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GEOMETRICAL STUDIES FOR 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 paper details the requirements for the FCC-ee arc BPMs and investigates button-type pickups with various geometries through electromagnetic simulations using FCC-ee design parameters. The simulation results are used to estimate key BPM characteristics, including impedance and heating.

INTRODUCTION

The FCC-ee is a 90.7 km circumference e^+-e^- collider proposed to be built at CERN [1]. It would operate at four key centre of mass energies and provide a Higgs factory at the precision frontier of high energy physics. This paper focuses on the BPM design for the arc sections of the collider ring.

The arc BPM system must deliver bunch by bunch, turn by turn and beam orbit measurements. The requirements for the arc BPMs are given in Table 1.

The impedance of the BPM shall also be low enough to prevent excessive heating of the button electrodes and to ensure beam stability. From the conceptual design report, 4000 BPMs in the collider, based on a design used at DANE, led to a total loss of 40.1 V/pC. This value was taken as an initial impedance budget for the BPMs [2]. However, due to heating concerns, the actual impedance may need to be significantly lower. The BPMs must also be reliable and have a suitable cost for mass production.

Table 1: Current Arc BPM Requirements

Parameter	Requirement
orbit resolution	0.1 µm
turn by turn resolution	1 µm
accuracy	20 µm
minimum bunch spacing	25 ns

These high resolution and low impedance requirements must be met across the four different running modes of the FCC-ee, as summarised in Table 2. They must also have sufficient resolution during commissioning, when the bunches would have a tenth of the nominal charge. The limits of heating must be met at the most extreme conditions foreseen. Simulations using CST Studio Suite show up to a factor 30 difference between the peak-to-peak voltage expected at the different extreme beam parameters.

Table 2: Beam Parameters of the FCC-ee at the Four Modes of Operation, the First Value for the Bunch Length is Before Collisions, and the Second, During Collisions [1]

Mode	Z	W	ZH	$t\bar{t}$
E [GeV]	45.6	80	120	182.5
Q_{bunch} [nC]	34.3	23.2	18.4	24.8
l_{RMS} [mm]	5.6/15.5	3.5/5.4	3.4/4.7	1.8/2.2
No. bunches	11200	1780	440	60
Bunch spacing [ns]	25			
I_{beam} [mA]	1270	137	26.7	4.9

This range of beam conditions makes it challenging to provide the required resolution at the lowest beam intensities, whilst maintaining acceptably low levels of impedance and heating at the highest beam intensities. Therefore, the geometry of the pickups must be optimised and suitable materials chosen.

BUTTON GEOMETRIES

Initially, a simplified BPM button was simulated with CST and the four dimensions highlighted in Fig. 1a were varied. A greater electrode peak-to-peak voltage corresponds to better resolution, while a smaller wake loss factor indicates a smaller impedance. The wake impedance as a function of frequency was also studied with the objective of mitigating resonances, either by reducing their amplitudes or by shifting them to higher frequencies, where the beam spectral content is smaller. The impact of each geometrical dimension on these figures of merit was explored to optimise the design.

In summary,

- **Peak-to-peak voltage**: increases significantly with the electrode radius, increases slightly with gap size, and decreases slightly with back gap size, whilst height has a negligible effect.
- **Wake loss factor**: increases with both radius and gap size, whilst back gap and height have negligible effect.
- **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.

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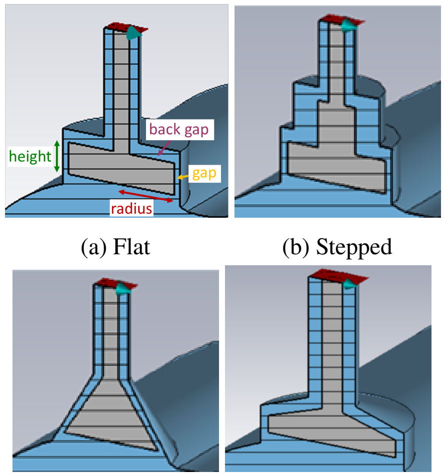

(a) Flat (b) Stepped

(c) Conical (d) Trapezoid

Figure 1: A labelled diagram of a flat BPM pickup, and perspective cross sections of other pickup geometries considered.

- **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.

Conical, flat and stepped buttons, examples shown in Fig. 1, were simulated. Conical pickups pushed the resonant peaks in the impedance spectrum to higher frequencies compared to a flat pickup. Stepped buttons were found to have no advantage. The wake impedance as a function of frequency for different shape pickups is shown in Fig. 2. For comparison, the beam spectra down to -20 dB for the operational modes with the widest (ttbar SR) and narrowest (Z BS) spectral content are also included.

Trapezoidal pickups have a response similar to conical pickups, whilst being easier to manufacture. CST results comparing a 1 mm tall flat button and a trapezoidal button with a 1 mm parallel section and 1 mm cone are shown in Figs. 3 and 4. The trapezoidal geometry improves the impedance characteristics and yields a voltage signal comparable to the flat button. Therefore, models of potential FCC-ee arc pickups will use a trapezoidal design.

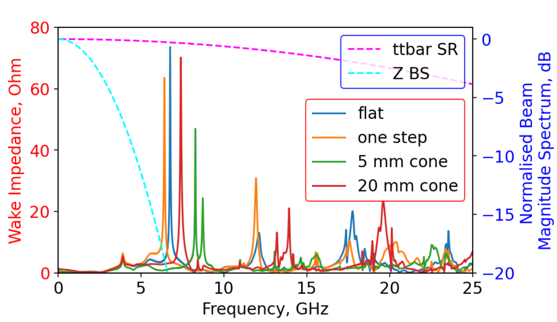

Figure 2: Wake impedance of conical and stepped buttons (solid lines) simulated in CST, along with the beam spectral content for operational modes with the widest and narrowest spectral content (dashed lines).

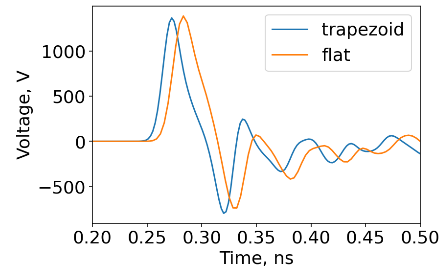

Figure 3: The results of CST simulations of 1 mm thick flat button and a trapezoid button with a 1 mm thick parallel section and a 1 mm high cone. These simulations used the parameters for the $t\bar{t}$ mode before collisions.

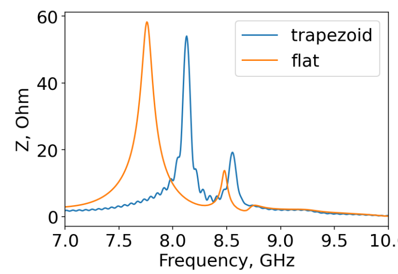

Figure 4: Wake impedance as a function of frequency, zoomed in to the first peak. The same models and parameters were used as in Fig. 3

POWER LOSS AND THERMAL STUDIES

Due to the high beam intensities expected in FCC-ee during runs with the Z mode, it is vital to model the expected power losses and resulting BPM heating, to ensure they remain within acceptable limits.

The first model submitted for power loss and thermal simulations is shown in Fig. 5. The results showed that there was a power loss of 50 W to the glass seal and pin, which would reach temperatures around 1000°C - well beyond the acceptable limit. Therefore, the BPM was redesigned to have a smaller radius and a smaller gap to reduce power loss. The seal material was changed to alumina as this has

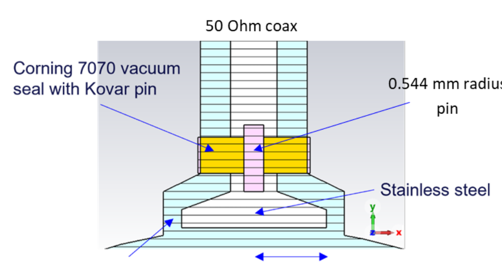

Figure 5: The first model submitted for power loss and thermal simulations.

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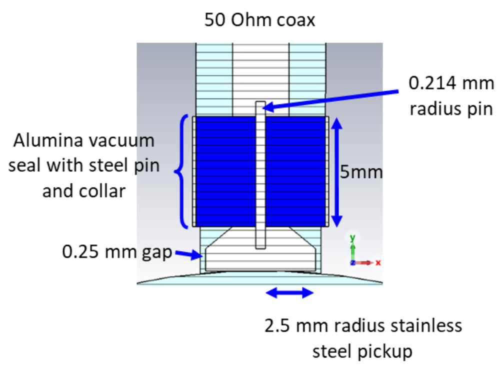

Figure 6: The model currently undergoing power loss and thermal simulations.

a thermal conductivity around 30 times greater than that of borosilicate glass. The new model is shown in Fig. 6.

To compare the difference made by changing the material and the difference made by changing the geometric parameters, the 4 mm radius design shown in Fig. 5 was also simulated with the seal material changed from borosilicate glass to alumina. The pin diameter was changed to maintain the 50 Ω impedance, while all other geometric parameters were kept constant. Similarly, the 2.5 mm model shown in Fig. 6 was simulated with a borosilicate glass seal and only the pin diameter changed. The maximum temperatures reached in each of these models is given in Table 3.

Table 3: The Maximum Temperatures Reached in the Thermal Simulations of Different Models of BPM Pickup Using the Z Mode Parameters and the Peak to Peak Voltage After a 75 MHz Filter Simulated for each Model Using the ZH Mode Parameters

Pickup radius, mm	Seal material	Max temp, °C	Filtered output in ZH mode, V_{pp}
4	glass	1148	0.308
4	alumina	1042	0.166
2.5	glass	384	0.107
2.5	alumina	265	0.0569

BENCHMARKING STUDIES

Measurements of an electron beam were taken using pre-existing BPMs at AWAKE [3]. A schematic of these BPM buttons is shown in Fig. 7. The measurements were benchmarked against CST simulations, to allow for more accurate prediction of the FCC BPM performance in reality, using only the CST results. One result from the AWAKE BPM benchmarking is shown in Fig. 8. The peak to peak voltage is similar but significantly more ringing is present in the measured signal compared to the simulated response. This could be due to resonances in structures not included in the CST simulation, such as bellows. The discrepancy is being studied. Analysis is ongoing of further benchmarking measurements taken at CLEAR and SwissFEL [4, 5].

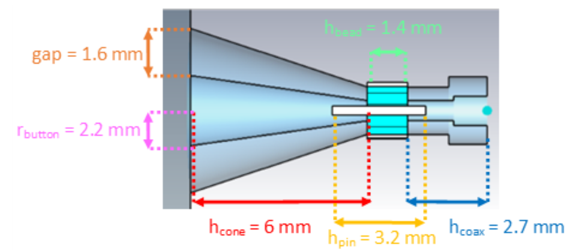

Figure 7: Cross section of the AWAKE BPM CST model, courtesy of B. Spear.

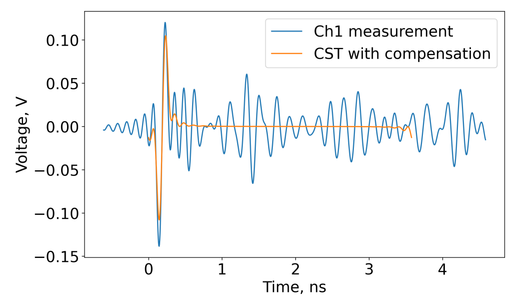

Figure 8: The voltage signals as a function of time for an AWAKE eBPM measurement and the CST simulation results, compensated for the cable and oscilloscope responses.

CONCLUSIONS

A trapezoidal pickup is used in the models for FCC-ee arc BPM pickups currently under study. Thermal simulations show that beam-induced heating will be significant in the Z mode operation, but can be mitigated by optimising the pickup geometry and selecting an insulator material with high thermal conductivity. Determining the expected resolution requires further study, as signal processing, analogue-to-digital conversion, and BPM sensitivity play significant roles. Further iterations of design modifications and thermal studies will be undertaken. Data from additional benchmarking measurements will be analysed. Once studies converge to a promising model, prototypes will be built and subsequently tested both in the laboratory and with beam.

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[3] AWAKE, https://home.cern/science/accelerators/awake

[4] CLEAR, https://clear.cern

[5] SwissFEL, https://www.psi.ch/de/swissfel