Stripline Beam Position Monitors with Improved Frequency Response and their Coupling Impedances

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Introduction

Stripline beam position monitors (BPMs) house their electrodes in the chamber.

BPMs are being used for measurements of beam position signals to suppress the beam instabilities at J-PARC MR.
In case that electron-cloud instability occurs in the future at J-PARC MR,

1. Improve the frequency performance of the BPMs!

2. No coupling impedance enhancement of the BPMs!
The frequency dependence of beam position monitor (BPM) on different electrode shapes

The transfer function $F(\omega)$:

$$F(\omega) = \frac{i\omega}{c} \int_0^l k(z) e^{-i\frac{2\omega}{c}z} \, dz$$

$k(z)$: coupling function, which describes the electrode shapes.

$l$: the electrode length.

is a key function, to analyze the frequency response.
① Rectangular electrode:

- The $z$-dependence of the coupling function: $k(z)$ diminishes.

- The transfer function $F(\omega)$ is calculated straightforwardly.
Simulation is done to obtain the transfer function.

The transfer function is proportional to the Fourier transform of the beam-induced voltage divided by that of the beam current.

*Beam-induced voltage*
Frequency characteristic of a rectangular electrode.

Theory

Simulation

- The dips emerge at \( f_n = \frac{nc}{2l} \) (\( n=0,1,2,... \)).
Qualitative understanding of the existence of the dips.
1. When a beam arrives at the front-end of the electrode \((t=0)\), the beam excites *two currents* with opposite polarities.
   - One current flows to the downstream with the beam, while the other does to the upstream side and enters the port1.
2. When the beam arrives at the back-end of the electrode \((t=l/c)\), new currents with opposite polarities (the dashed-pulse) are additionally excited there.

- The total signal to the port 2 is cancelled by superposing the currents (the **solid** and the **dashed** pulses).
3. If successive pulse trains arrive with its interval $2l/c$, the subsequent pulse (the solid pulse) compensates the prior signal (the dashed pulse) created by the predecessor pulse.

- Finally, all beam-induced signals with the frequency: $f_n = nc/2l$, cannot be detected at all outside the chamber.
To avoid the demerit of the *rectangular electrode*, no pair of image currents should be generated by the leaving pulse.

It is enabled by *narrowing the electrode toward downstream* (and carefully reclining the electrode to the chamber, to preserve the characteristic impedance $Z_c$ of the electrode.).
② Exponential electrode:

- In 1970's Linneca suggested an exponential electrode for better frequency characteristic.

- The electrodes are narrowed toward downstream.
- The electrodes are reclined to the chamber.
The results for the exponential electrode.

- The dips disappear in the exponential electrode.
In J-PARC MR, the exponential electrodes are placed **straight as a flat plate**, because it was difficult to **bend them exponentially** as required for a good impedance matching.
The transfer function is found by measuring $S_{21}$. 
Measurement results of the transfer function

While the peak to peak modulation is about 30% below 1 GHz, it is drastically worsen at high frequency.
The simulation results both for the case that
- the electrode is put straight as a flat plate,
- the electrode is precisely inclined.

On the red, the peak to peak modulation was 23 % below 1 GHz.

On the blue line, the peak to peak modulation is worsen to about 30 % below 1 GHz.
An issue is clarified.

The precise bent of electrodes is the key issue to make maximum use of the merit of the exponential electrode, which is quite difficult in practice.

Consequently,

We start with a simple shape and gradually increase its complexity to improve the frequency performance.
③ Triangle electrode.

- The simplest shape next to the rectangle electrode is a triangle.
- It requires no sophisticatedly bending to attain a good impedance matching along the electrodes.
The result for a triangle electrode.

Except the large overshoot at low frequency, the triangle electrode has a better frequency characteristic (refer to an exponential electrode).
To eliminate the overshooting effect, one more complexity is introduced in the triangle shape. (That is to replace the long, straight sides of the triangle by a three-point polyline.)

This deformation transforms the triangle to a concave pentagon.

Its fabrication and setup remain to be easy.
The result for the concave pentagon electrode

- The overshooting effect in the triangle electrode is suppressed in the concave pentagon electrode.
- The frequency characteristic of the concave pentagon (green) is surprisingly similar to that of the exponential electrode (blue) in the simulation result.
A simple treatment to improve the frequency performance

In the all simulation results, the signal strength starts to be *declined* beyond the first transverse magnetic (TM) waveguide mode:

$$f_c = \frac{0.144}{a_1 = 65\text{mm}} = 1.76\text{GHz}$$
This is due to a large gap between the chamber wall at the upstream end of the electrode.

Some of the image current running on the chamber surface before the electrode *jump* to the electrode over this gap as a displacement current.

For short wavelength modes, this gap prevents a smooth flow of the displacement current.

Thus, the image current running on the electrode loses some parts of high frequency components.
By attaching a plate perpendicular to the upstream edge of the plate ("an apron"), this gap for the image current can be reduced.
The simulation results with the apron

- The signal strength is maintained up to the second TM mode:

\[ f_c = \frac{0.262}{a_1 = 65mm} = 4GHz \]
The results with the apron for a smaller chamber ($a_1=40\text{mm}$).

The apron plate is effective to sustain a signal strength up to higher frequency as a chamber has a smaller radius.
Measurement results without and with the apron.

- The overshooting effect appearing in the triangle electrode diminishes in the concave pentagon electrode.
- The apron is effective to suppress the signal fluctuations.
Comparison with the measurement results: (exponential) vs (triangle & concave pentagon with apron)

- The concave pentagon (right) electrode with the apron significantly improves the frequency response of the exponential electrode (left) at J-PARC MR.
Coupling impedance of the electrodes

- The simulation results of the wake function for the different (triangle, exponential and concave pentagon) electrode shapes without apron.

- No significant difference is visible.
- The simulation results look like the $\delta'$-wake function.
The theoretical and the simulation results for the exponential electrode.

Both results are the same order of magnitude.

The impedance is theoretically inductive, and indicates the wake function behaves like the $\delta'$-function.
The impedance dependence on the electrode shapes

- $Z_L$ without the apron: for triangle, exponential, and concave pentagon.

(The solid is the real, the dashed line is the imaginary.)

The difference is invisible on this scale.

- No significant difference among the different electrodes.
The effect of the apron on the impedances

The impedances do not depend on the existence of the aprons.
Measurement results for triangle, and pentagon.

**Without apron**

![Graph without apron]

**With apron**

![Graph with apron]

- The impedance with the apron (right) looks enhanced,
- but this is because
- the distance of the electrode from the chamber wall is larger
- than that without apron
- in the fabrication process, (which was found by TDR).
Summary

- The *concave pentagon* electrode with *apron* plates significantly improved high frequency performance of the exponential electrode in J-PARC MR.
  - The fabrication is easier than that of the exponential electrode.
  - The apron plate maintains the signal strength up to the second TM-mode.

- The coupling impedances do not significantly depend on the electrode shapes and the existence of the apron.

- The significant efforts to improve the impedance-mismatch along the electrodes will realize the better frequency performance as well as the lower coupling impedances of the electrodes.