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A technical report on the:

Choice of the ESS BPM Button Sizes

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1. INTRODUTION

This technical report discusses the choice of the ESS BPM button sizes. A button style design similar to the European XFEL [1] is assumed for the Spokes and all the downstream linac sections. The BPM button voltage has been calculated using the transfer impedance method. A button size is then suggested based on the following two criteria:

1- The BPM voltage should be large enough so that by a reasonable amount of amplification (typically less than 20 dB) it can be matched to the ADC input range.

2- The BPM signal should be large enough so that it can be used for a rough position and phase measurement even if the beam is significantly de-bunched.

2. BPM VOLTAGE ALONG THE LINAC

The BPM voltage can be calculated using the method of transfer impedances [2].

$$Z_t(\omega,\beta) = \frac{1}{\beta c}\frac{1}{C_{button}}\frac{\pi a^2}{2\pi b}\frac{i\omega R C_{button}}{1+i\omega R C_{button}}$$

$$f_{cut} = \frac{1}{2\pi R C_{button}} \qquad \text{(Eq. 1)}$$

Here, β is the relative beam velocity, *c* is the speed of light, C_{button} is the parasitic button capacitance, *a* is the button diameter, *b* is the beam pipe diameter and *R* is the characteristic impedance of the BPM cable.

Then, the button voltage with a centred beam can be calculated by multiplying the BPM transfer impedance by the beam current:

$$V_{button}(\omega) = Z_t(\omega,\beta).\, I_{beam}(\omega)$$

In these calculations, the beam pipe diameter is assumed to be 40 mm in the MEBT, 20 mm in the drift tubes, 60 mm in the spokes and 100 mm in all the downstream linac sections after the spokes. Fig. 1 shows the BPM voltage as a function of BPM number assuming button diameters of 10 mm, 8 mm, 16 mm and 26 mm for the MEBT, drift tubes, spokes and downstream sections respectively. The bunching frequency was set to 352 MHz and the average beam current I_{DC} was set to 62.5 mA. C_{button} was assumed to be 1 pF and R was set to 50 Ohm in these calculations.

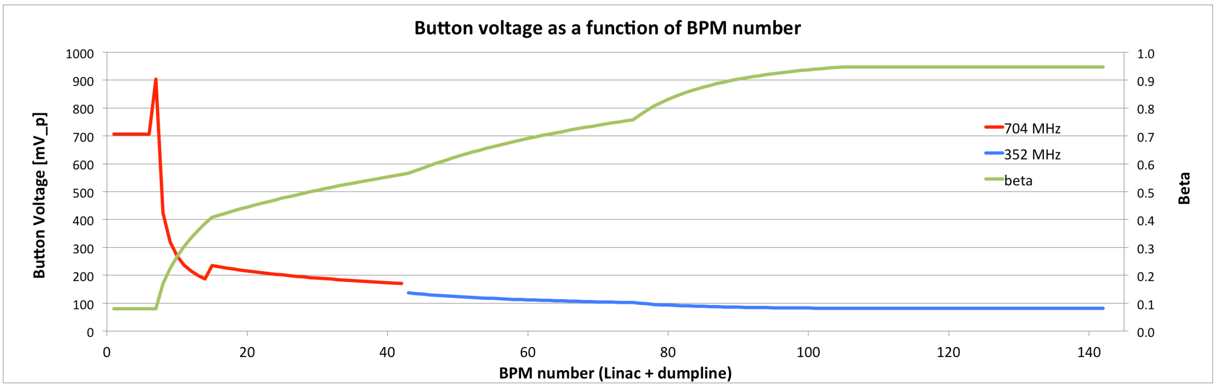

Figure 1: calculated button voltage as a function of BPM number. The dumpline section is added to the end of the linac. The exponential-like decays are due to the increase of the beam velocity and the sharp changes are mainly due to the variations in the beam pipe and button diameters. The processed frequency is 704 MHz in the spokes and the upstream sections and 352 MHz in all the other sections.

As the figure shows, the button voltage at low energies is relatively high. This is due to the low beam velocity[1] and small aperture. At high energies, the button voltage decreases to <100 mV_p and an amplification factor of ~18 dB (including cable attenuation) will be needed to match the voltage to the ADC input range (i.e. 2 V_{pp}).

From the perspective of voltage levels, it would be beneficial to have a larger button. The button size, however, cannot be made too large due to mechanical limitations and parasitic effects, ex. trapped modes. In the European XFEL design, the button diameter in the warm section is 16 mm with a beam pipe diameter of 40.5 mm [1]. By maintaining the same ratio for the ESS, the button size will be 24 mm for the 60 mm beam pipe and 40 mm for the 100 mm beam pipe. The button coverage angle in both cases will be 46°. Fig. 2 shows the button voltage along the linac with these button sizes.

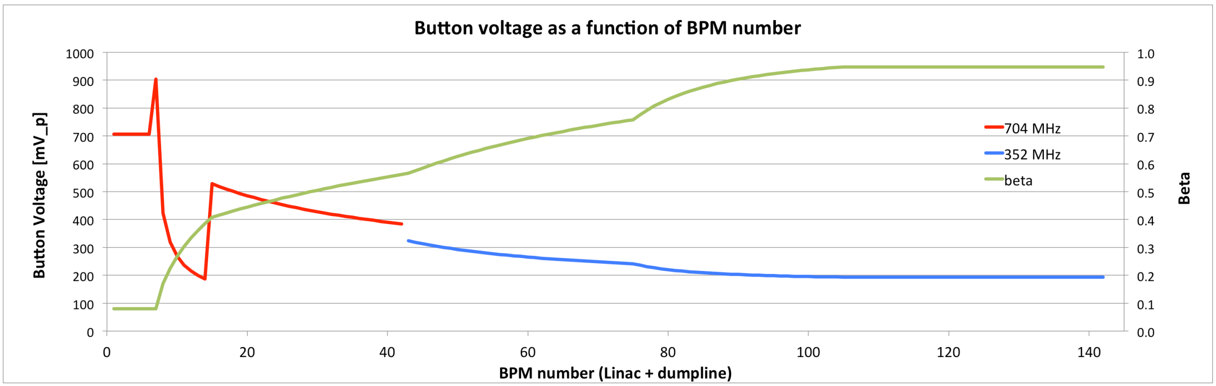

Figure 2: button voltage with button diameters of 24 mm and 40 mm for the beam pipe apertures of 60 mm and 100 mm respectively.

[1] The button voltage is proportional to the charge and the charge is inversely proportional to the beam velocity. The inverse proportionality of V_{button} to β is explicitly expressed in Eq. 8.4 in [7].

The button voltage at high energy now increases to 200 mV_p approximately and the required gain decreases to about 11 dB.

In the rest of this report, it is assumed that the 24 mm and 40 mm button sizes will be used for the 60 mm and 100 mm beam pipe apertures respectively unless otherwise stated.

In the MEBT and DTL[2] sections, the beam velocity will be low and even a small button will provide a large voltage. Although the mathematical model represented by Eq. 1 might not give accurate results with β values smaller than 0.5[3], it can be generally said that a button diameter in the order of 10 mm will give enough voltage.

2.1 BPM sensitivity

The BPM sensitivity can be calculated from the Eq. 2 [7].

$$\frac{R-L}{R+L} = \frac{4\sin(\phi/2)}{\phi}\frac{x}{b} + higher \quad order \quad terms \qquad \text{(Eq. 2)}$$

$$x \approx k.\frac{R-L}{R+L} \quad (mm)$$

With the 24 mm and 40 mm buttons, the sensitivity factor *k* has been calculated at 15 mm and 26 mm respectively.

2.2 BPM resolution

The BPM resolution can be calculated from the S/N ratio using the following equation [3]:

$$\sigma_X = \frac{b}{2}.\frac{\sqrt{2}\sigma_V}{2V} = \frac{b}{2\sqrt{2}}.\frac{1}{\sqrt{SNR}} \qquad \text{(Eq. 3)}$$

The noise has been calculated as the sum of the thermal noise and the effective input noise of the BPM RTM (Rear Transition Module) [4]. With the 24 mm and 40 mm button sizes and the 62.5 mA nominal beam, the resultant BPM resolution will be 3 µm and 9 µm respectively, meeting the BPM specifications.

By decreasing the beam current, the button voltage decreases accordingly degrading the S/N ratio and the resultant BPM resolution. With a beam current of 6.25 mA, the BPM resolution at the end of the spokes section is calculated at 31 µm and at the end of the linac it is calculated at 89 µm.

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[2] The type of the DTL BPMs is not decided yet. An alternative to the button BPM would be stripline BPM.

[3] This is because: 1) the electromagnetic field generated by the beam is not TEM anymore while the model is mainly valid for TEM modes. 2) in the MEBT, the beam might not be very well bunched.

3. BPMS FOR THE RASTERING SYSTEM

It is planned to use a rastering system upstream of the target station. The rastering system will use two sets of horizontal and vertical dipole magnets to paint the beam over a rectangular area on the target wheel, hence it uniformly spreads the power over a larger area to avoid damages to the target wheel [5]. Two BPMs are planned for the rastering system to measure the actual beam position and compare it to the expected one. These BPMs have to meet some additional requirements due to the large aperture, large beam excursions from the centre, high radiation level, limited space and expanded beam size [6]. These BPMs will need a special design; therefore they are not discussed in this report.

4. EFFECT OF THE PARASITIC BUTTON CAPACITANCE

The BPM transfer impedance presented by Eq. 1 has a high-pass characteristic. The -3 dB cut-off frequency depends on the cable impedance and the button capacitance. Figure 3 shows the calculated transfer impedance with the 100 mm beam pipe assuming C_{button}=1 pF.

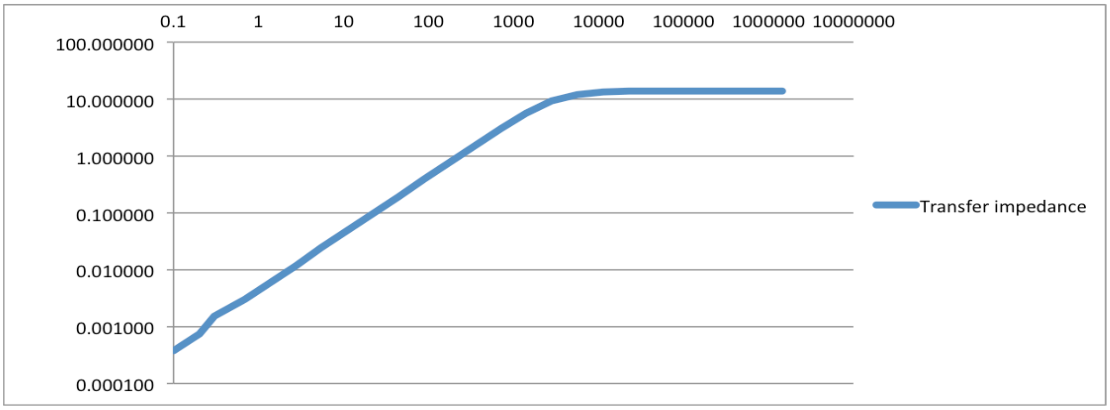

Figure 3: frequency response of the BPM transfer impedance. The horizontal axis is the frequency in MHz and the vertical one is the transfer impedance in Ohm. The working frequency (352 MHz in this case) is lower than the cut-off, resulting in an overall capacitive behaviour.

The cut-off frequency is about 3.2 GHz. As the working frequency will be significantly lower, the transfer impedance will have an overall capacitive effect and the button voltage will be proportional to the derivative of the beam current [2].

Increasing the button capacitance will result in a lower cut-off frequency (i.e. smaller separation of the working frequency with respect to the flat part of the curve). However, as Z_t is inversely proportional to the button capacitance (see Eq. 1), that would lower the amplitude of the Z_t as well. The overall effect is negative, meaning that a lower button capacitance is generally more favourable for having a large enough button voltage. The ESS button capacitance should be limited to a few pF by maintaining a large separation between the button and the housing (similar to the XFEL BPM button design). With C_{button} > 5 pF, a significant reduction is seen on the button voltage.

5. BPM VOLTAGE WITH A DE-BUNCHED BEAM

Assuming a Gaussian beam, the frequency spectrum will also be Gaussian. If the beam is longitudinally well focused, the spectrum will extend to frequencies in the order of several GHz and the amplitude of the low beam harmonics will be approximately $2I_{DC}$ where I_{DC} is the average beam current during the pulse. If the beam gets de-bunched, though, the beam harmonics will get weaker and weaker starting from the higher harmonics and extending to the lower ones degrading the S/N ratio and the BPM resolution. Fig. 4 shows longitudinal bunch length growth with no powered cavities after the spokes.

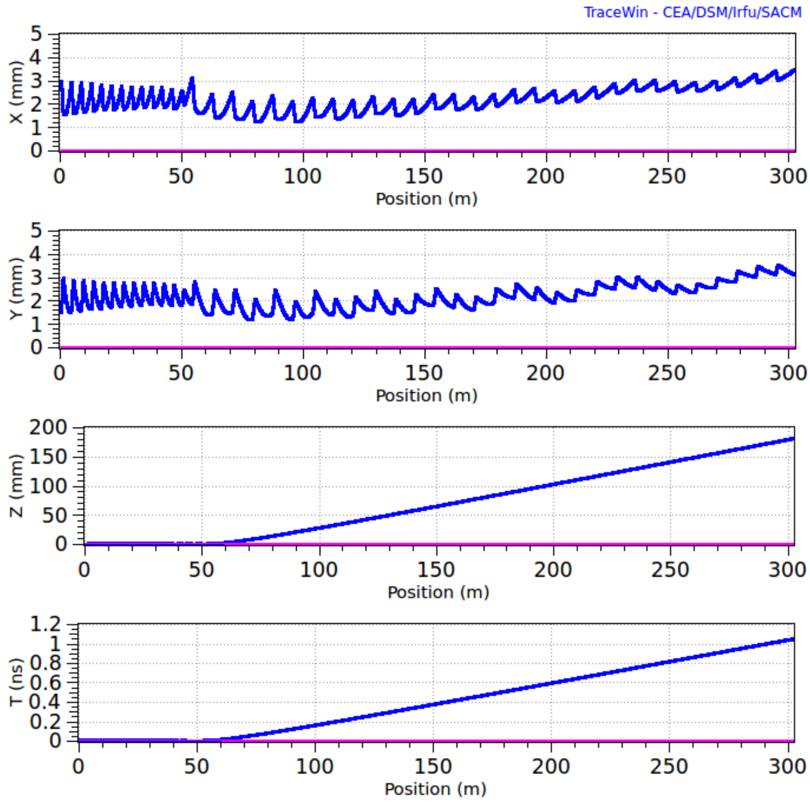

Figure 4: calculated bunch sizes in the superconducting linac along the x, y and z axis with no powered cavity after the spokes. Calculations by: R. Miyamoto (ESS, Beam Dynamics group)

As shown in Fig. 4, the longitudinal bunch growth is about 0.72 mm/m. The distance from the spokes to the target station is about 500 m. If the bunch size increases over this distance, the σ_z will increase to 360 mm approximately (linear approximation). Then, the beam current will be almost DC due to the large overlap between consecutive bunches.

Fig. 5 shows the effect of the de-bunching on the 352 MHz and 704 MHz harmonics of the beam current. The amplitude of the 352 MHz beam harmonic (this will be the processed frequency downstream of the spokes) will be very small with a σ_z about 200 mm corresponding to a distance of 250 m approximately.

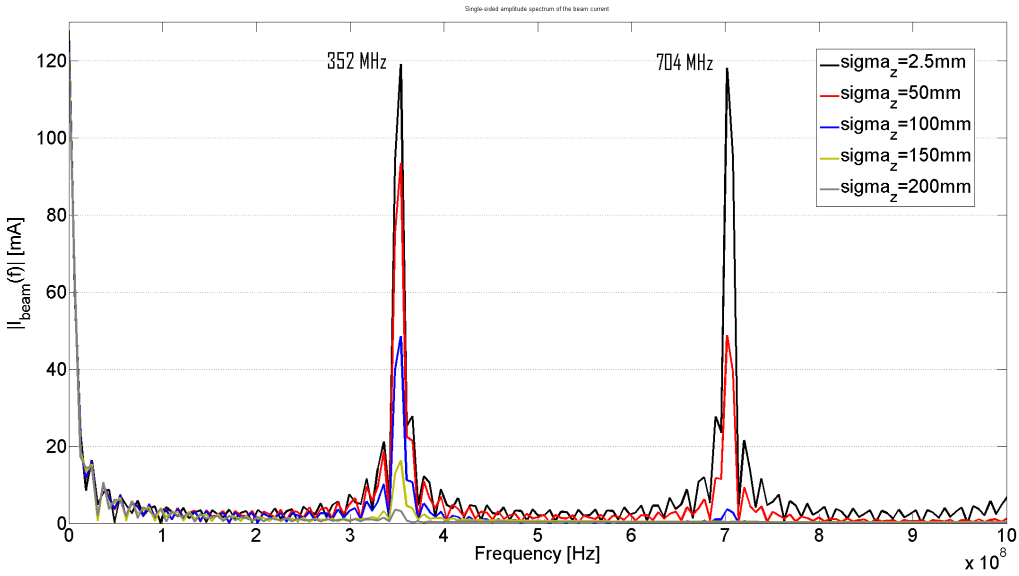

Figure 5: amplitude reduction of the beam current harmonics as a result of de-bunching.

Table 1 summarizes the de-bunching effect on the BPM resolution after the spokes (β=0.56) with the 40 mm button and the nominal beam.

Table 1: Effect of beam de-bunching on the BPM resolution

σ_z [mm]	**Distance from the Spokes [m]**	**I_{352} [mA_p]**	**$V_{button-352}$ [mV_p]**	**BPM resolution [µm]**
2.5	0	120	327	5
50	69	90	236	7
100	139	48	126	14
150	208	15	39	44
200	278	4	10	164

With higher σ_z values, the 352 MHz beam harmonic will be negligible and the beam position calculation will be very inaccurate, or even impossible, due to the poor S/N ratio.

If the beam current decreases to one-tenth of the nominal (i.e. beam current of 6.25 mA), the $V_{button-352}$ will decrease and the resolution will increase by the same factor, resulting in a resolution of 55 µm and 1636 µm with a σ_z of 2.5 mm and 200 mm respectively.

In practice, the BPM resolution might be worse due to error sources not taken into account, ex. electromagnetic disturbances and/or power supply ripples.

6. SUMMARY AND CONCLUSIONS

- The method of transfer impedances is a simple and effective method, which could be used for the calculation of the button voltage in time and frequency domains.
- The button voltage in the 60 mm and 100 mm beam pipes has been calculated with the aim of determining the right button size based on the following criteria: the button voltage at the processed frequency should be large enough so that, on one hand, by < 20 dB of amplification it can be matched to the ADC input range, and on the other hand, it gives enough S/N ratio for position/phase calculations with a de-bunched beam.
- In the calculations, the ratio of the button to the beam pipe diameter has been assumed to be equal to the one of the European XFEL warm linac section. This, results in a button diameter of 24 mm for the spokes and 40 mm for the elliptical, upgrade, A2T and the dump-line. Calculations show that with this choice of the button sizes, the requirements on the amplifier gain and the BPM resolution will be met.
- In practice, due to the mechanical constraints, the button size will be subject to some limitations, particularly for the larger button. In that case, the button size can be made a little smaller to meet the mechanical limitations.
- In the MEBT and DTL sections, the β factor will be less than 0.5 and the transfer impedance model might not lead to accurate results. Nevertheless, it can be generally said that a small button size in the order of 10 mm should provide enough voltage.
- The parasitic button capacitance can significantly reduce the button voltage. For the ESS buttons, it should be limited to a few pF by maintaining a large gap between the button and the housing.
- Beam de-bunching degrades the S/N ratio and the BPM resolution. If the ESS beam gets de-bunched over the whole distance from the spokes to the target station, the BPM system will probably not be able to measure the position due to the very poor S/N ratio. At distances up to 250 m, position calculations might still be possible, but with a significantly degraded resolution.

7. REFERENCES

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