STUDIES OF UNUSUAL PICKUP GEOMETRIES FOR THE ARC BEAM POSITION MONITORS OF THE FCC-ee

E. Howling*, P. N. Burrows, John Adams Institute for Accelerator Science, Oxford, UK
M. Gasior, European Organization for Nuclear Research, Geneva, Switzerland

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 presents studies of different unusual pickup geometries including elliptical, asymmetric and retracted buttons. The impact of the different geometries on the simulated wake impedance and expected voltage signal of the pickups is explored and the potential benefits and disadvantages are described. These studies will inform the design of the FCC-ee arc BPM pickups.

REQUIREMENTS FOR FCC-EE BPMS

The FCC (Future Circular Collider) is a proposed collider project to be built at CERN, with the FCC-ee being the electron-positron machine stage of the project. It would be the largest ever operating accelerator, with high intensity electron beams, and high luminosity goals. Therefore the requirements for the performance of the arc BPMs are stringent, and the conditions they will be operating in are challenging. The resolution requirements are 0.1 µm for orbit, and 1 µm for turn by turn measurements [1].

The FCC-ee will have four different operational modes, each with a different set of beam parameters. The highest beam current will be 1270 mA during the Z mode [1]. To ensure the level of beam heating of the BPM is acceptable, the impedance of the buttons must be very low and the materials used must have suitable thermal properties.

Button BPMs typically have a circular button, but due to the challenging combination of high resolution and low impedance requirements for the FCC-ee arc BPMs, a more unusual geometry may be required.

ELLIPTICAL BUTTONS

Simulation studies using CST showed that elliptical BPM pickups with the longer axis of the ellipse along the z axis of the beam pipe have a smaller wake-loss factor than a round button of the same area [2]. The results suggest that elliptical buttons could be beneficial to reduce the impedance of the FCC-ee arc BPMs, as long as the wake potential ringing is sufficiently low so as not to interfere with the following bunch by an unacceptable amount.

To investigate whether elliptical buttons would be suitable for the FCC-ee arc BPMs, simulations of simplified elliptical buttons of different ratios were run in CST using FCC-ee beam parameters for the $t\bar{t}$ (SR) and Z (BS) operating modes

Table 1: FCC-ee Beam Mode Parameters Used [1]

Mode	Bunch charge [nC]	Bunch length [mm]
Z (BS)	34.3	15.5
$t\bar{t}$ (SR)	24.8	1.8

and the FCC-ee beam pipe. The two modes' relevant parameters are summarised in Table 1. SR and BS refer to whether just synchrotron radiation or also Beamstrahlung radiation respectively is taken into account when calculating the bunch length. Of the FCC-ee operating modes, the $t\bar{t}$ mode has the widest beam energy spectrum and the Z (BS) mode has the highest beam intensity during operation, so both are particularly important for resonance and impedance considerations.

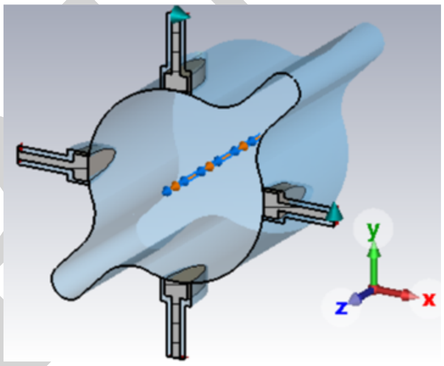

Figure 1: A cross section of the CST model of an elliptical button of ratio 4 in the FCC-ee beam pipe.

The area of the ellipse was kept constant. The 'ratio' refers to the length along the z axis of the button divided by the width along the x or y axis. A CST model of an elliptical pickup with ratio 4 in the FCC-ee beam pipe is shown in Fig. 1. The background is modelled as a perfect electric conductor (PEC) and the vacuum is shown as translucent. The beam pipe winglets are shown skewed, but in reality these would be along the x-axis and the BPMs skewed. However, this setup with the buttons on axis is more compatible with CST.

The CST simulations were run using both the 'direct' and 'indirect interfaces' wake integration settings. Both gave the same trends in results, but with slightly different values. If otherwise unspecified, the 'indirect interfaces' results are shown, as these tend to be more accurate for CST models with waveguide ports. The results for the simulated wake-loss factor for different ellipse ratios using the $t\bar{t}$ (SR) parameters are shown in Fig. 2, with a hyperbolic curve fit to them.

* emily.howling@physics.ox.ac.uk

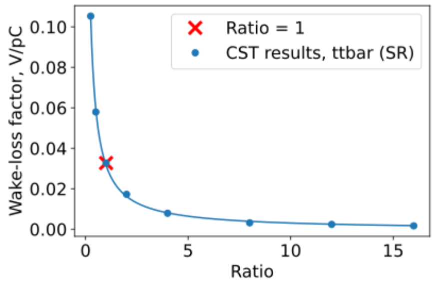

Figure 2: wake-loss factor vs ratio for elliptical buttons.

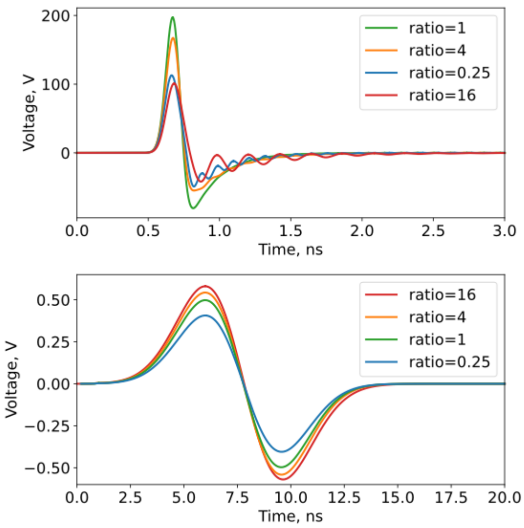

Figure 3: Voltage vs time for the simulated response of elliptical BPM buttons, unfiltered (top) and after a simulated 75 MHz filter was applied (bottom), using the Z (BS) parameters.

The voltage results from these simulations (Fig. 3) show that the more eccentric the ellipse, the lower the raw peak-to-peak voltage, with a ratio of 0.25 and 16 (same eccentricity) showing similar results. However, after a simulated 75 MHz Gaussian low pass filter (LPF) is applied, the higher the ratio, the greater the peak-to-peak voltage. This filtered version is likely to be closer to the signal expected after the FCC-ee arc BPM signal processing chain.

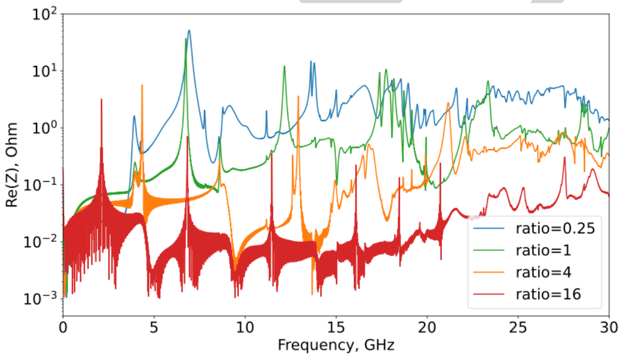

Figure 4: The real part of the wake impedance spectrum vs frequency for different ratio elliptical buttons, using the $t\bar{t}$ (SR) parameters.

The real part of the wake impedance spectrum for 4 different ratios (Fig. 4), shows that the smaller ratio buttons show resonant peaks of much higher amplitudes and greater widths.

The wake potential created by buttons of different ratios is shown in Fig. 5. The higher the ratio, the lower the initial amplitude of the wake potential, but there is slightly higher amplitude ringing for higher ratio buttons after a few metres. Depending on the gap between particle bunches at FCC-ee, this could cause issues due to bunches interacting with the bunches following. However, particularly for ratios less than 4, the increased ringing effect is not very significant.

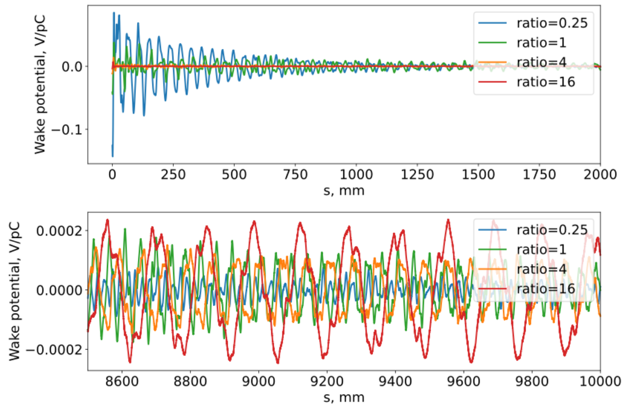

Figure 5: The wake potential vs distance for elliptical buttons of different ratios, showing the initial ringing (top) and the ringing after a few metres (bottom), using the $t\bar{t}$ (SR) parameters.

A higher ratio ellipse button is beneficial both in terms of reducing the wake-loss factor and increasing the filtered peak-to-peak voltage. Since the added benefits decrease as ratio increases, and ringing in the wake potential is greater for higher ratios, a ratio of 4 could be a good compromise between significantly reducing the wake-loss factor whilst keeping ringing in the wake potential low. This reduces the wake-loss factor by ~75% in the $t\bar{t}$ mode and ~25% in the Z (BS) mode compared to a circular button.

Other similar shapes were simulated and the results compared to the elliptical button: a pill-shaped and a rectangular button. The compared buttons all had an area of 64π mm^2 and a ratio of 4 between the length along the z axis and the length along the x or y axis. The peak-to-peak voltage after the 75 MHz LPF was the same to within 0.05 % for the three models. The wake potential for the rectangular button results showed some beating and slightly higher amplitude ringing after a few metres than the other models.

The wake-loss factors for the different models are summarised in Table 2. All the ratio-4 shapes have a lower wake-loss factor than the circular button, with the elliptical button having the lowest. Overall, the ellipse has the best properties of the four shapes for use in the FCC-ee arc BPMs.

Table 2: Wake-loss Factor for Different Button Shapes

Button shape	Wake-loss factor [V/pC]
Circle	3.27×10^{-2}
Ellipse	0.788×10^{-2}
Pill	1.34×10^{-2}
Rectangle	1.93×10^{-2}

ASYMMETRIC PICKUPS

In this case an 'asymmetric' pickup refers to a pickup with a non-constant gap, i.e. the button is off-centre of the hole it fits into. This asymmetry could reduce the amplitude of resonant peaks caused by the gap.

A simplified cylindrical BPM was simulated in the FCC-ee beam pipe model with $t\bar{t}$ (SR) beam parameters, and gap asymmetries created by offsets of the button (but not the feed-through pin) in the y and z directions. Only one button was offset of the four and in this case the 'direct' wake integration setting was used to reduce simulation time.

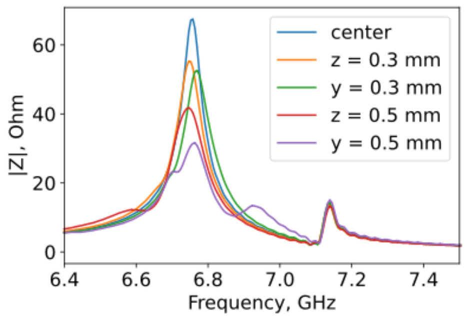

Figure 6: Magnitude of the wake impedance spectrum vs frequency for different button offsets.

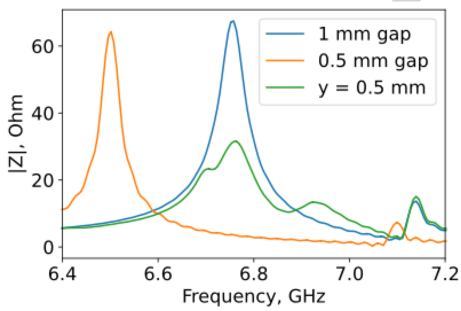

Figure 7: Magnitude of the wake impedance spectrum vs frequency for different gap sizes of an offset button.

The results showed that the greater the offset in any direction, the lower the amplitude of the largest resonant peak in the wake impedance spectrum, as shown in Fig.6. Offsets orthogonal to the beam direction had a slightly greater impact. The frequency of the largest resonant peak is similar for each model. The other resonances were not affected, nor was the peak-to-peak voltage response or wake-loss factor significantly different for each model.

The results for a circularly symmetrical gap of 1 mm and 0.5 mm were compared to a button with an mean gap of 1 mm, but offset so the minimum gap was 0.5 mm. All buttons had a radius of 8 mm. These results (Fig. 7) show that offsetting the button reduces the resonance peak amplitude to less than the largest resonance peak of an equivalent button with a smaller gap, whilst keeping it at a higher frequency, matching the largest resonant peak frequency of the model with the larger gap. Both these properties are beneficial, as higher frequency resonances typically interact less with the beam.

RETRACTED BUTTONS

The idea behind a retracted button is that it could be easier to manufacture and align, especially if an ellipse or other unconventional geometry is used. Rather than manufacturing a button with that shape, only the hole would need to be that shape. If the pickup material has a high thermal conductivity, it could also help reduce heating - a larger bulk of material could be used in the pickup, but with a large proportion of it screened from interacting with the beam so that the power loss to the pickup is equivalent to that of a smaller pickup, but with a greater mass of material to absorb it.

A model with a 3 mm retraction of an 8 mm radius button screened behind a 4 mm radius hole was compared to a 4 mm radius pickup at the beam pipe radius. There was an over 50 % reduction in peak-to-peak voltage when the button was retracted by 3 mm. Therefore, any advantage for the alignment and heating of the BPM is outweighed by the significant reduction in signal and retracted BPMs are not suitable for use in the FCC-ee.

CONCLUSION

Elliptical buttons of ratio 4 are a good candidate geometry for use in the FCC-ee arc BPMs. Other ratios greater than 1 are also worth considering. A pill shaped button shows similar properties to an elliptical button, and could be beneficial for manufacturing and alignment, but has properties overall not as advantageous as an ellipse.

It is beneficial to have slightly asymmetrical buttons, as this reduces the amplitude of the largest resonance in the wake impedance spectrum, whilst keeping the resonant frequency of the largest peak the same. Other ways of making the button more asymmetrical, such as offsetting the feed-through pin or having irregularly shaped gaps could be studied in the future to further reduce resonances.

Retracted BPMs significantly reduce the voltage response of the button, so are disadvantageous for the high resolution requirements of the FCC-ee arc BPMs.

The next steps would be to model a more realistic elliptical button in CST, with a vacuum seal and non-ideal materials. Then, once the design has matured, produce prototypes of elliptical BPMs for testing in the lab and with beam.

REFERENCES

[1] B. Auchmann *et al.*, “Future Circular Collider Midterm Report”, CERN, Geneva, Switzerland, 2024. doi:10.17181/mhas5-1f263

[2] A. Novokhatski *et al.*, “The design and electromagnetic analyses of the new elements in the FCC-ee IR vacuum chamber”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2508–2511. doi:10.18429/JACOW-IPAC2024-WEPR18