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

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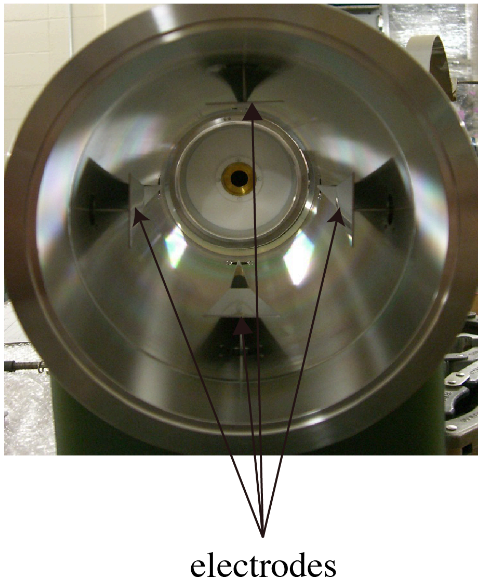
➢Introduction

- 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(ω):

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

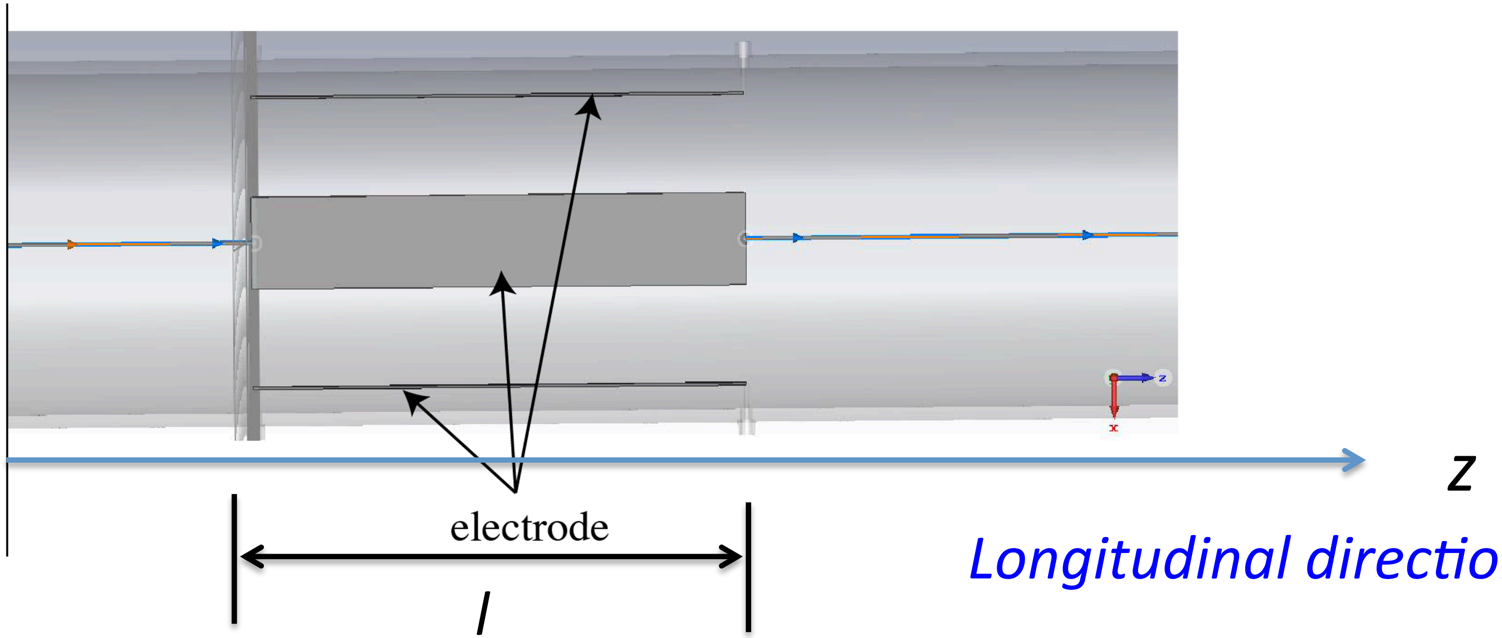
k(z): coupling function, which describes the electrode shapes.

l: the electrode length.

is a key function,

to analyze the frequency response.

① Rectangler electrode:

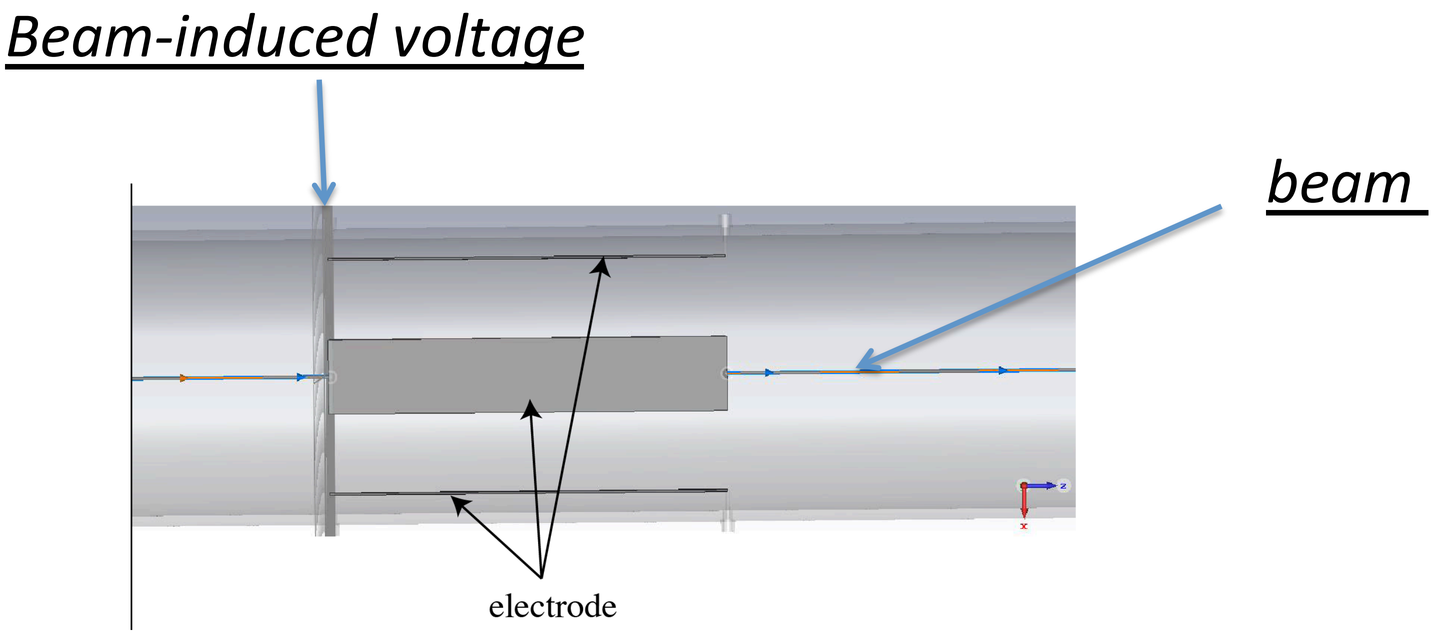


Longitudinal direction

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

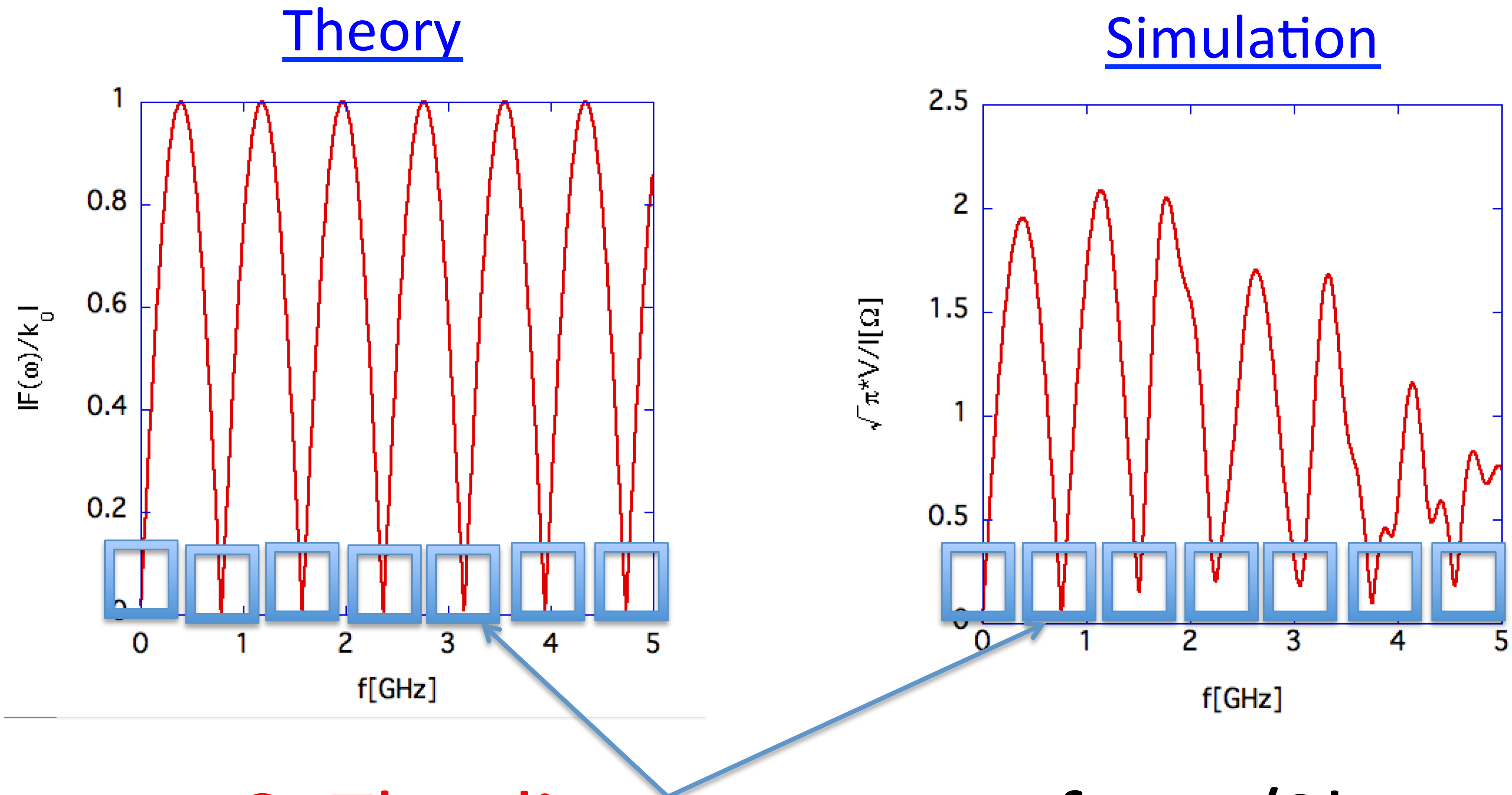
- The transfer function F(ω) is calculated straightforwardly.

◆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.

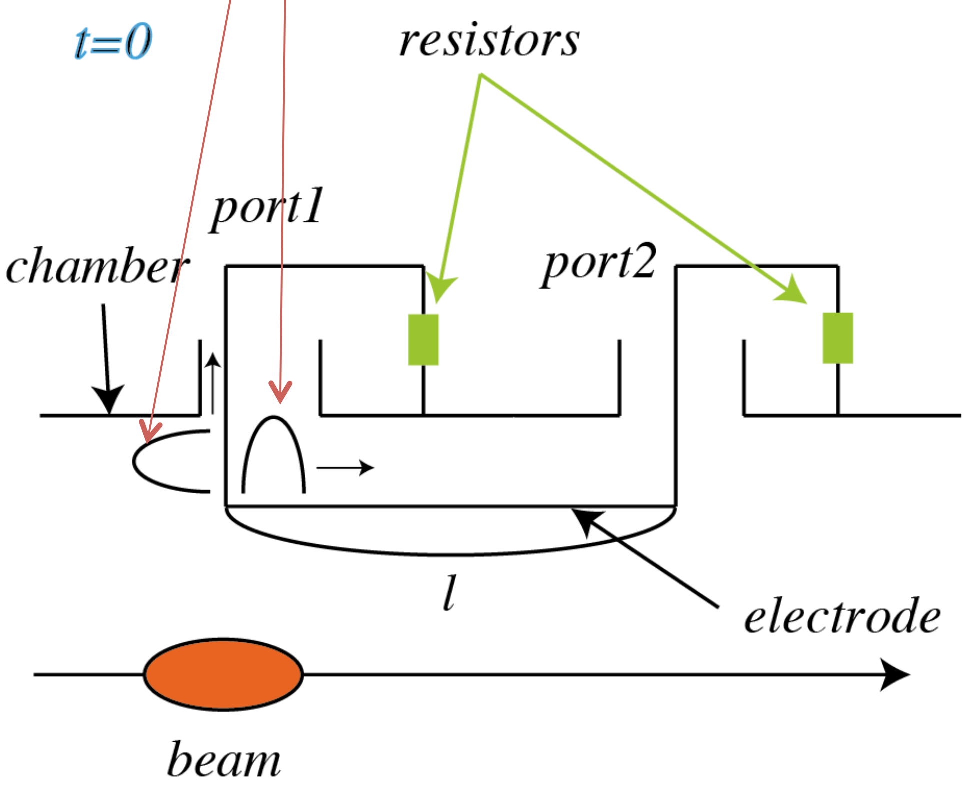
Frequency characteristic of a rectangler electrode.



- The dips emerge at f_n=nc/2l (n=0,1,2,...).

Qualitative understanding of the existence of the dips.

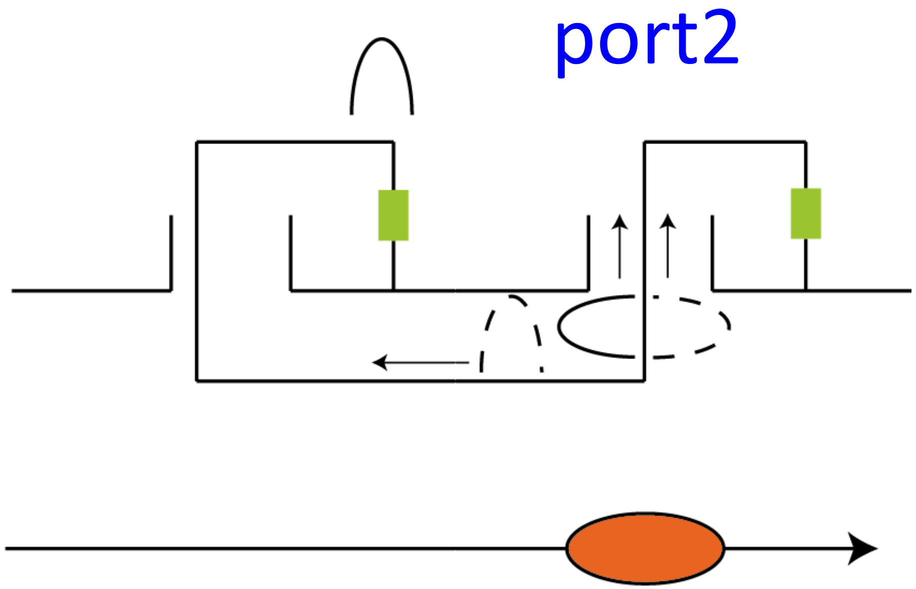
1. When a beam arrives at the front-end of the electrode (t=0), the beam excites *two currents* with opposite polarities.
   - One current flows to the downstream with the beam, while the other does to the upstream side and enters the port1.



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).

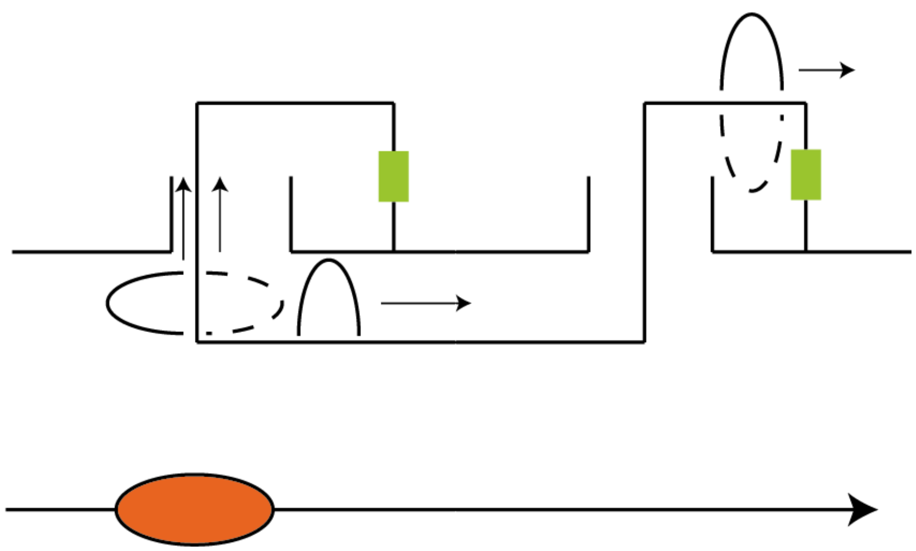
$t=l/c$



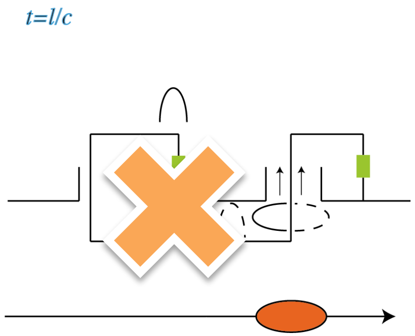
3. If successive pulse trains arrive with its interval 2l/c, the subsequent pulse (the **solid** pulse) compensates the prior signal (the *dashed* pulse) created by the predecessor pulse.

- Finally, all beam-induced signals with the frequency : $f_n = nc/2l$, cannot be detected at all outside the chamber.

$t=2l/c$



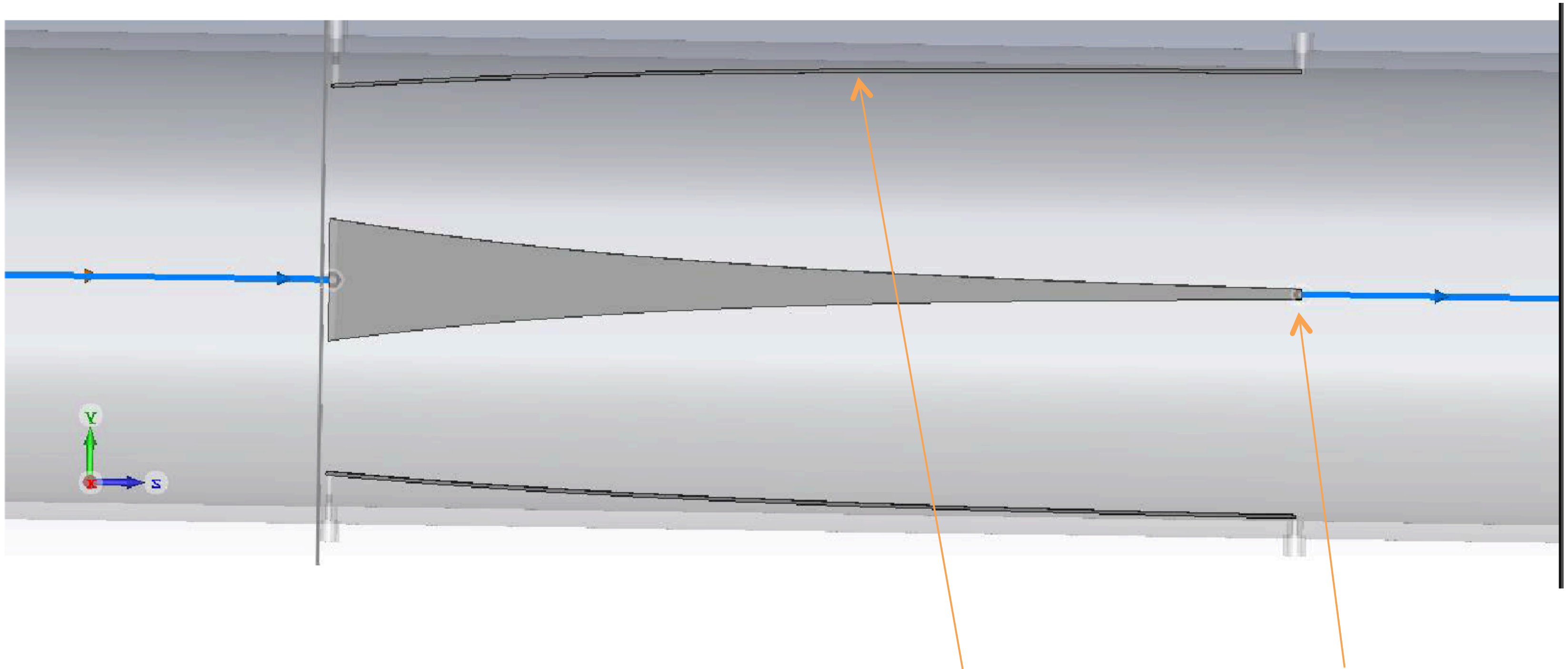
◆To avoid the demerit of *the rectangular electrode*,
no pair of image currents should be generated by the leaving pulse.



● 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:

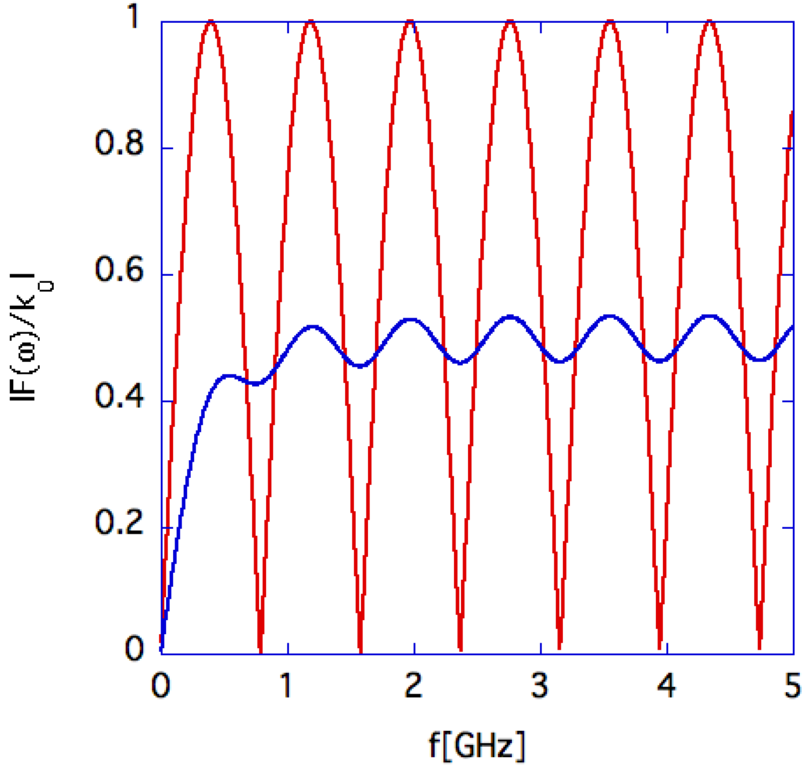
- In 1970's Linnecar suggested an exponential electrode for better frequency characteristic.



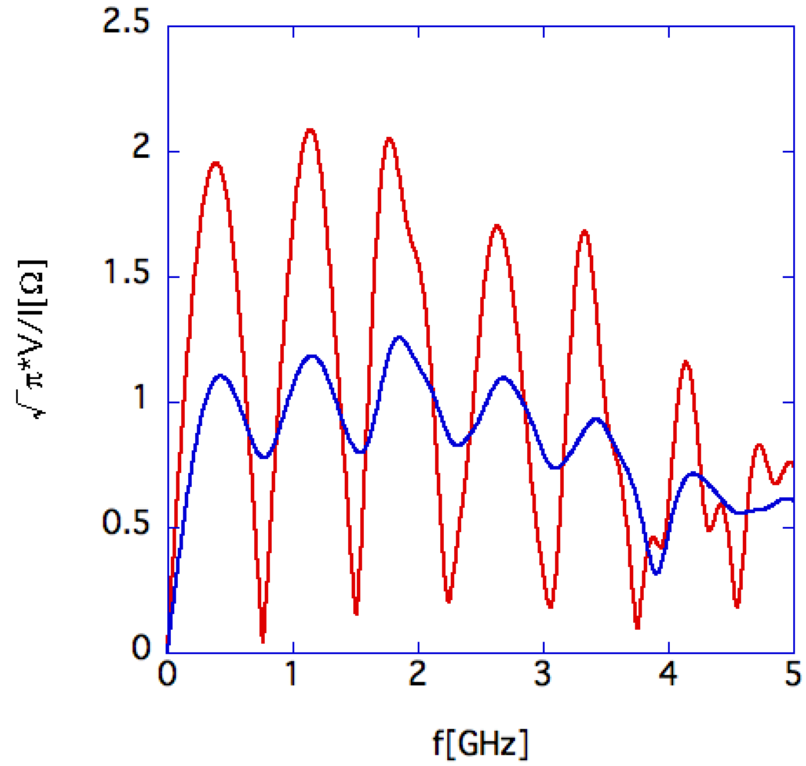
- ✓ *The electrodes are narrowed toward downstream.*
- ✓ *The electrodes are reclined to the chamber.*

◆The results for the exponential electrode.

Theory



Simulation

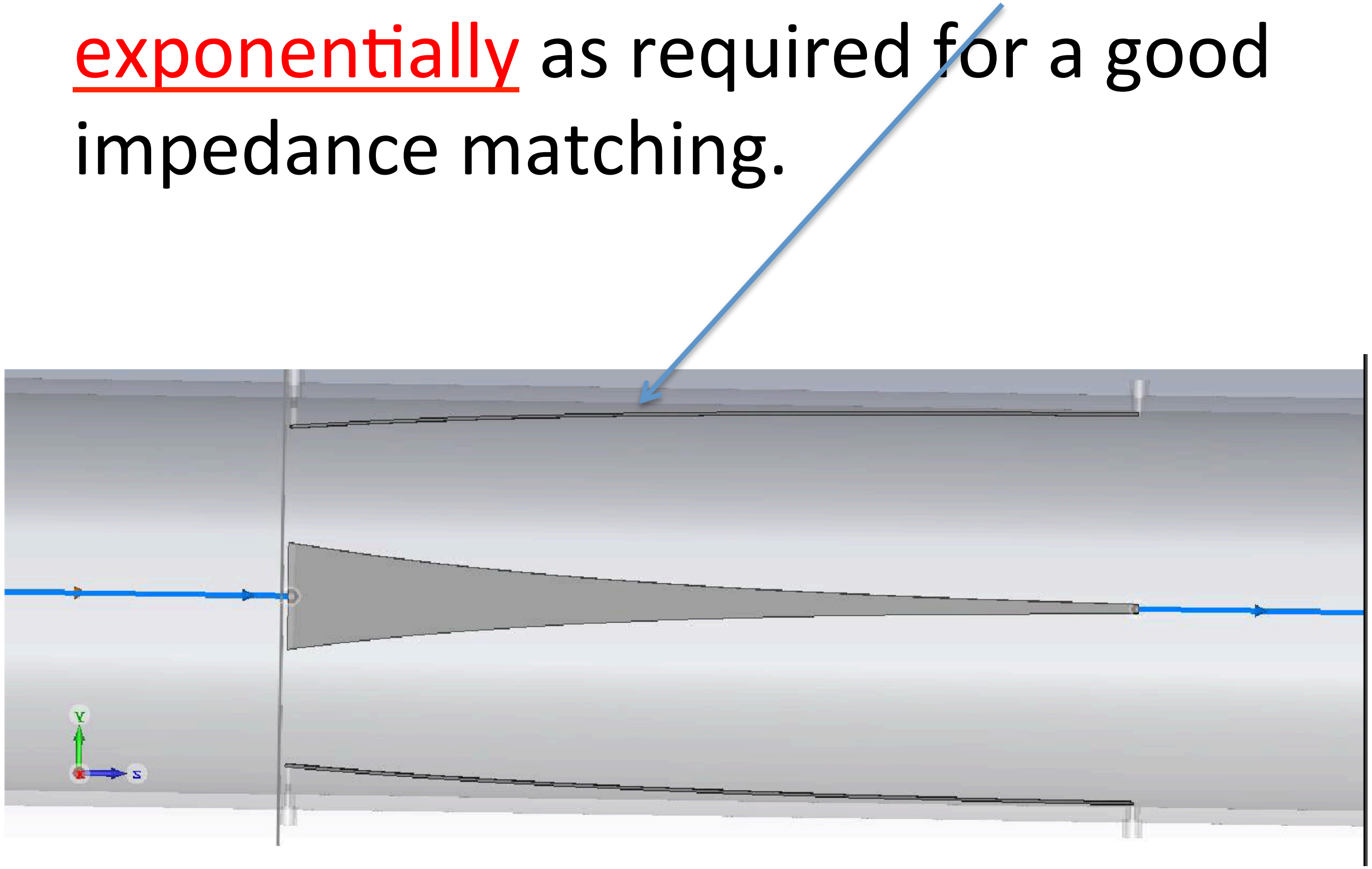


● The dips disappear

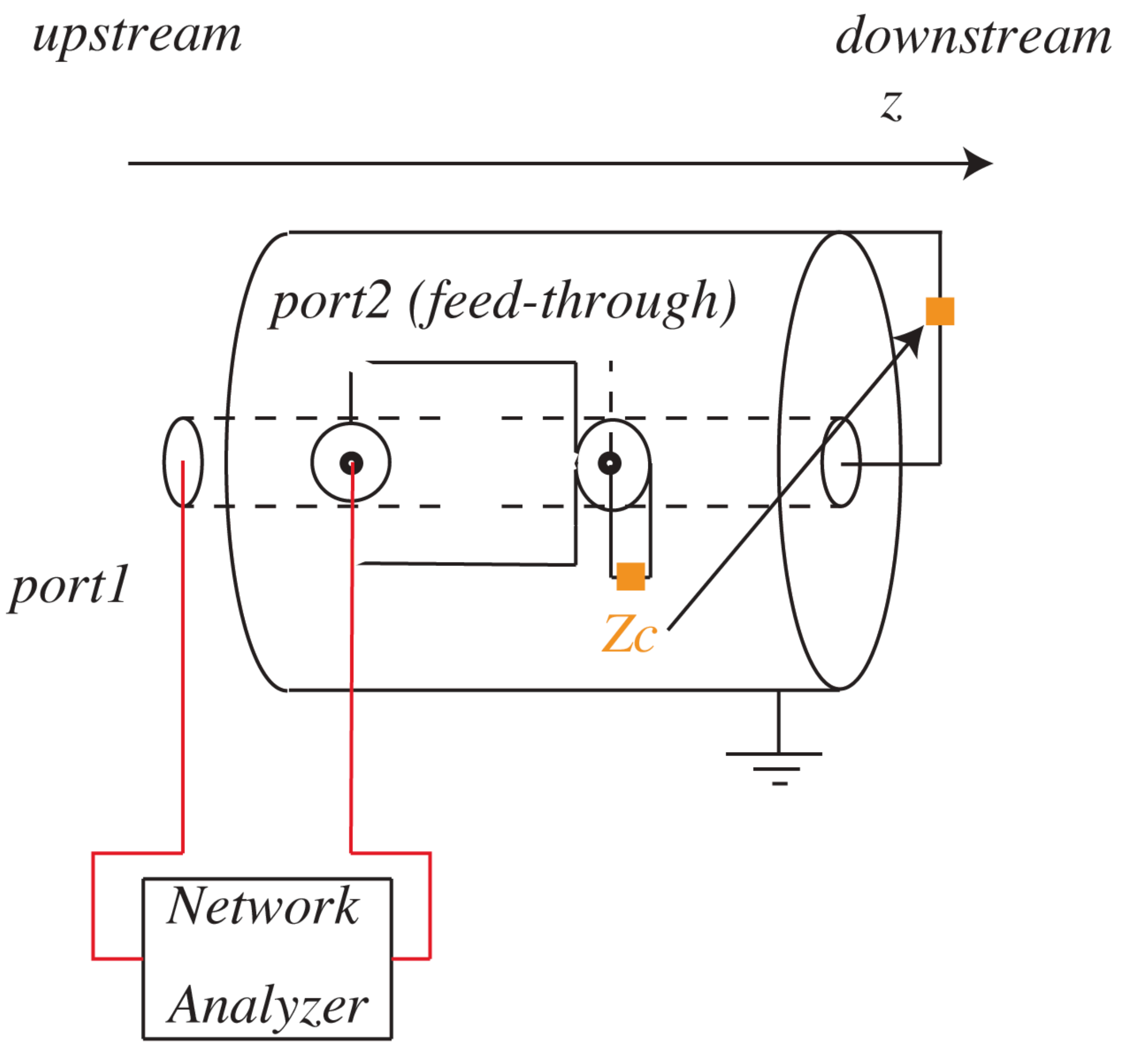
in the exponential electrode.

◆Reality bites

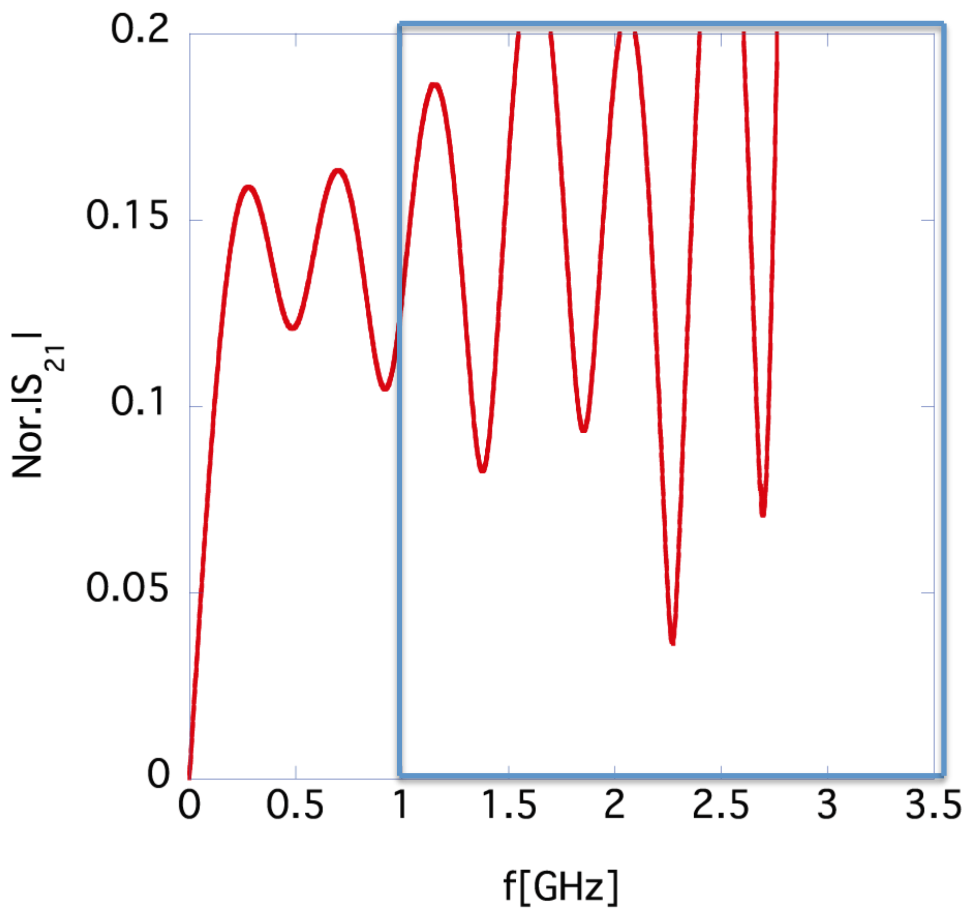
- In J-PARC MR, the exponential electrodes are placed **straight as a flat plate**, because it was difficult to bend them exponentially as required for a good impedance matching.



The transfer function is found by measuring S_{21} .



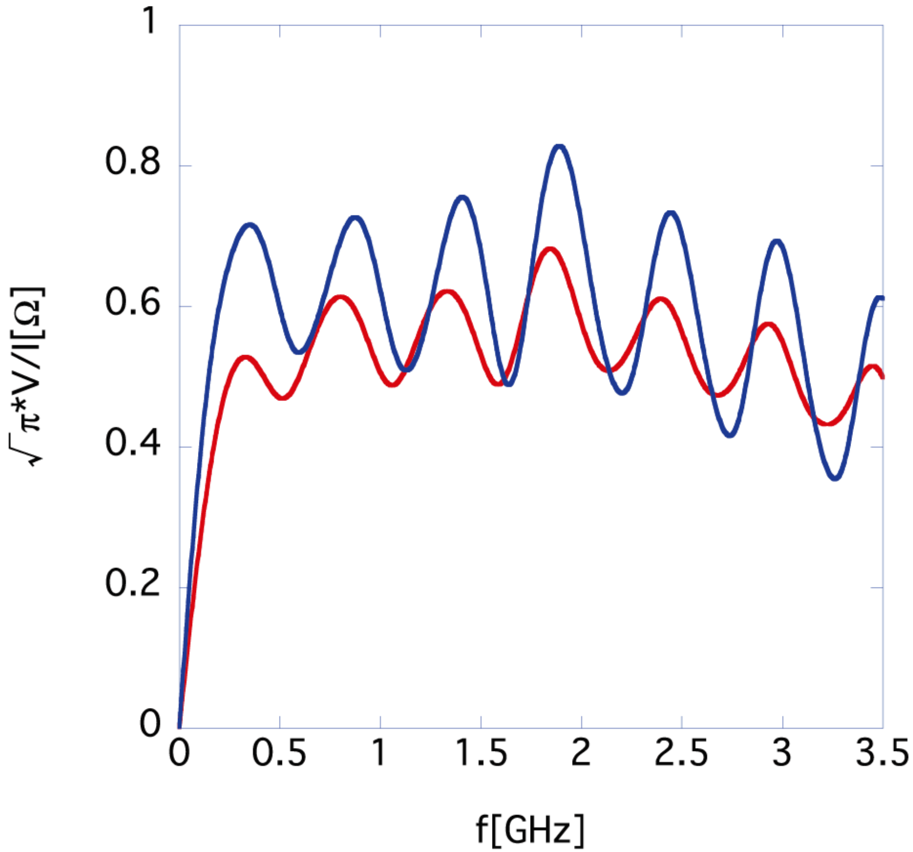
◆ Measurement results of the transfer function



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 reclined.



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.

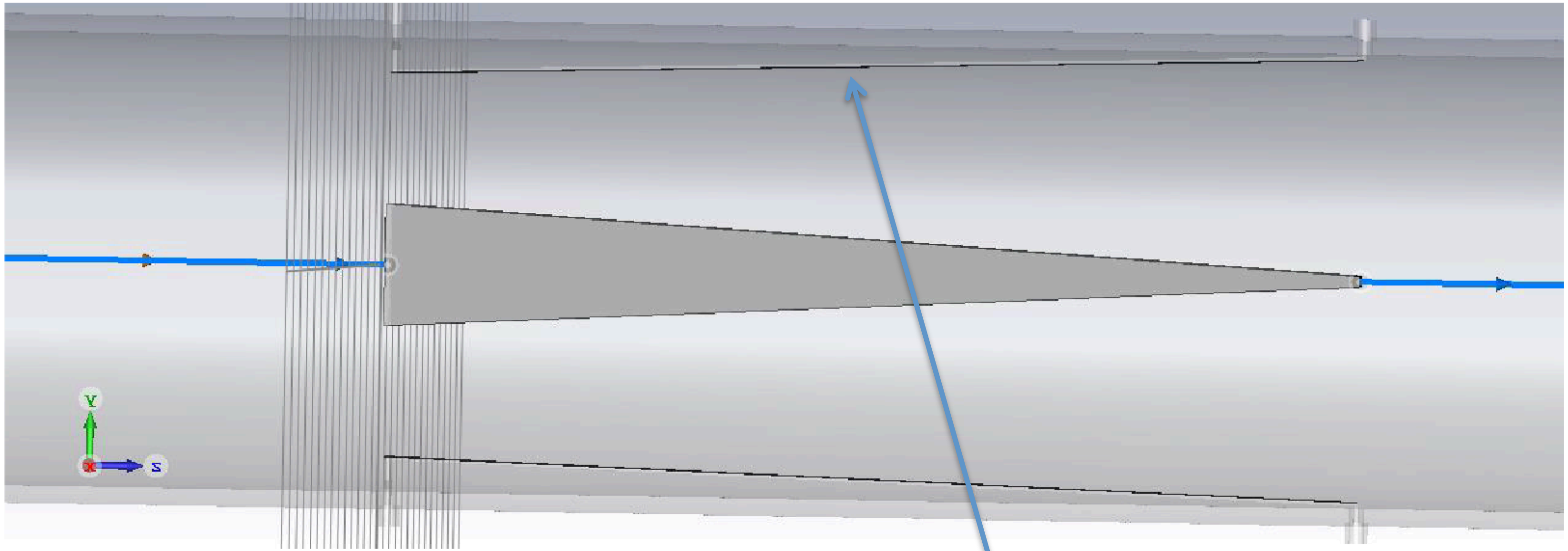
❖ An issue is clarified.

◆ *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.

③Triangle electrode.

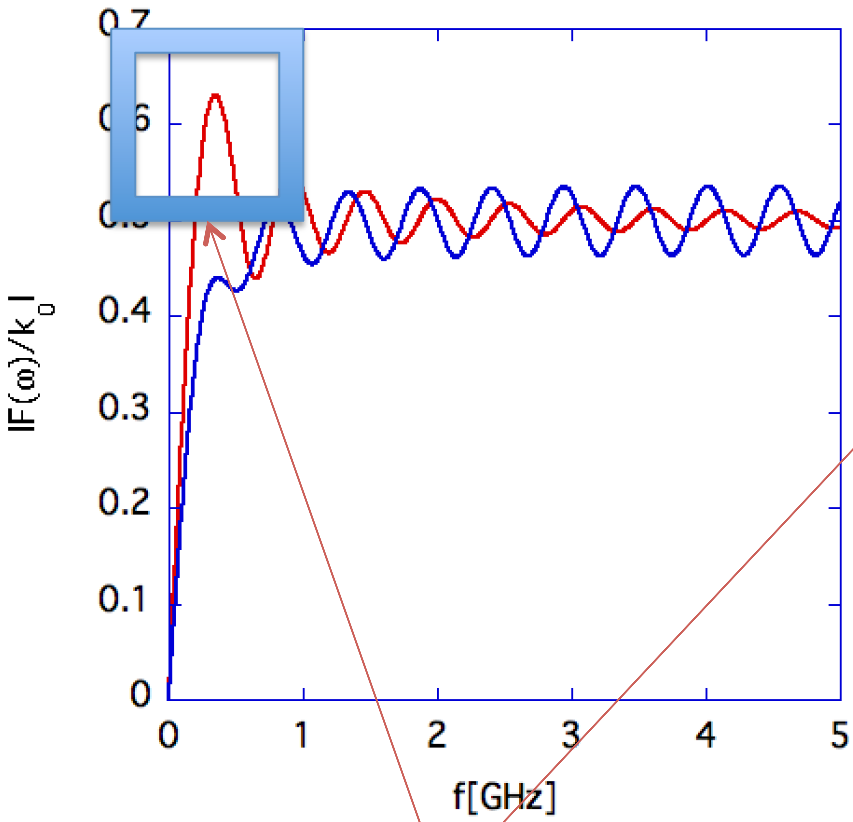


- The simplest shape next to the rectangle electrode is a triangle.

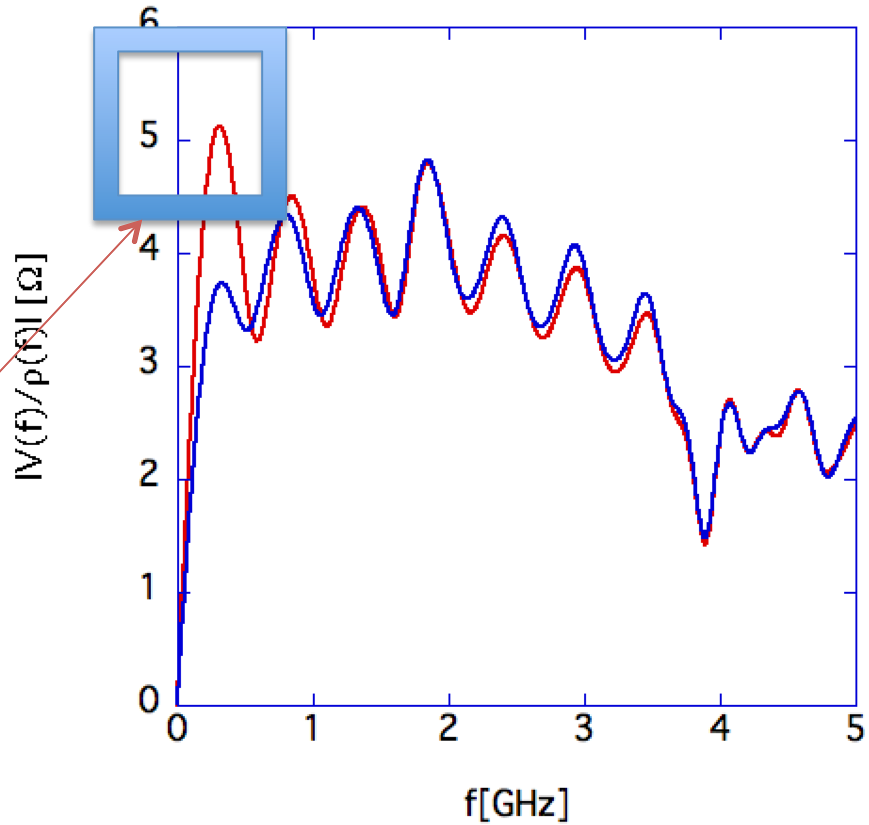
- It requires no sophisticatedly bending to attain a good impedance matching along the electrodes.

◆ The result for a triangle electrode.

Theory

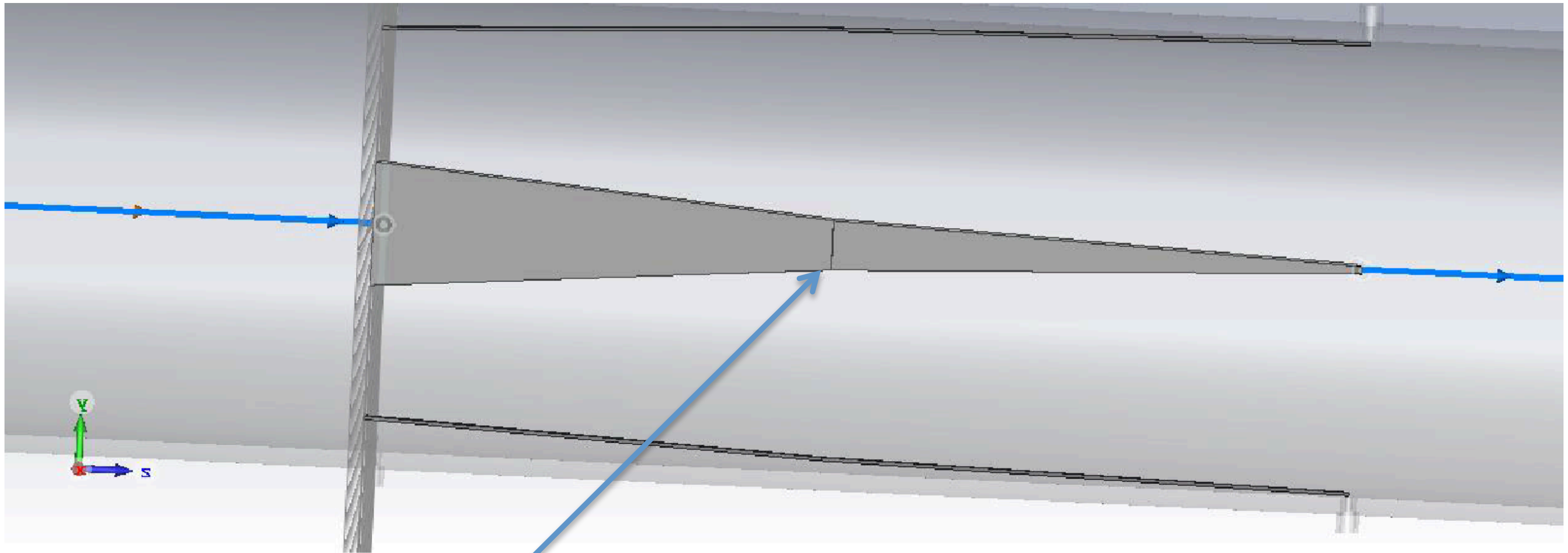


Simulation



- Except **the large overshoot** at low frequency, the triangle electrode has a better frequency characteristic (refer to an exponential electrode).

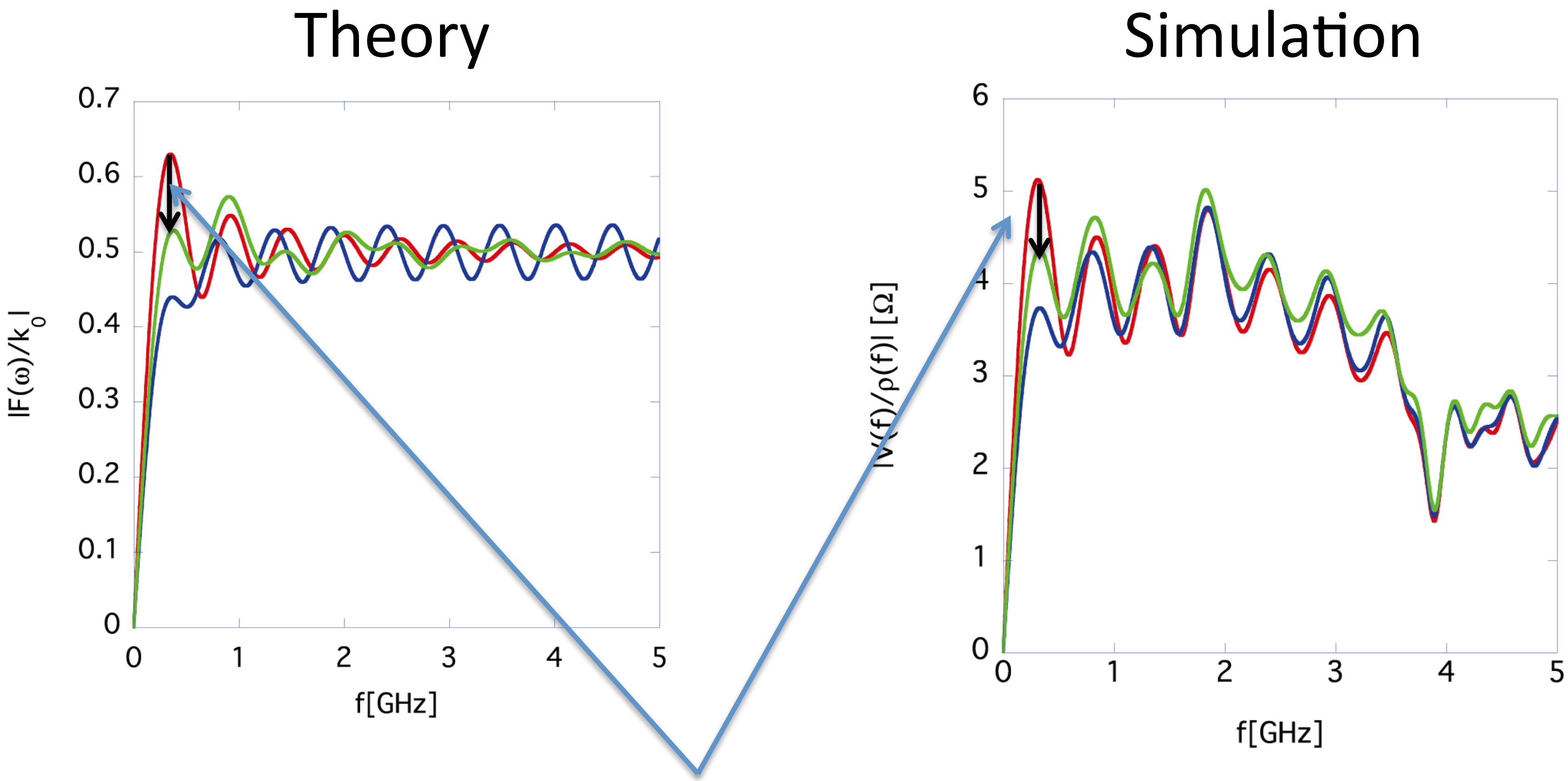
④Concave pentagon electrode



- 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

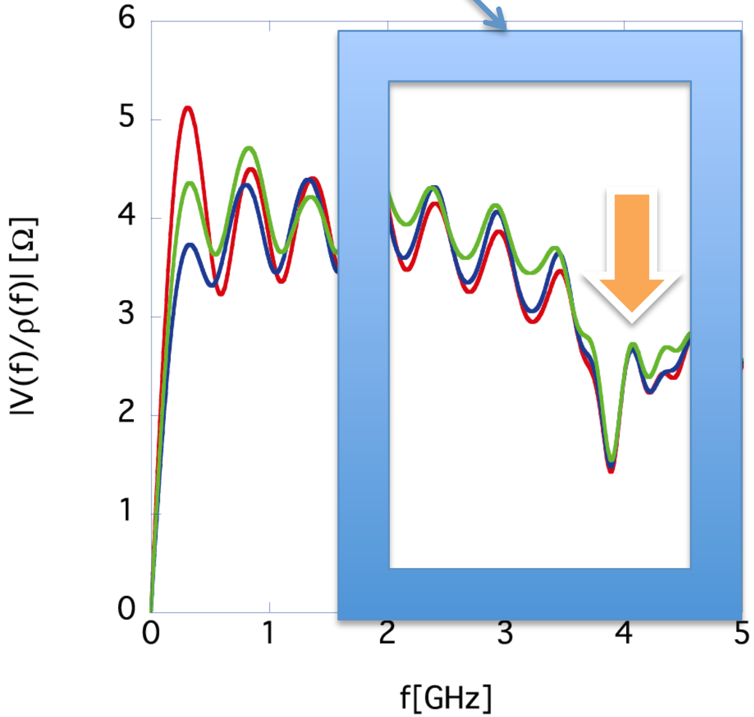


- The overshooting effect in the triangle electrode is suppressed in the concave pentagon electrode.
- The frequency characteristic of the concave pentagon (green) is surprisingly similar to that of the exponential electrode (blue) in the simulation result.

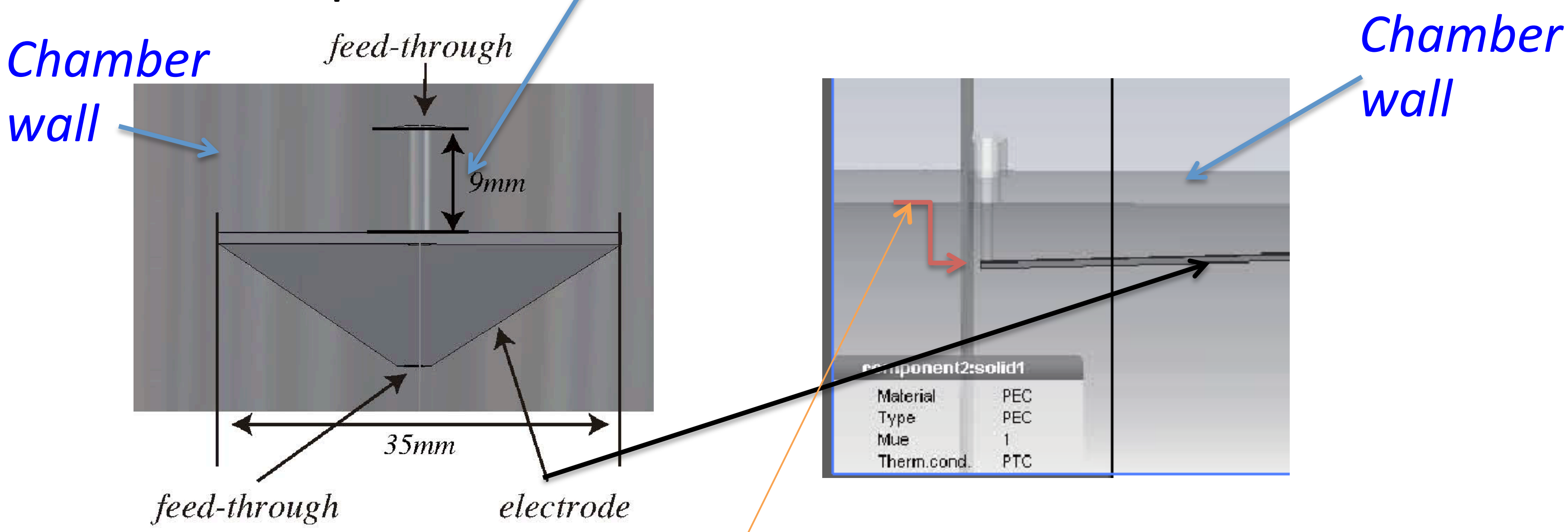
A simple treatment to improve the frequency performance

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

$$f_c = \frac{0.144}{a_1 = 65mm} = 1.76GHz$$

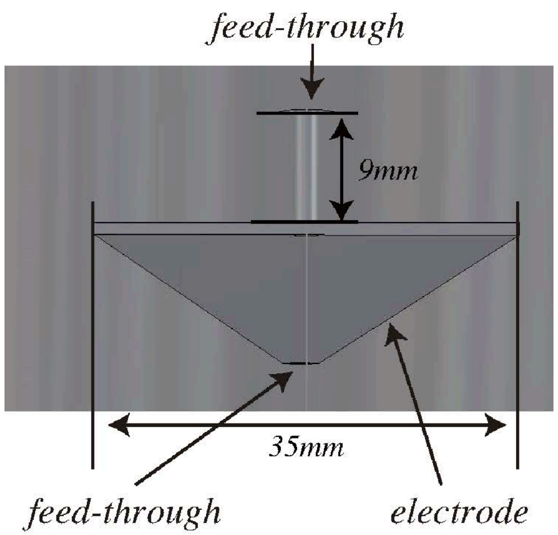


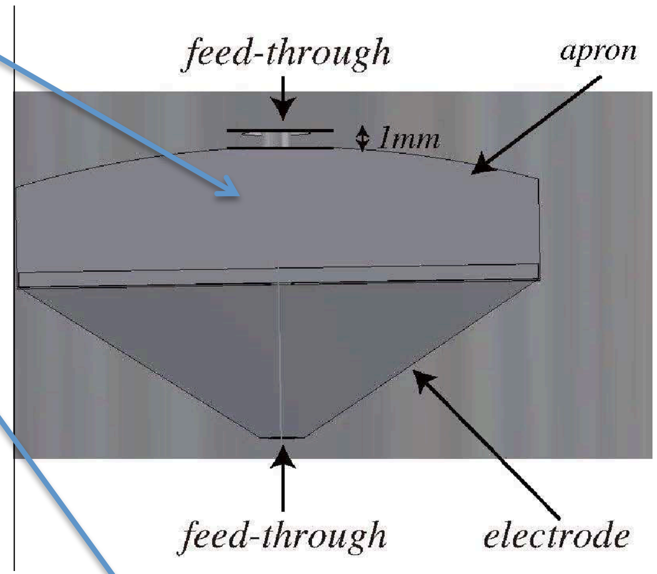
◆ This is due to **a large gap** between the chamber wall at the upstream end of the electrode.

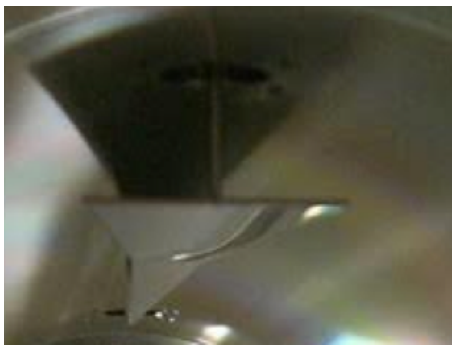


- Some of the image current running on the chamber surface before the electrode *jump* to the electrode over this gap as a displacement current.
- For short wavelength modes, this gap prevents a smooth flow of the displacement current.
- Thus, the image current running on the electrode loses some parts of high frequency components.

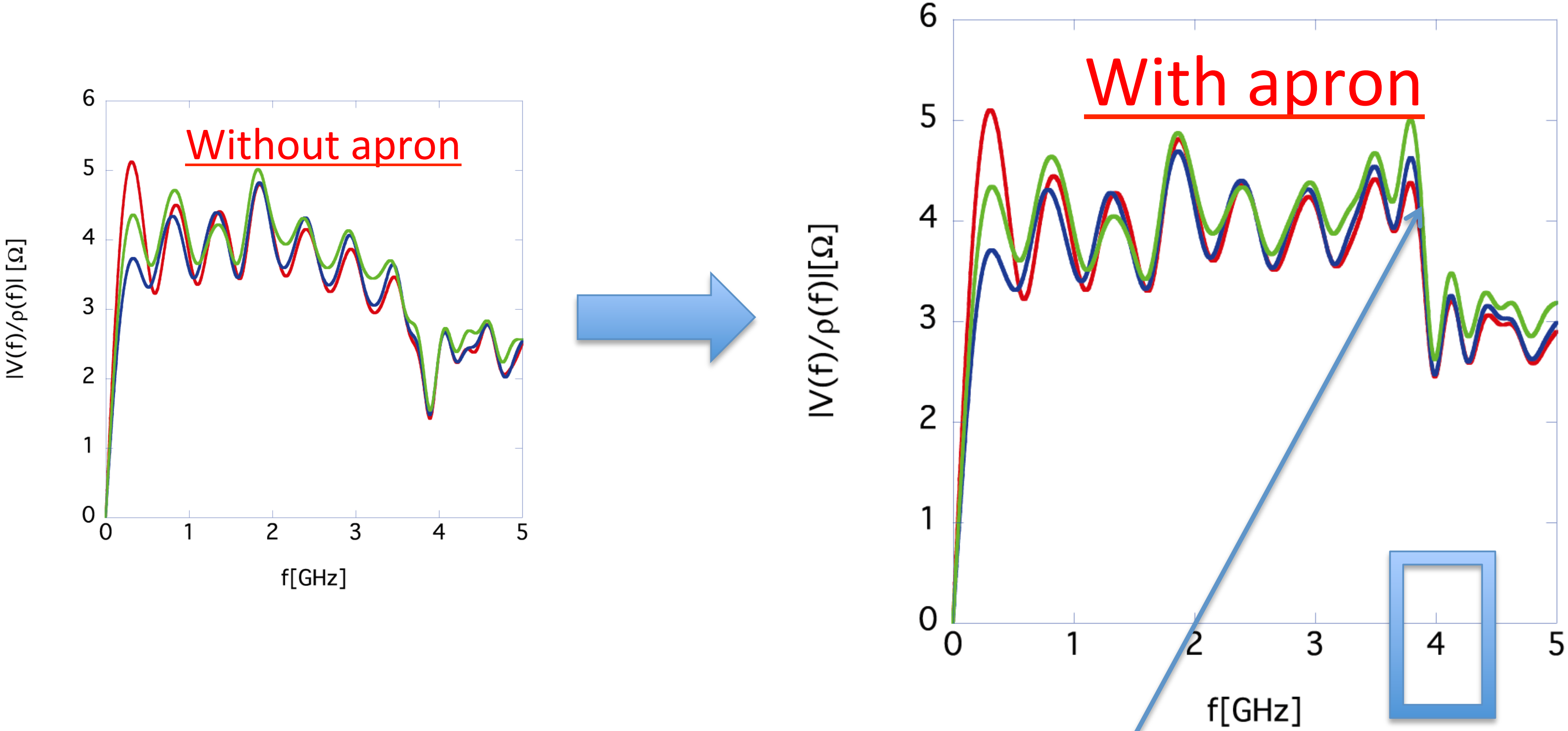
- By attaching **a plate** perpendicular to the upstream edge of the plate (``an apron”),
  this gap for the image current can be reduced.







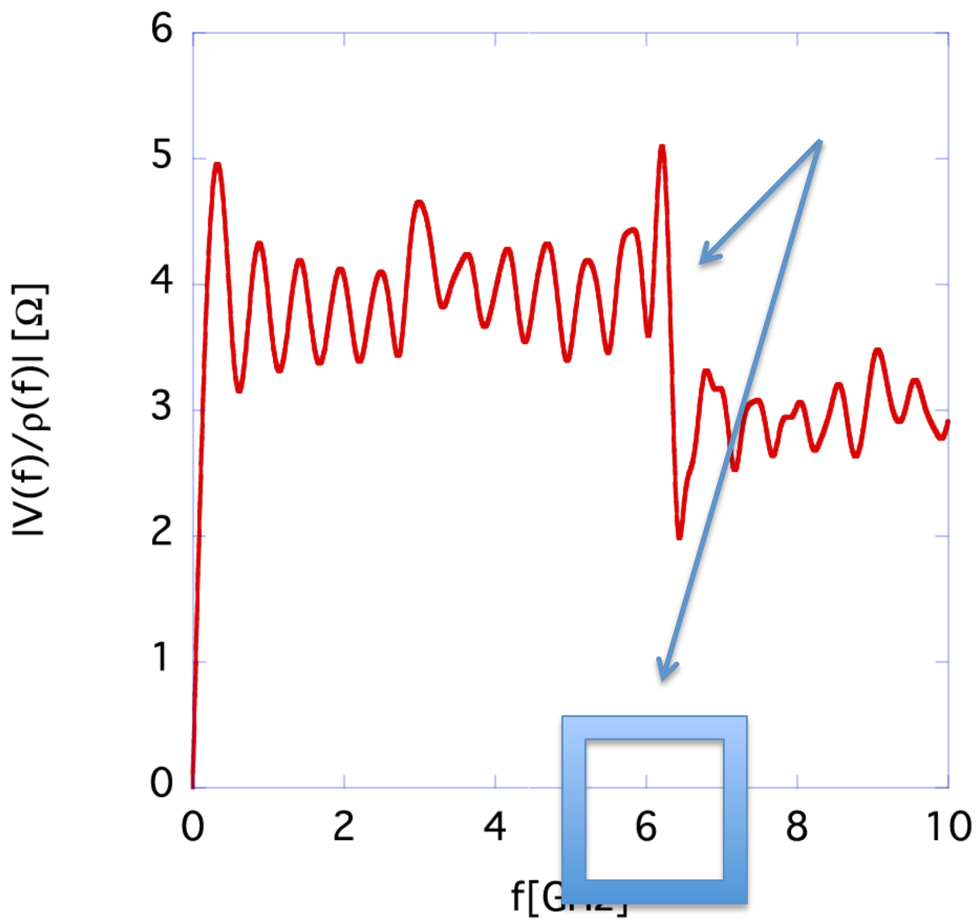
◆ The simulation results with the apron



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

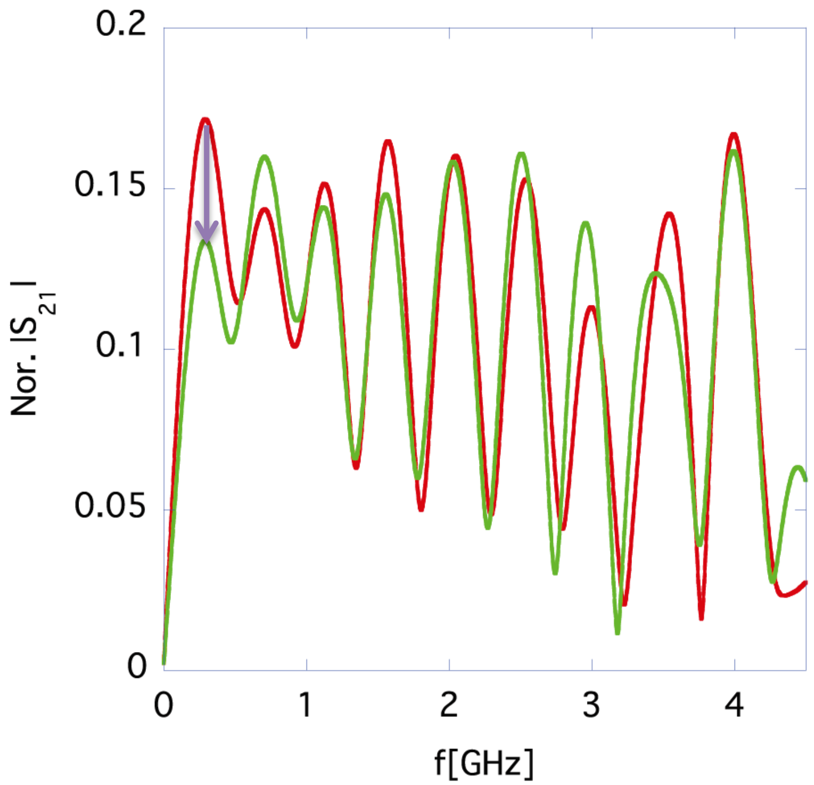
$$f_c = \frac{0.262}{a_1 = 65mm} = 4GHz$$

◆ <u>The results with the apron for a smaller chamber (a_1=40mm).</u>

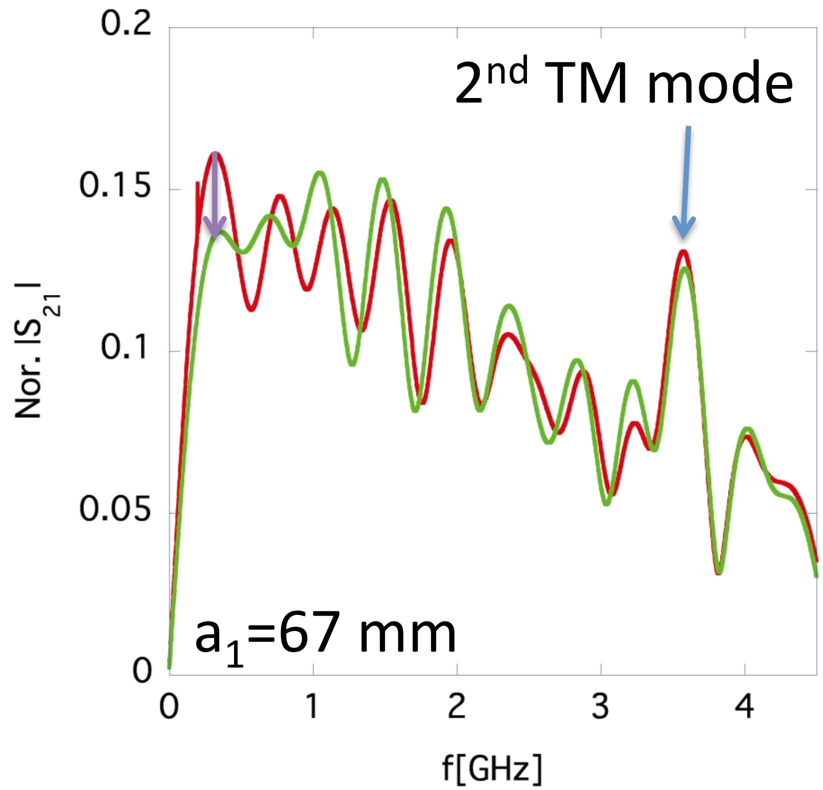


● The apron plate is effective to sustain a signal strength up to *higher frequency* *<u>as a chamber has a smaller radius.</u>*

◆ Measurement results without and with the apron.



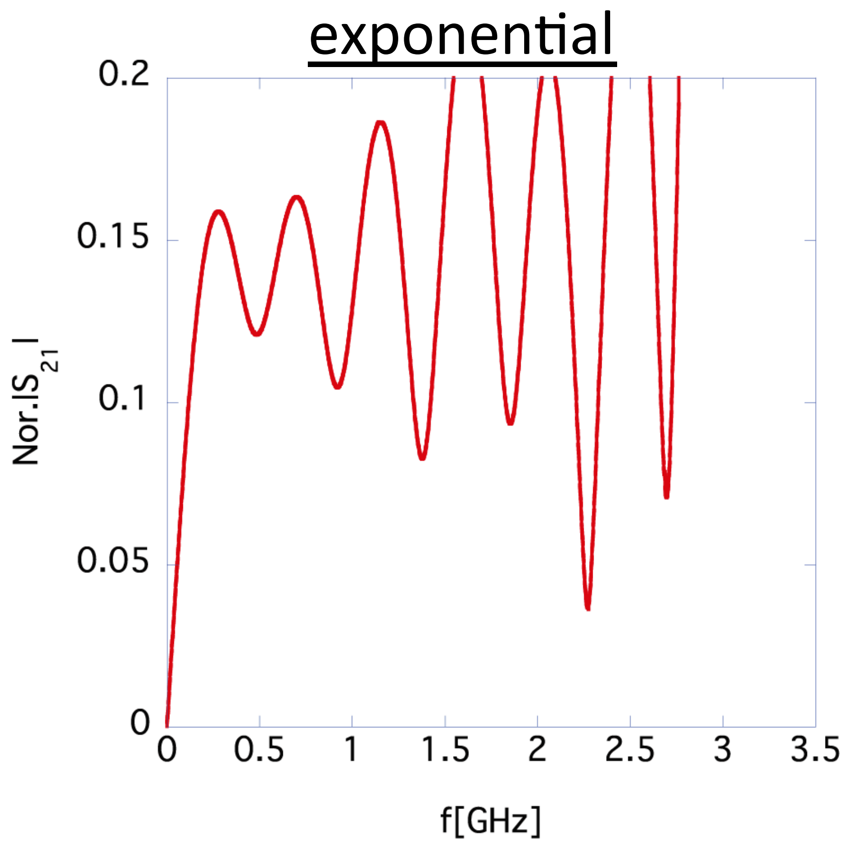
Without apron

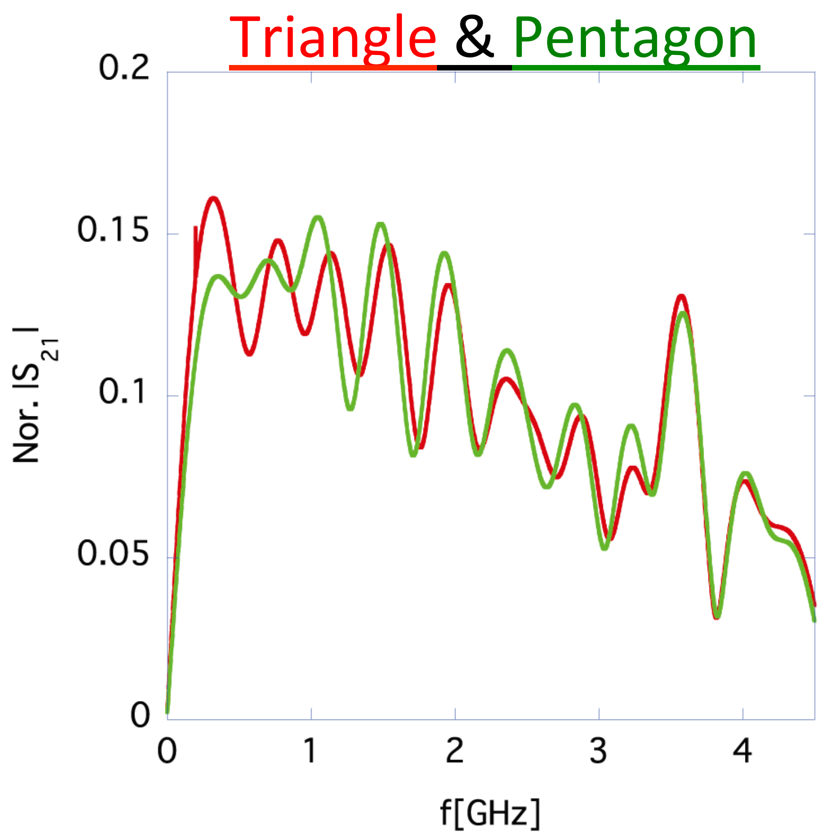


With apron

- 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)

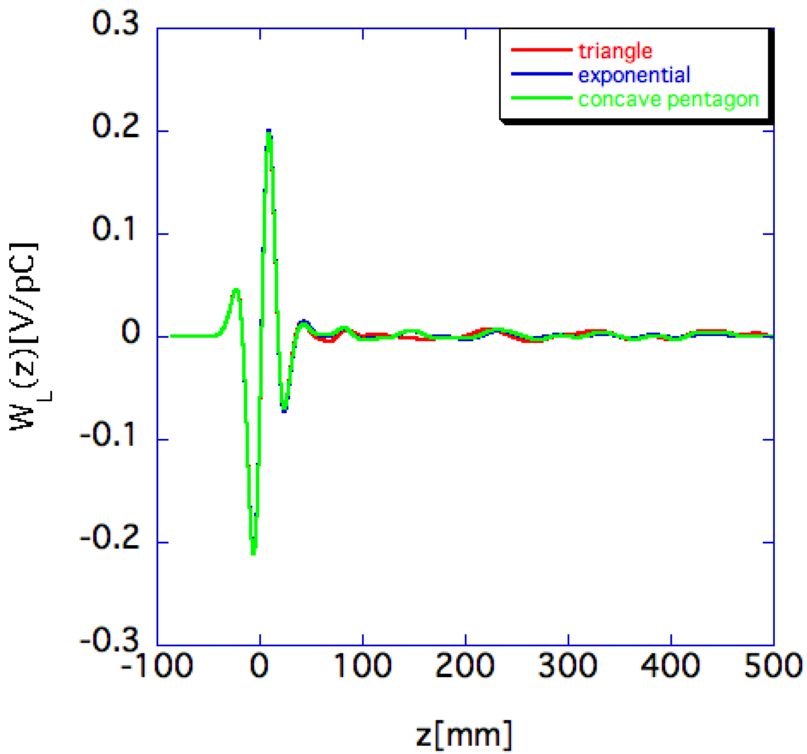




- The concave pentagon (right) electrode with the apron significantly improves the frequency response of the exponential electrode(left) at J-PARC MR.

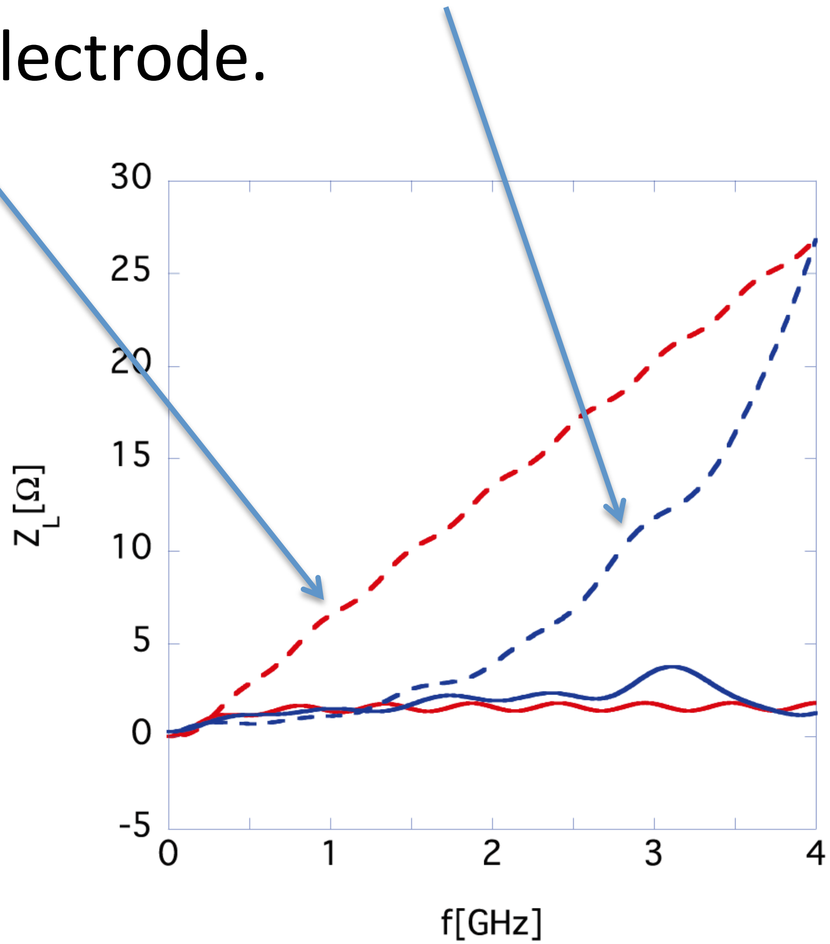
Coupling impedance of the electrodes

- 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 δ'-wake function*.

◆ The theoretical and the simulation results for the exponential electrode.

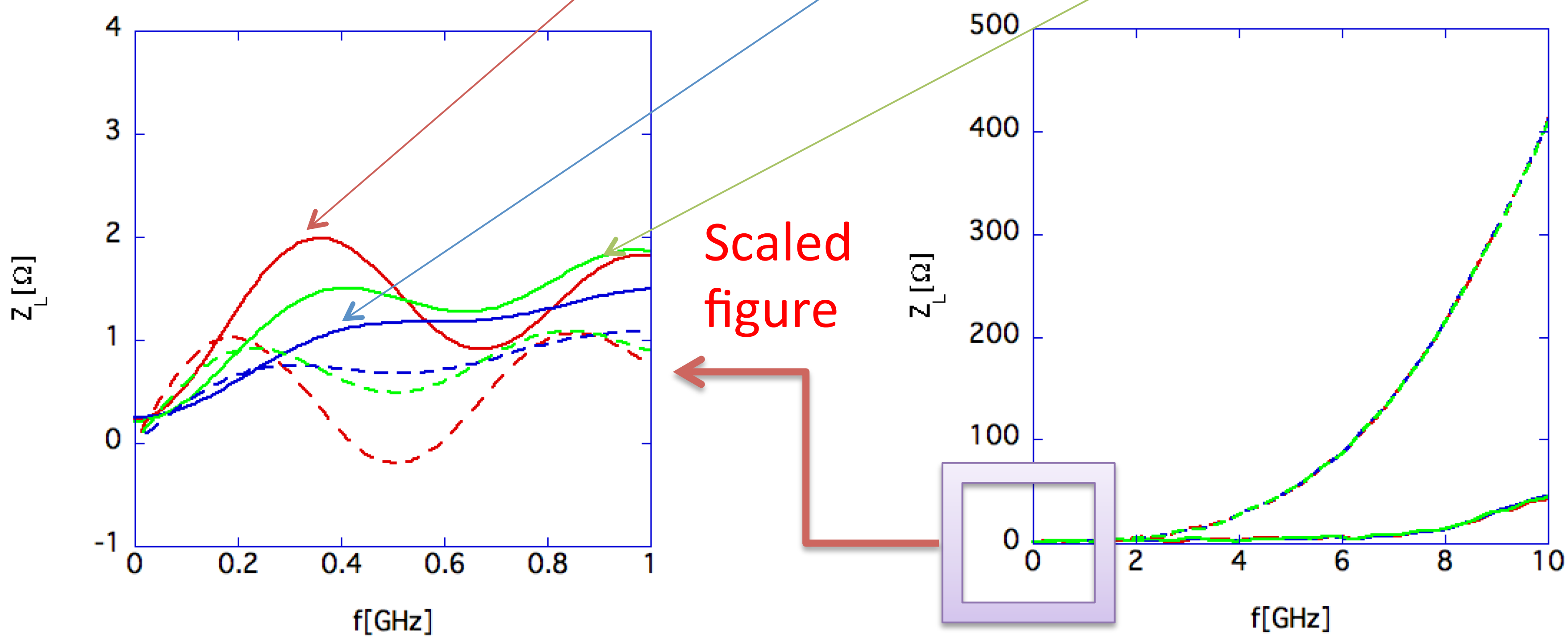


- Both results are the same order of magnitude.
- The impedance is theoretically inductive, and indicates the wake function behaves like the δ'-function.

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.)*

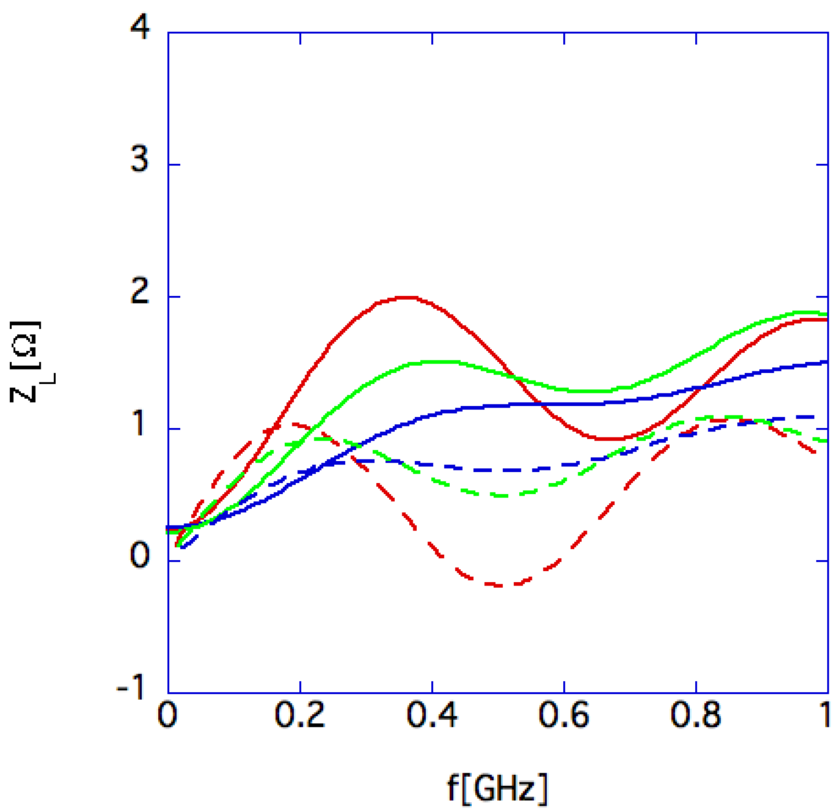


The difference is invisible on this scale.

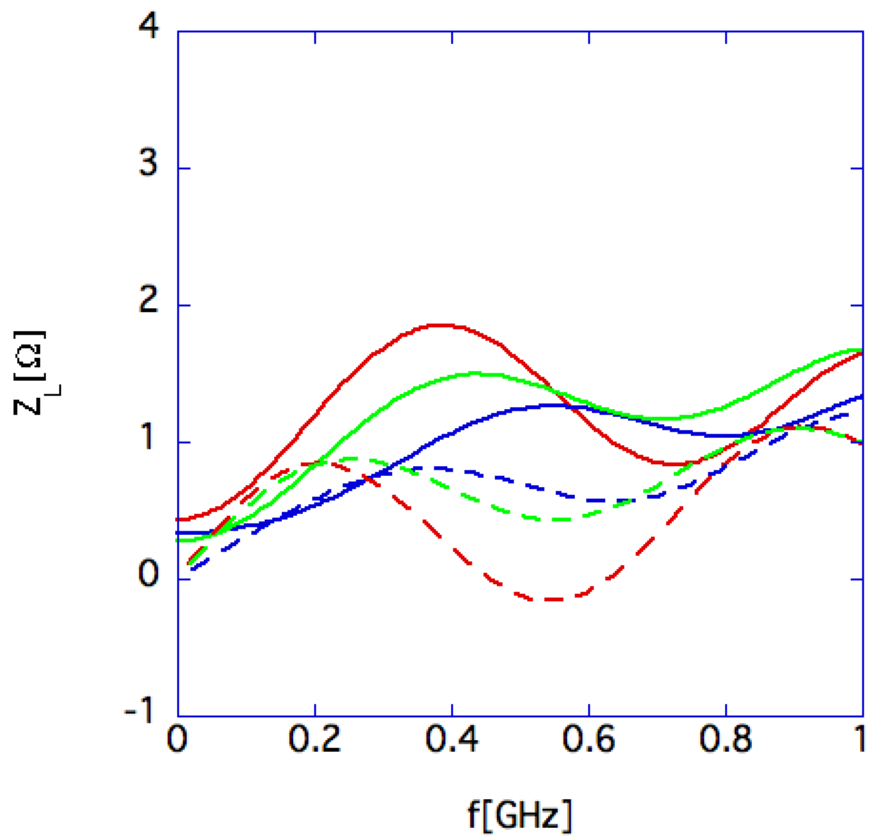
- No significant difference among the different electrodes.

● The effect of the apron on the impedances

Without apron



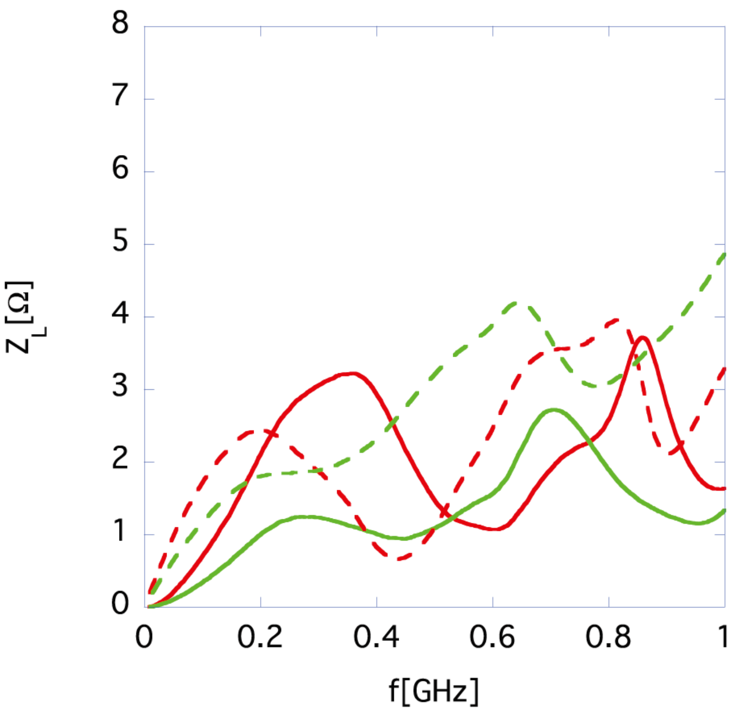
With apron



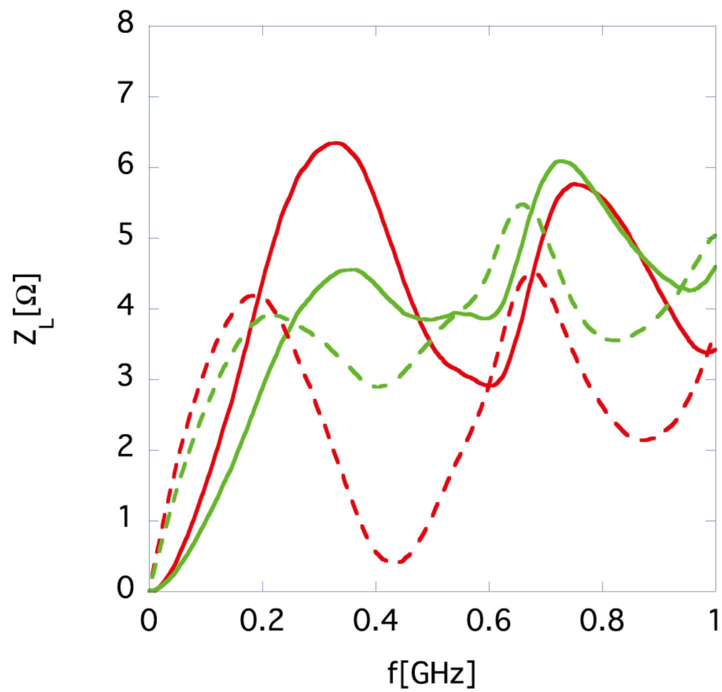
● The impedances do not depend on the existence of the aprons.

Measurement results for triangle, and pentagon.

Without apron



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.