurement of oscilloscope response and the model fit to it.

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 3: Summary of the CST and AWAKE eBPM benchmarking.

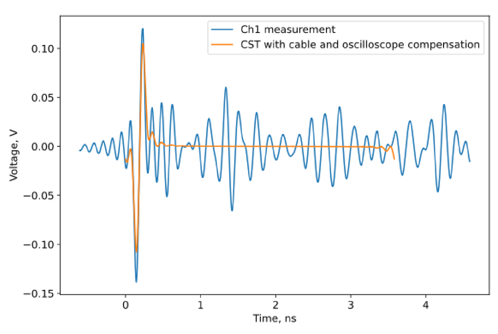

Fig 21: Measured voltage response over time of AWAKE eBPM compared with CST results, compensated for the cable and oscilloscope responses.

Response to Different FCC-ee Modes

- FCC-ee will run at several different beam modes, summarised in Table 2.
- The BPM must have sufficient resolution at the lowest beam intensity mode and acceptable impedance at the highest beam intensity mode.
- A simplified BPM was simulated at the different FCC-ee modes, with voltage results shown in Figs 1-3.

Mode	Z	W	ZH	$t\bar{t}$
Energy, GeV	45.6	80	120	182.5
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 with 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 2: Beam parameters of the different running modes of the FCC-ee collider from the CDR.

- There was a factor 18 difference between the raw peak to peak V of the lowest and highest intensity beams. Therefore the mode used has a significant impact on the BPM response.

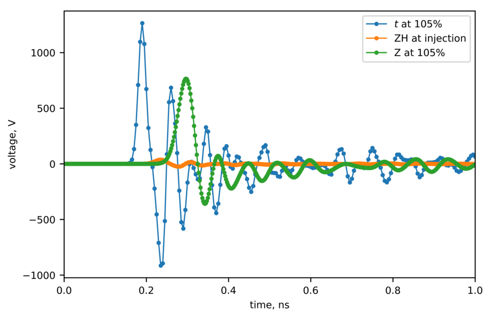

Fig 1: The Voltage signal from a simplified pickup simulated in CST for the most extreme FCC-ee beams.

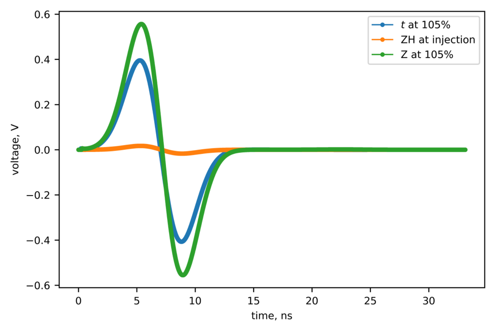

Fig 2: The Voltage signal from a simplified pickup simulated in CST for the most extreme FCC-ee beams, with a 75 MHz filter applied.

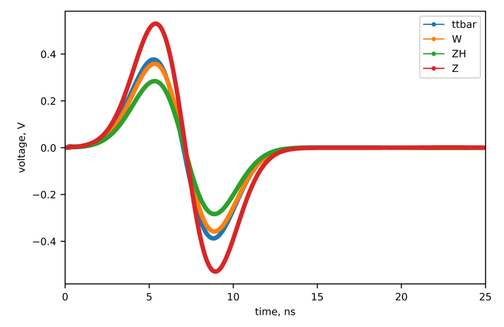

Fig 3: The Voltage signal from a simplified pickup simulated in CST for the SR FCC-ee beam modes, with a 75 MHz filter applied.

Stepped, Conical and Trapezoid Buttons

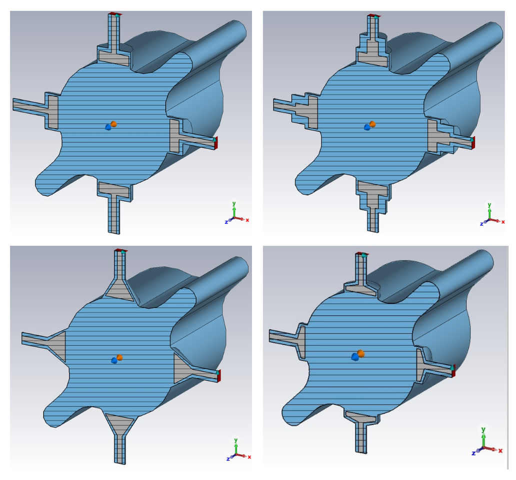

Fig 12: Cross-sections of some of the geometric models used in CST. From top left clockwise they are flat, stepped, conical and trapezoid.

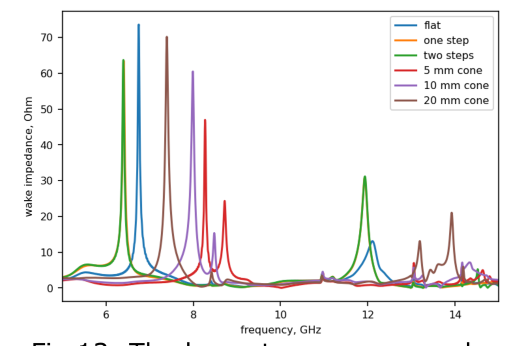

Fig 13: The largest resonance peaks in the wake impedance frequency spectrum for different pickup geometries, simulated in CST with the ttbar (SR) mode.

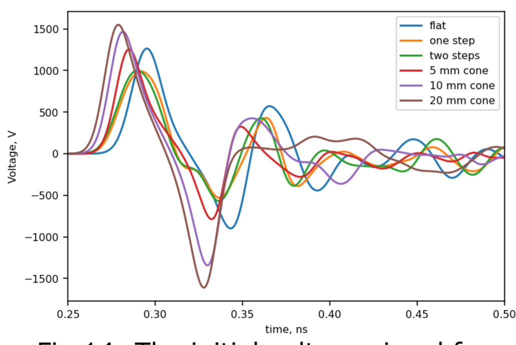

Fig 14: The initial voltage signal for different pickup geometries, simulated in CST with the ttbar (SR) mode.

- 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.
- 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.

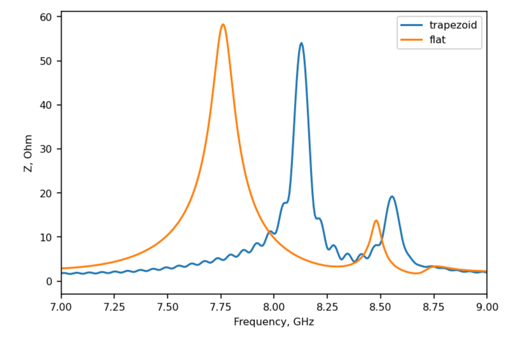

Fig 15: The largest impedance resonant peaks for a flat and a trapezoid pickup, simulated in CST with the ttbar (SR) mode.

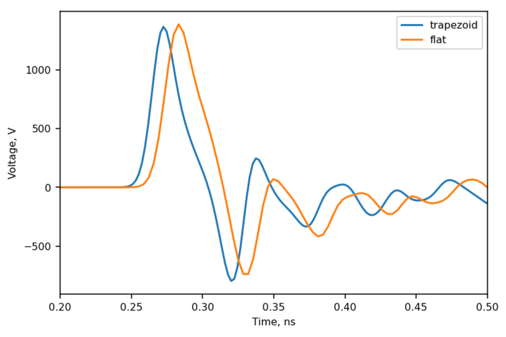

Fig 16: The initial voltage signal over time for a flat and a trapezoid pickup, simulated in CST with the ttbar (SR) mode.

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

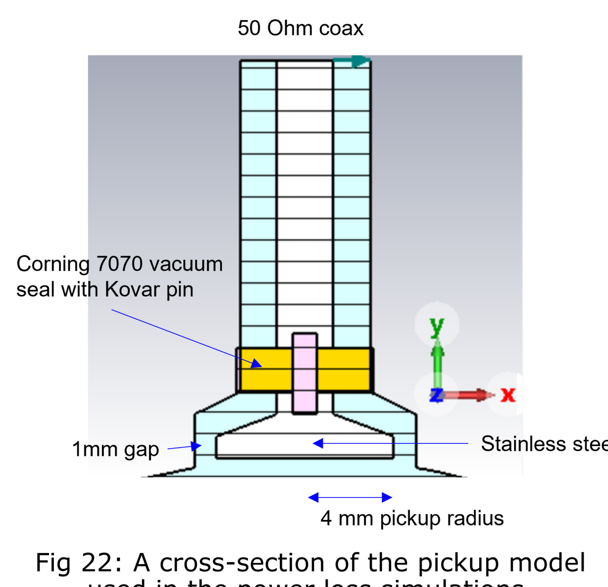

Fig 22: A cross-section of the pickup model used in the power loss simulations.

Conclusions and Next Steps

- 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.
- Beam heating studies ongoing will be analysed.
- 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.

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