Wideband Stripline BPM for Precise Measurements of Internal Bunch Motion in Proton Synchrotrons

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Contents

- Introduction
- Improvements
  - principle of the device
  - practical problem
  - possible solutions?
    a) Concave polygon
    b) 3D exponential
- Application
  - intra-bunch feedback @J-PARC MR
- Conclusion

Wideband beam position monitor is necessary for

Observing various instability

Sensor of feedback

as well as other components:

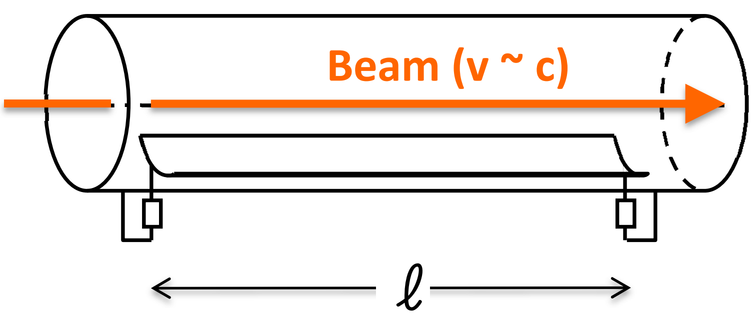
kicker, amplifier, processor, cable

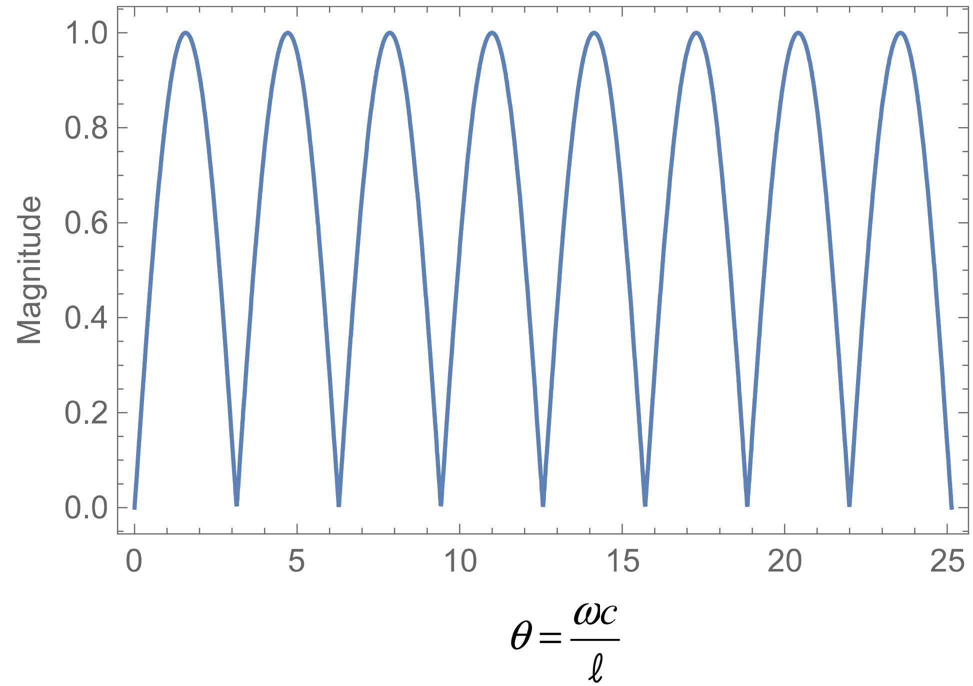
Stripline (rectanguler)

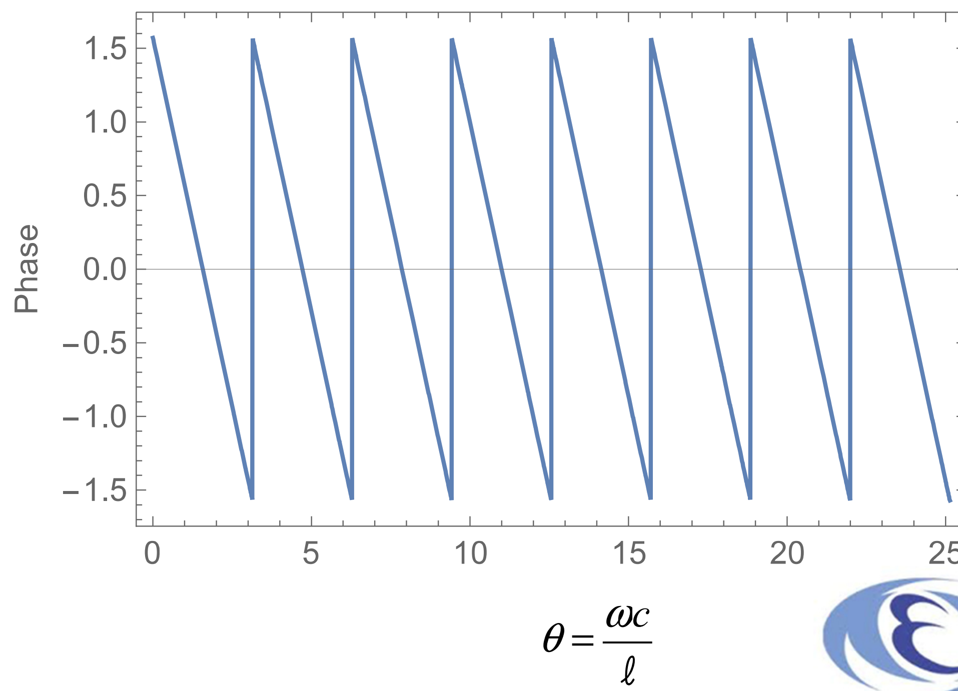
$$k(z) = k_0$$ coupling constant

Frequency response

$$F(\omega) = j\ k_0\, e^{-j\omega\ell/c} \sin(\omega\ell / c)$$



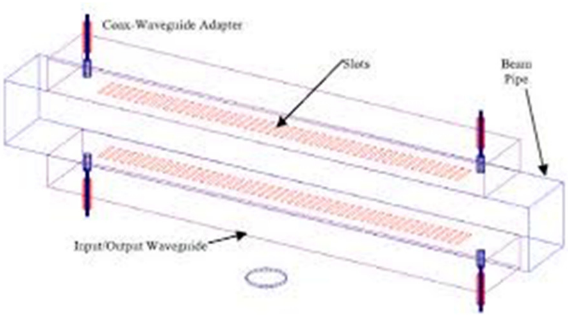


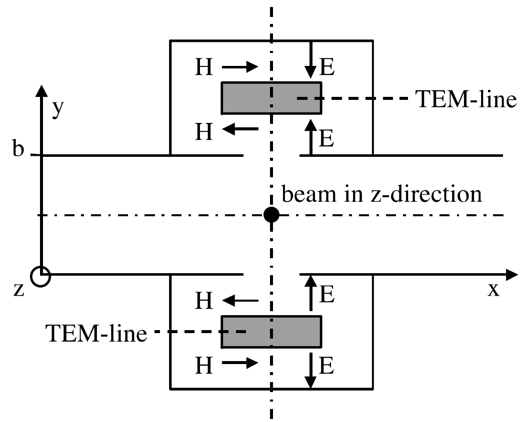


Several wideband pickups has been proposed and used . . .

Slot-type structure . . .

L. Faltin, NIMA241 (1985) 416-428.





L. Faltin, Slot-type pick-up and kicker for stochastic beam cooling, Nucl. Instrum. Methods **148**, 449 (1978).

F. Caspers, Planar slotline pick-ups and kickers for stochastic cooling, Report No. CERN-PS-85-48-AA, 1986.

C. Peschke, F. Nolden, and M. Balk, Planar pick-up electrodes for stochastic cooling, Nucl. Instrum. Methods Phys. Res., Sect. A **532**, 459 (2004).

J. M. Cesaratto, J. D. Fox, C. H. Rivetta, D. Alesini, A. Drago, A. Gallo, F. Marcellini, M. Zobov, S. De Santis, Z. Paret, A. Ratti, H. Qian, H. Bartosik, W. Hofle, and C. Zannini, SPS wideband transverse feedback kicker: design report, Report No. CERN-ACC-NOTE-2013-0047, SLAC report number: SLAC-R-1037, 2013.

slotted wave guide slow wave arrays
McGinnis, PAC1999, 1713

We concentrate on the stripline pickups here

One of the promising detector
is the "tapered-coupler"

First introduced in the CERN SPS by Linnecar
back to 1970's

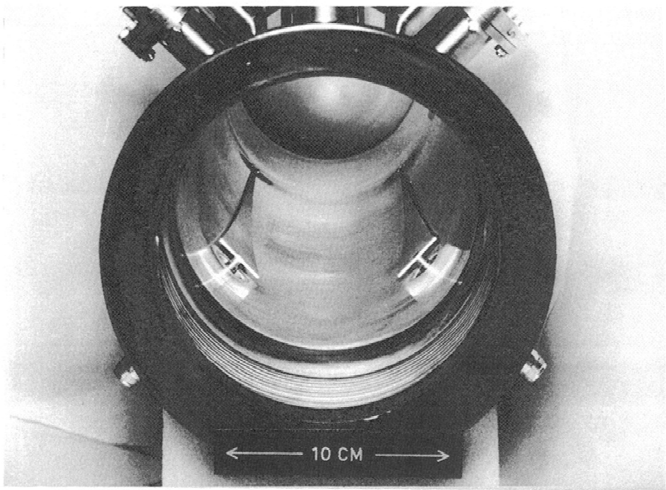
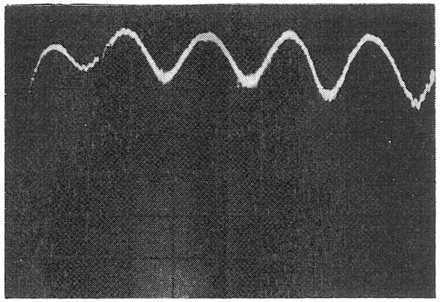
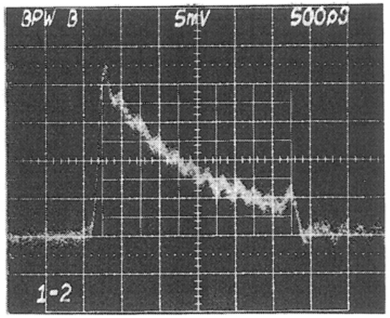


Fig. 31b - Interior of directional coupler pick-up



Frequency response of sum signal from directional coupler pick-up
200 MHz/div 2.5 dB/div



c) Stripline output
5 mV/div 500 ps/div

Fig. 33 - Response of single stripline to test pulse

Linnecar, CERN-SPS-ARF-SPS/78/17

Principle of the stripline pickup / directional coupler

One of the reference in the Linnecar's paper

the IRE, May 7, 1952; revised manuscript received, August 12, 1954.
† Formerly Bell Telephone Labs., Inc., Murray Hill, N. J.; now Hewlett-Packard Company, Palo Alto, Calif.
[1] J. R. Carson and R. S. Hoyt, "Propagation of periodic waves over a system of parallel wires," *Bell Sys. Tech. Jour.*, vol. IV, no. 3, pp. 495–545; July, 1927.
[2] L. A. Pipes, "Matrix theory of multiconductor transmission lines," *Phil. Mag.*, vol. 24, pp. 97–100; 1937.
[3] S. Koizumi, "Mehrpolleitungstheorie," *Arch. für Electrotech.*, vol. 33, pp. 171–188, 609–622; 1939.

$$\frac{e_2}{e_1} = \pm\sqrt{\frac{L_{22}}{L_{11}}} = \pm\sqrt{\frac{C_{11}}{C_{22}}} \qquad (2)$$

$$e_1 i_1 = e_2 i_2. \qquad (3)$$

The choice of the plus sign corresponds to "lateral" excitation in Fig. 1(a), the minus sign to "diagonal"

Since this is the characteristic impedance of line 1 in the presence of line 2, the voltage and current at BB' will still be zero if the conductors AB and $A'B'$ are extended an arbitrary distance to the left and then terminated in Z_a. This follows since the induction in each added elemental section produces no voltages or currents at its right-hand terminals. The entire induced voltage and current in each elemental section appear at the left and are of the proper relative polarity to launch a wave traveling to the left. Any voltage or current appearing at the extreme right is a result of reflection. We

gnetic Couplers

en the lines are identical (i.e. if $a_1 = a_2$, $d_1 =$ be written:

$$k = \frac{\log \sqrt{1 + \left(\frac{d}{s}\right)^2}}{\log \frac{d}{a}}.$$

nall coupling $[(d/s) \ll 1]$ this simplifies to

$$k \cong \frac{d^2}{2s^2} \frac{1}{\log \frac{d}{a}}$$

. for lines in air becomes

transform (spectrum) of $\frac{1}{2}k(vt/2)$. Thus, *the step function response is one half the coupling function $k(z)$ with $vt/2$ substituted for z*, i.e.

$$s(t) = \frac{1}{2}\, k\left(\frac{vt}{2}\right). \tag{14}$$

Further, since the impulse response, $f(t)$, is the time derivative of the step response we have

$$f(t) = \frac{v}{4}\, k'\left(\frac{vt}{2}\right). \tag{15}$$

Suppose now we wish to realize a coupler having a specified transmission $F(\omega)$ between input and coupled

Inverse Fourier transform

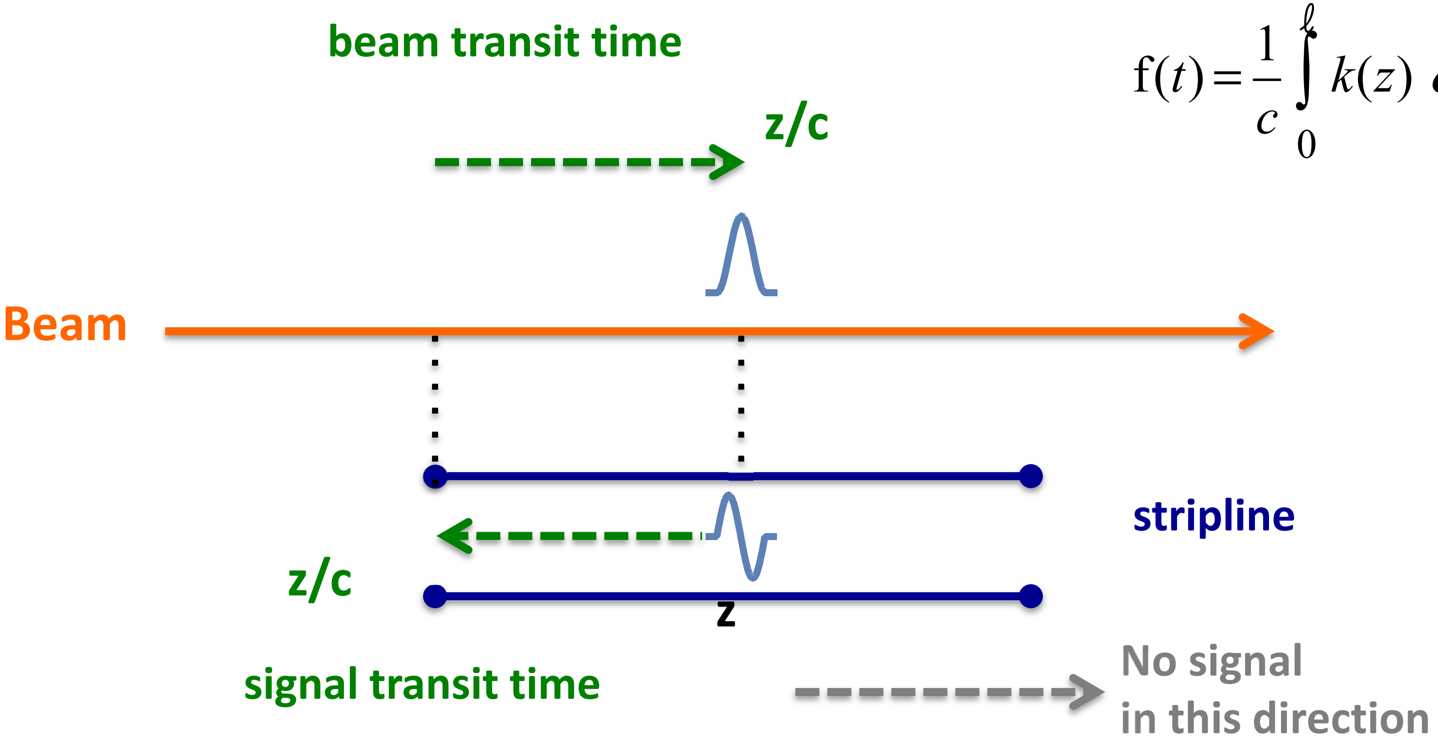
$$f(t) = \frac{1}{c}\int_0^{\ell} k(z)\ \delta'(t - 2z/c)\,dz$$

Differential of the delta function

Coupling constant

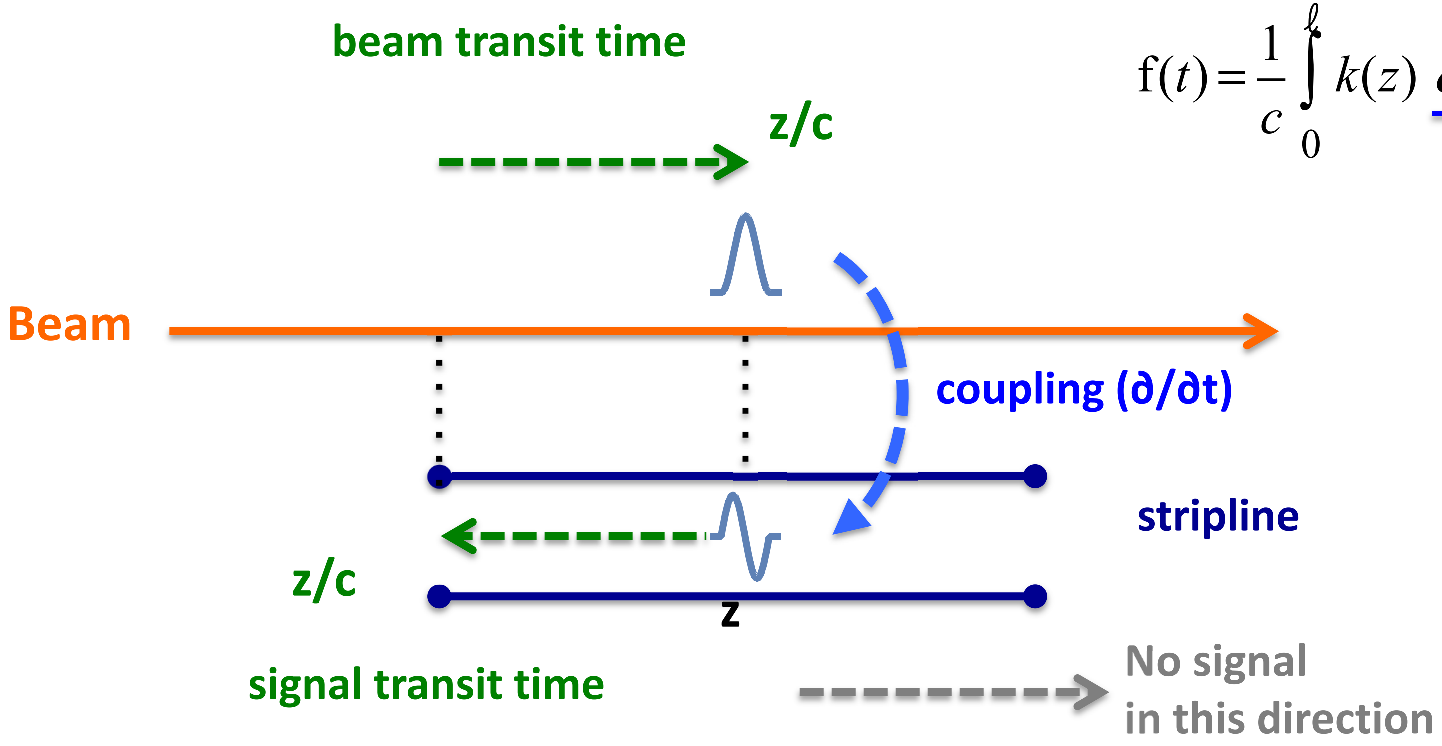
How is it possible to eliminate the notches and to improve the response?

$$f(t) = \frac{1}{c}\int_0^{\ell} k(z)\ \delta(t - 2z/c)\,dz$$



How is it possible to eliminate the notches and to improve the response?

$$f(t) = \frac{1}{c} \int_0^{\ell} k(z)\ \underline{\delta(t - 2z/c)}\, dz$$



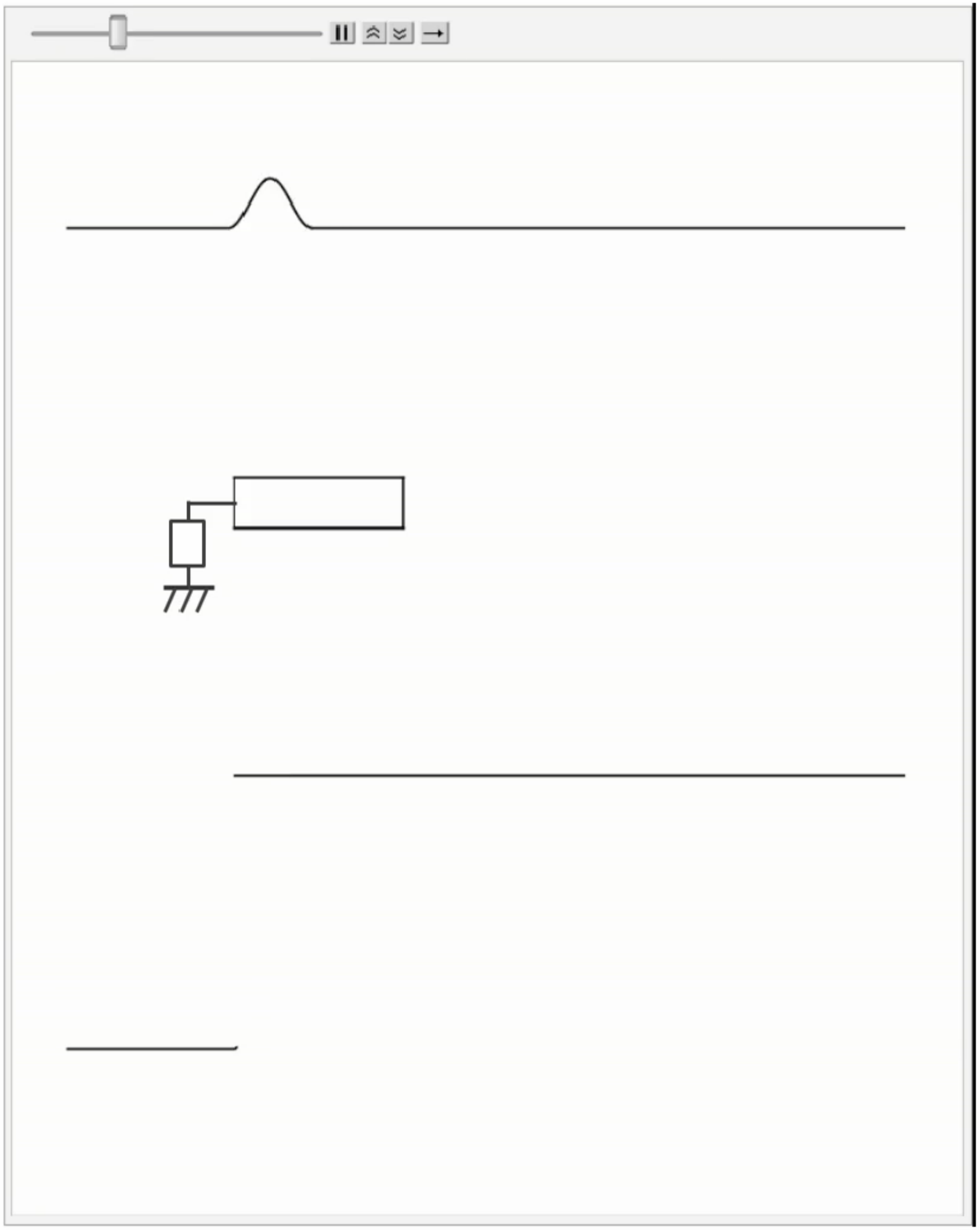
Stripline (rectanguler)

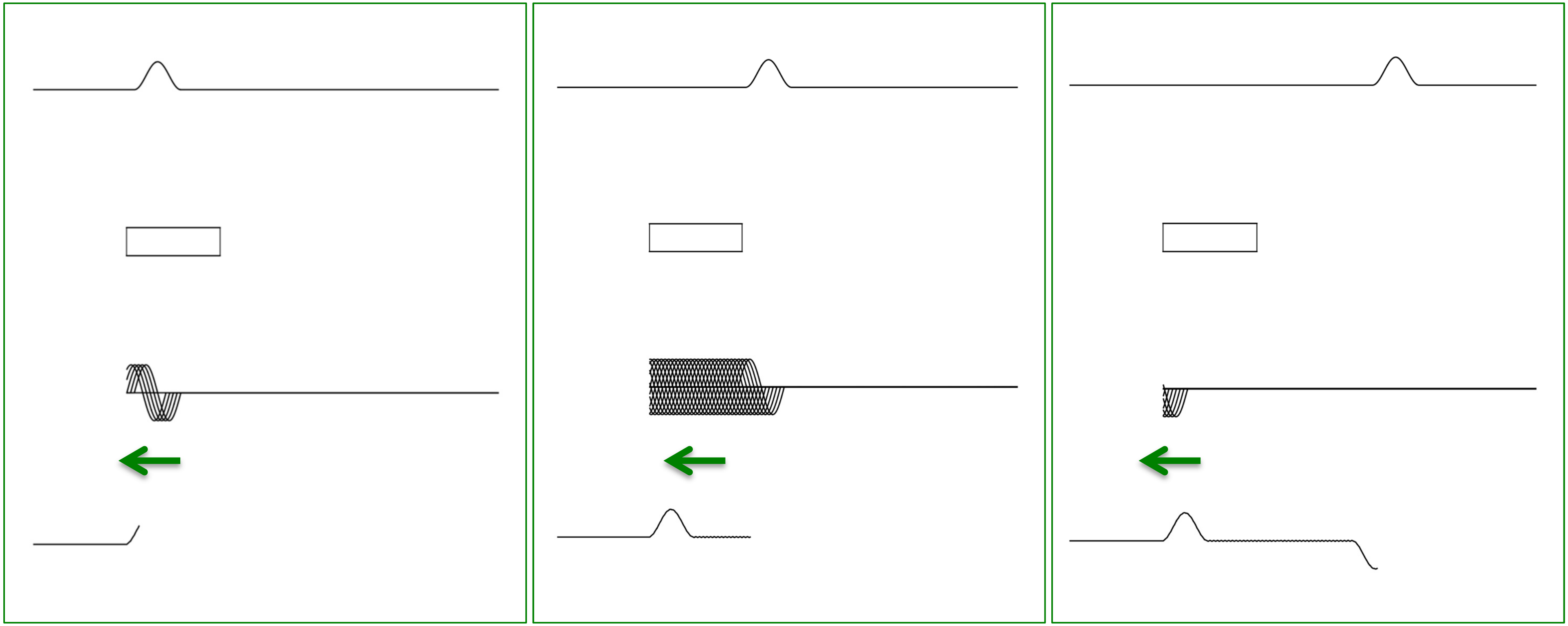
Beam

Stripline

Signal transmission

Signal observed at the upstream terminal





At first
signal is positive

positive and negative part
of successive pulses
cancel out

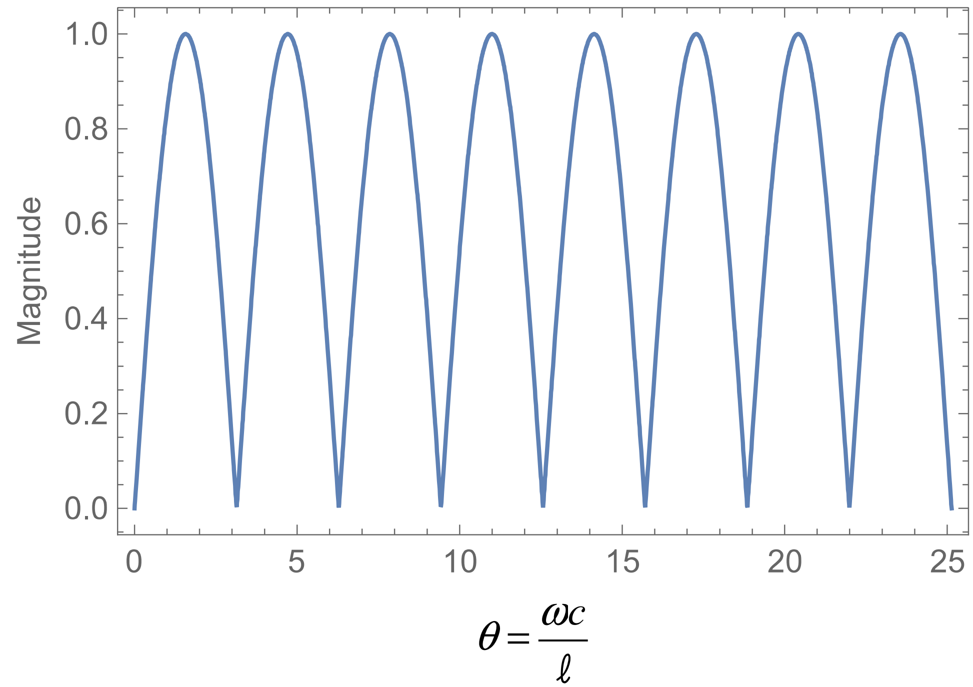
At the end
negative part
dominates

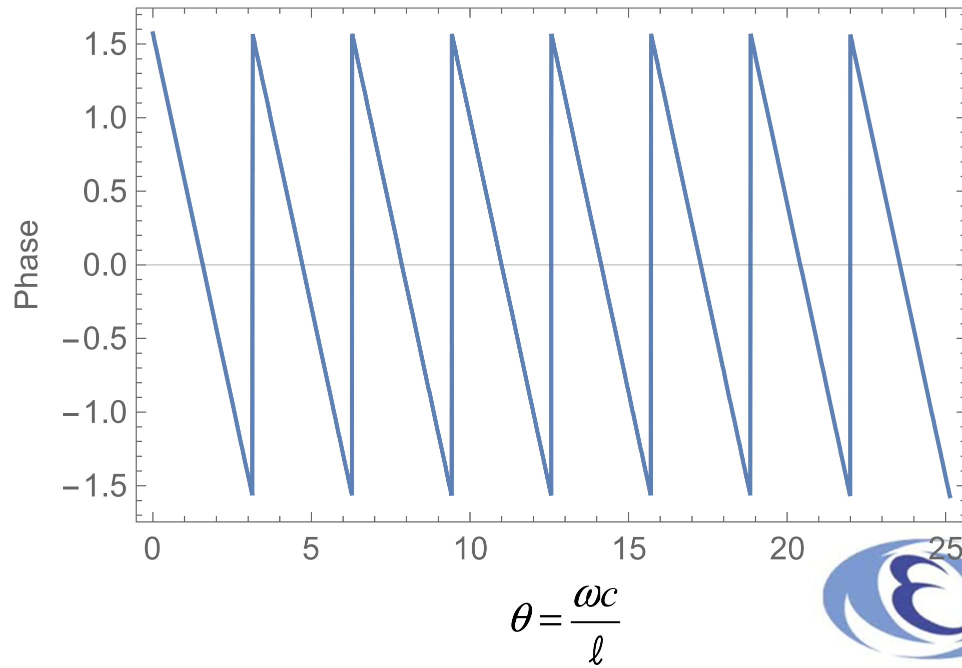
Stripline (rectanguler)

$$k(z) = k_0$$ coupling constant

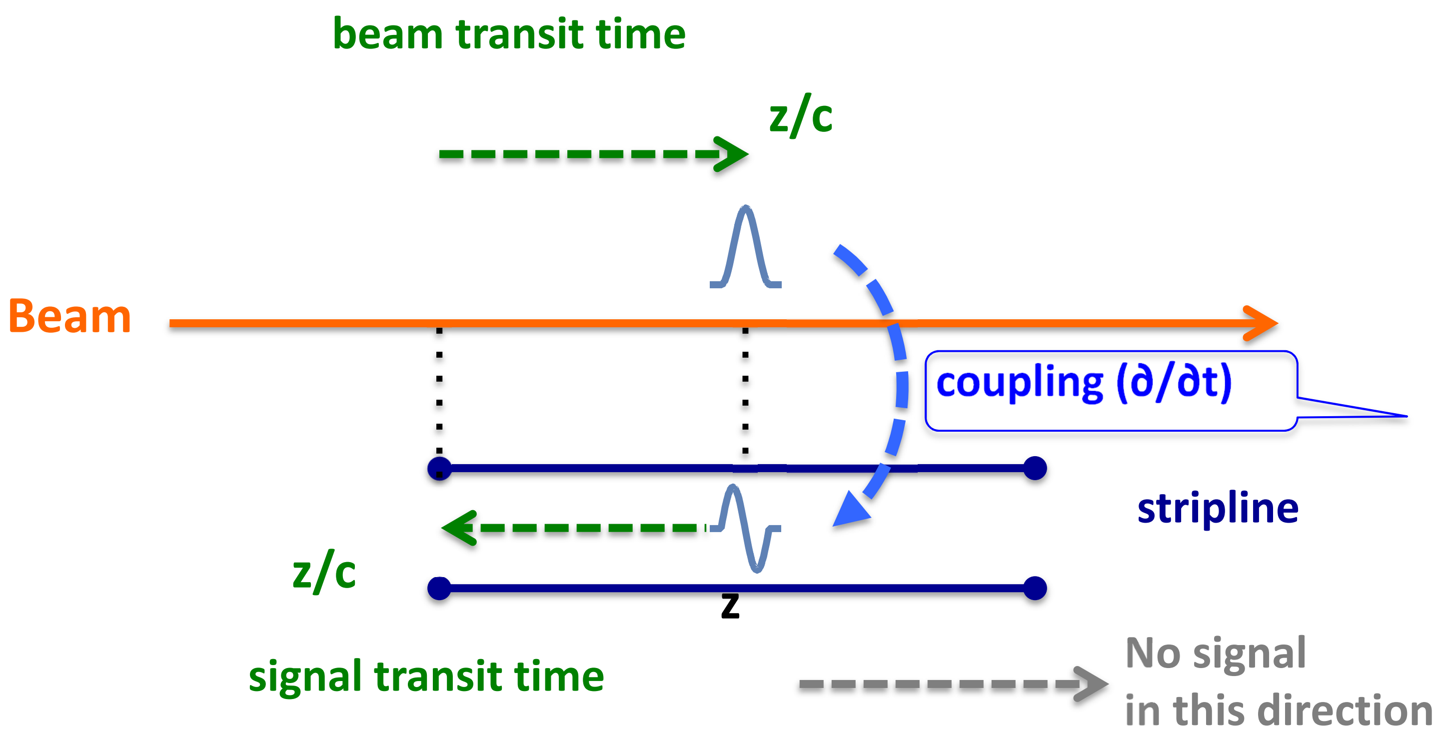
Frequency response

$$F(\omega) = j\ k_0\, \mathrm{e}^{-j\omega\ell/c} \sin(\omega\ell / c)$$





How is it possible to eliminate the notches and to improve the response?



- gradually decreasing
- keep Zc constant

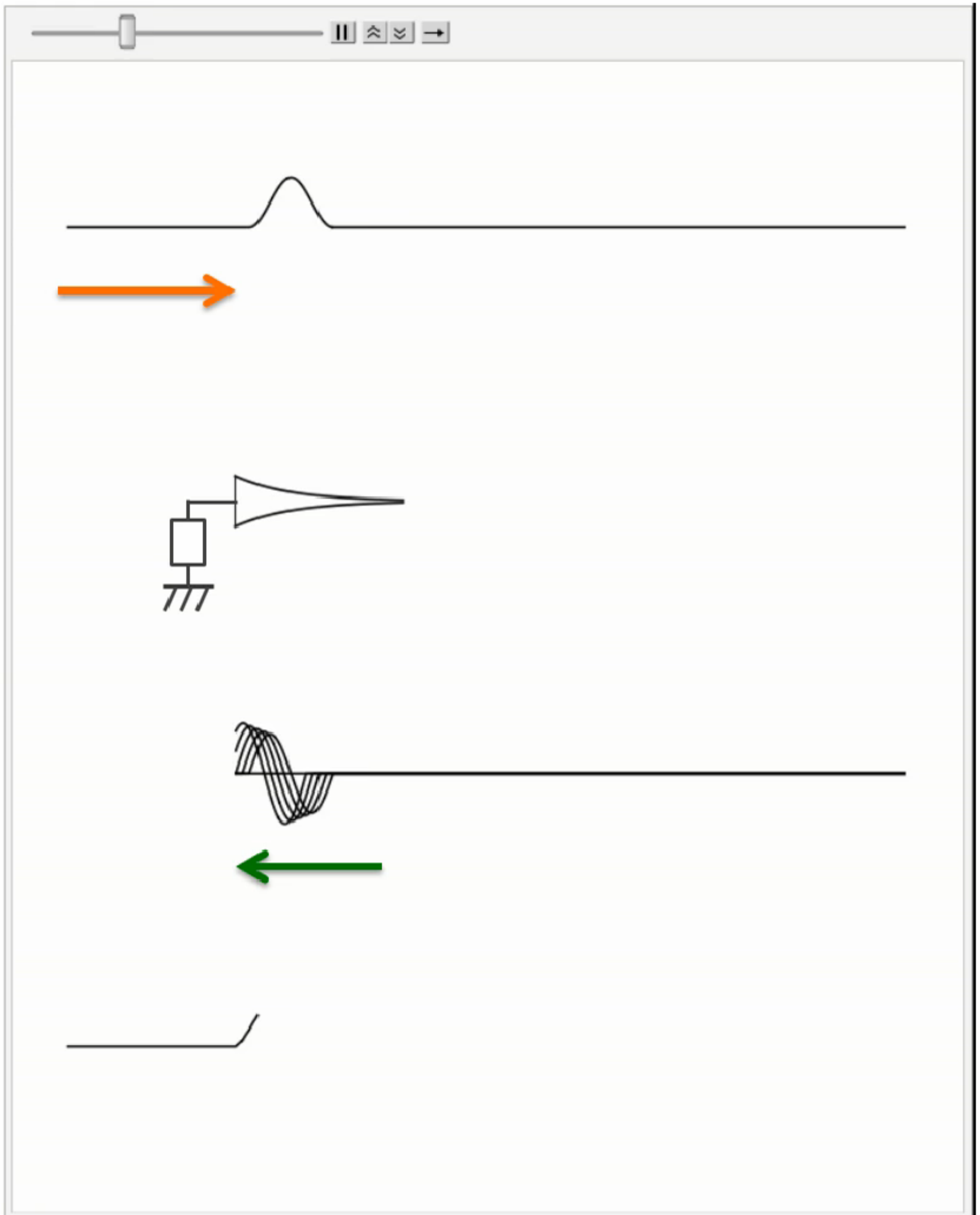
Stripline (exponential)

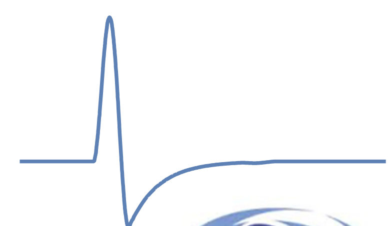
Beam

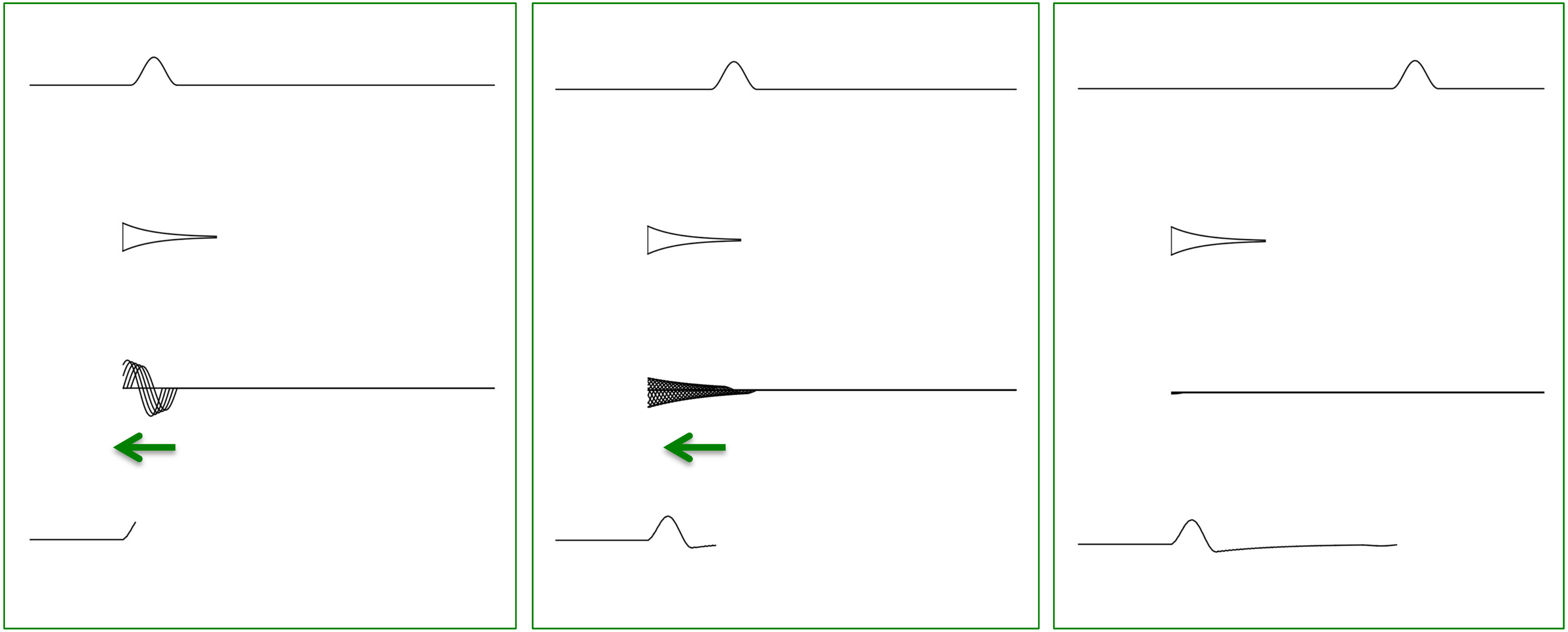
Stripline

Signal transmission

Signal observed at the upstream terminal







At first
signal is positive

positive and negative part
of successive pulses
cancel out
but slightly negative

At the end
almost zero

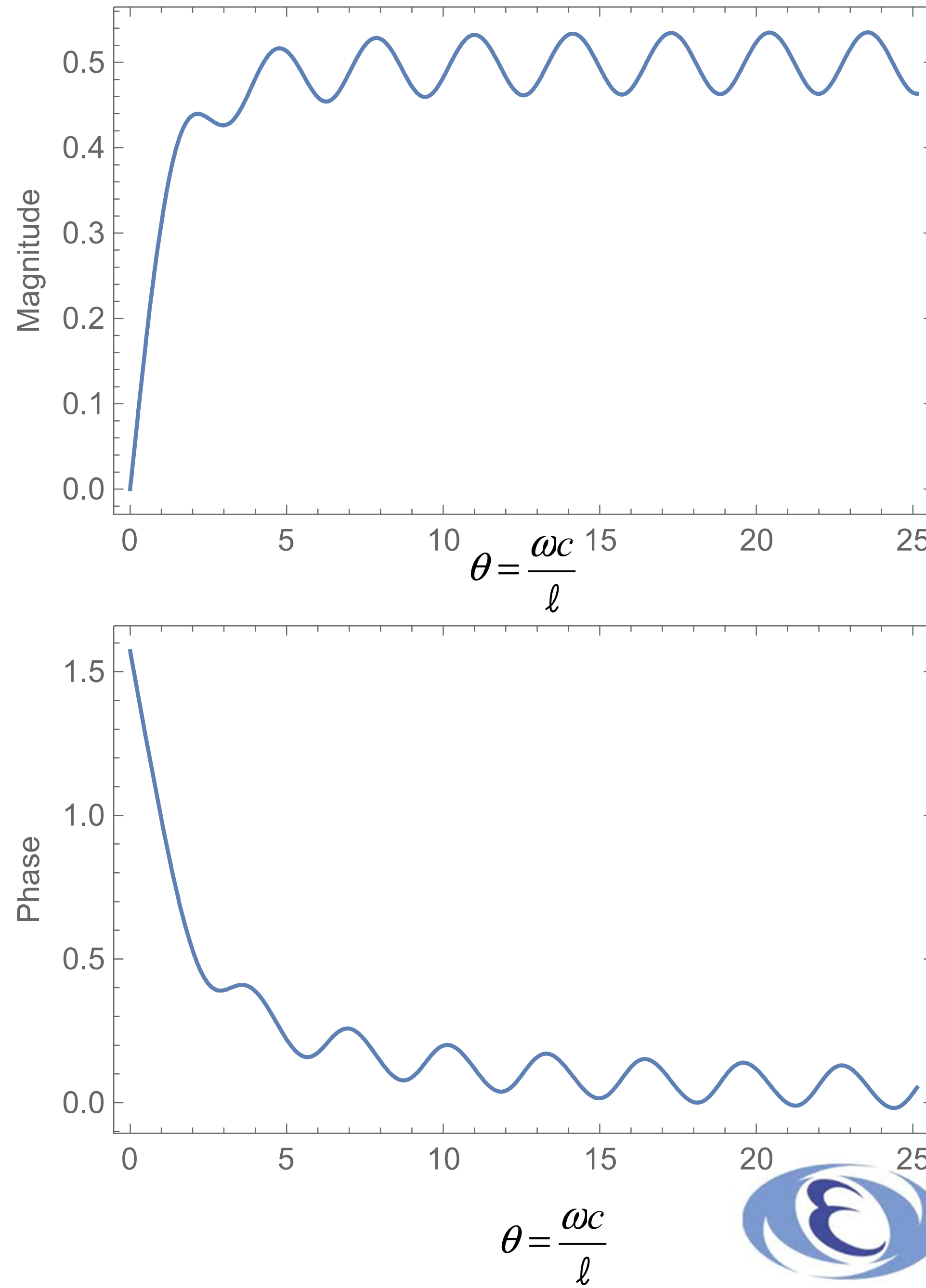
Stripline (exponential)

coupling constant

$$k(z) = k_0 e^{-\frac{a z}{l}}$$

Frequency response

$$F(\omega) = k_0 \frac{i\omega l(1 - e^{-a-i\frac{2\omega l}{c}})}{c(a + \frac{i2\omega l}{c})}$$



Exponetial tapered coupler
developed for SPS by T. Linnecar in 1970's
Reference: CERN-SPS-ARF-SPS/78/17

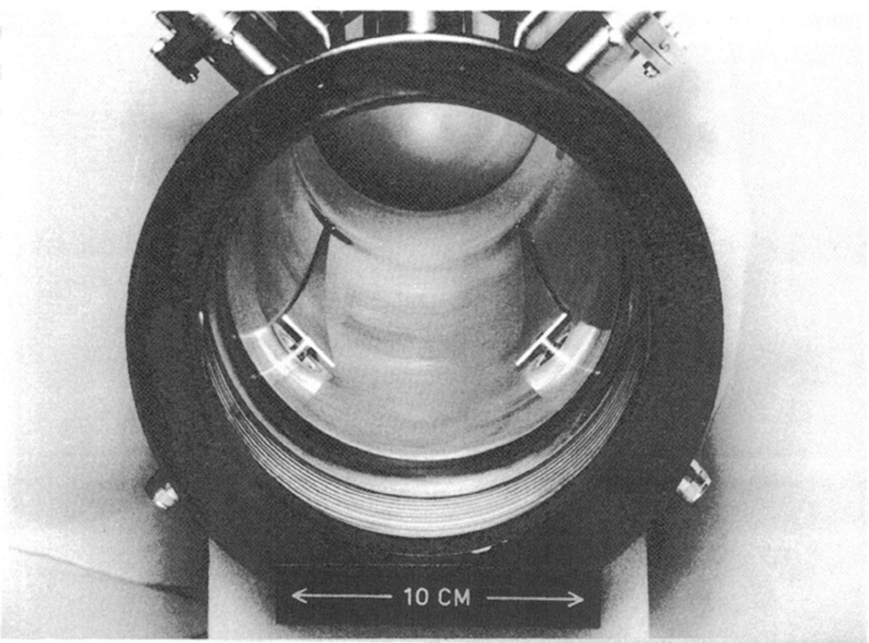


Fig. 31b - Interior of directional coupler pick-up

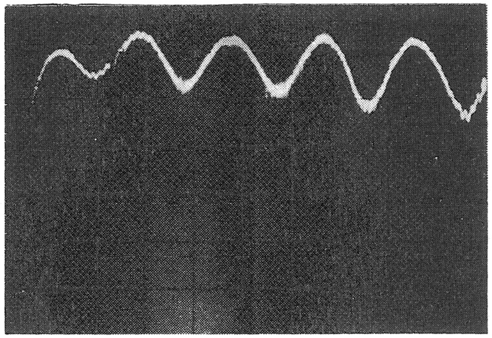
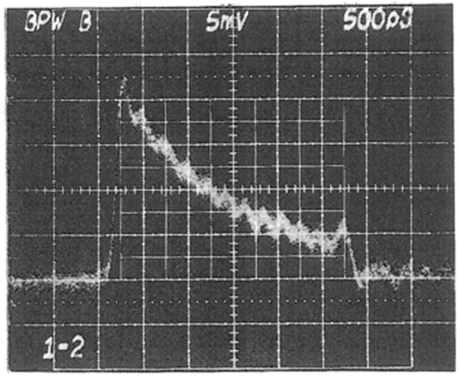


Fig. 37 - Frequency response of sum signal from directional coupler pick-up
200 MHz/div 2.5 dB/div



c) Stripline output
5 mV/div 500 ps/div

Fig. 33 - Response of single stripline to test pulse

Exponential electrode

CST Model

R. de Maria, IPAC2010, WEPEB054

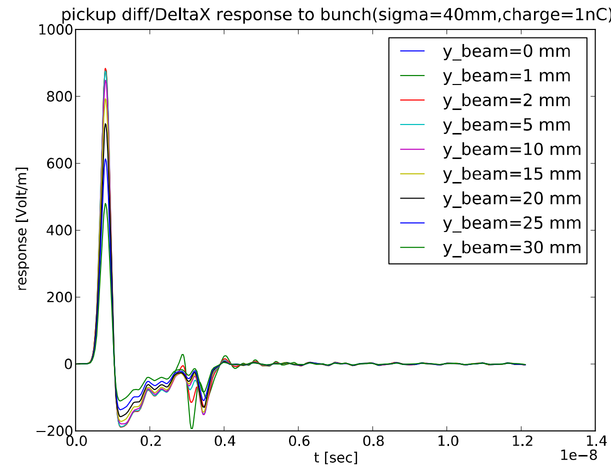
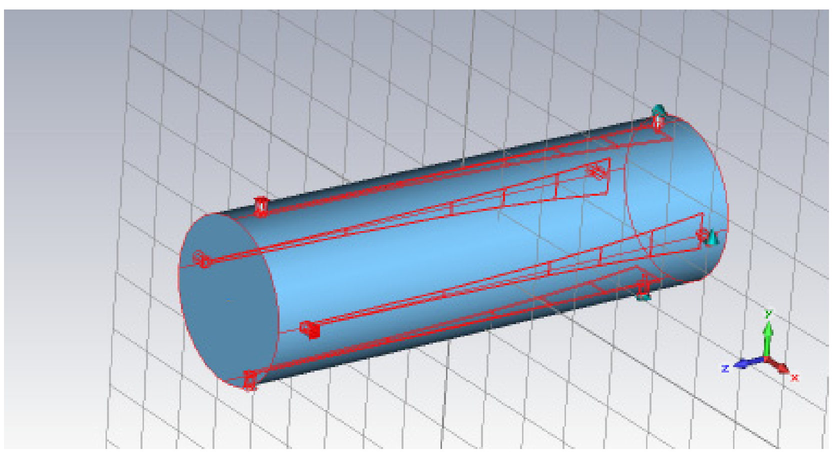


Figure 5: Pickup normalized displacement response in time domain



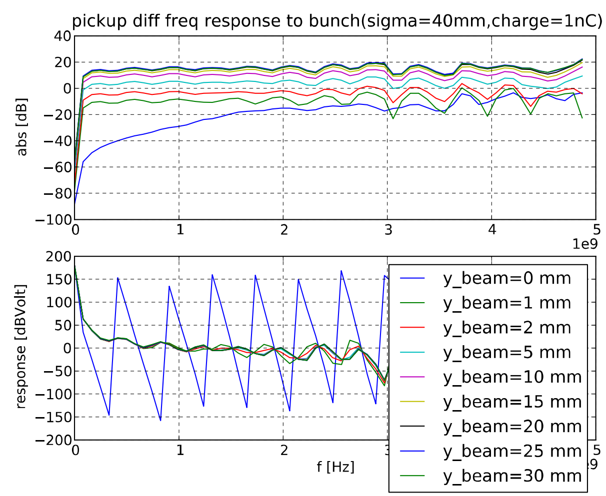


Figure 6: Pickup displacement response in frequency domain

T. Linnecar wrote in CERN-SPS-ARF-SPS/78/17

Finally, to conclude this section, it is plain that many different shapes for the stripline may be chosen. In particular, the equal ripple Chebyshev or even more complicated forms, could be used to reduce the ripple in the passband. This is a possibility for future development.

Theoretical best solution was surveyed

Y. Shobuda, Y.H. Chin, PRST-AB 17, 092801 (2014)

$$k(z) = k_0 \frac{(l-z)^\sigma}{l^\sigma},$$

σ = 2.63

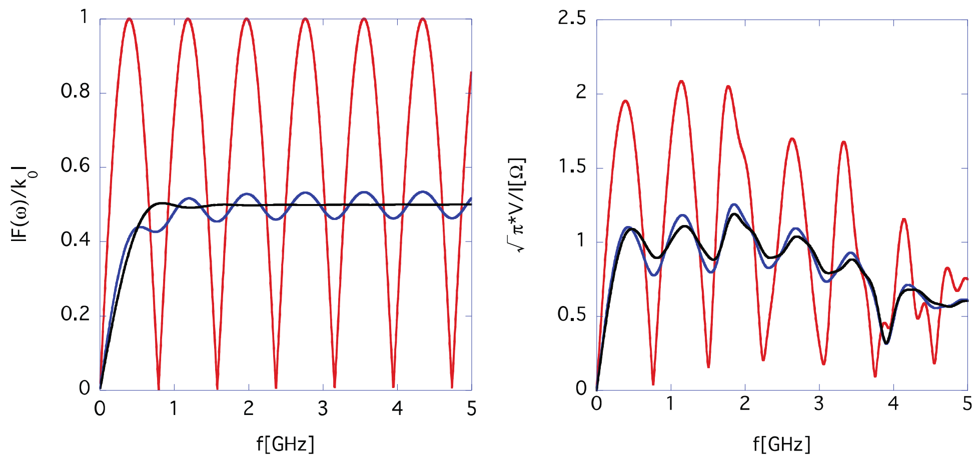
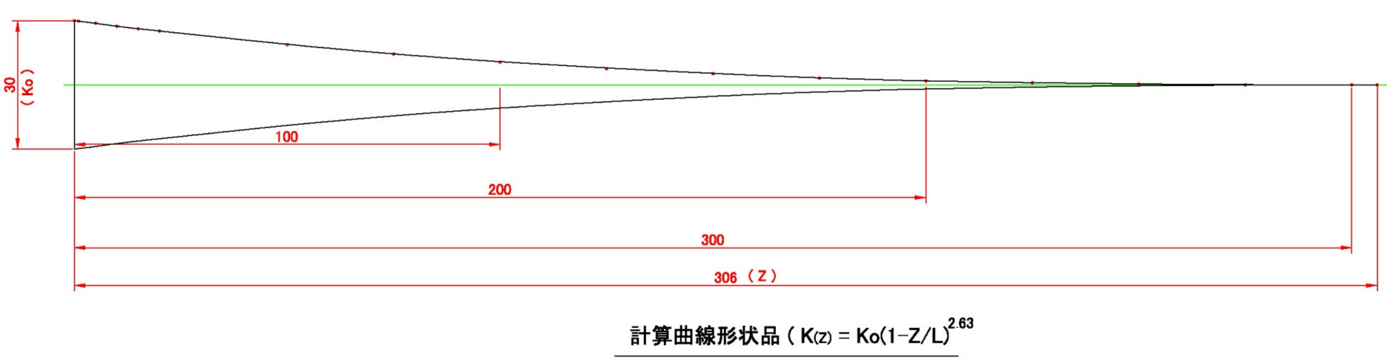


Figure 2: The theoretical (left) and the simulation (right) results of the transfer function $|F(\omega)|$.



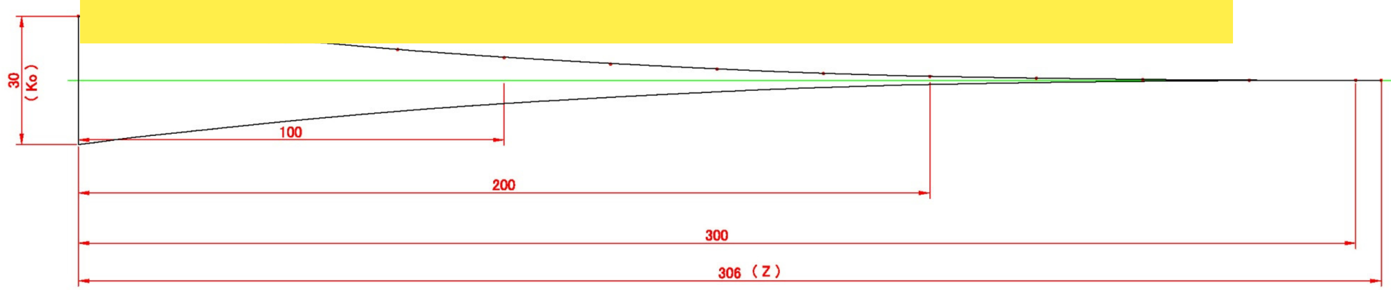
Theoretical best solution was surveyed

Y. Shobuda, Y.H. Chin, PRST-AB 17, 092801 (2014)

$$k(z) = k_0 \frac{(l-z)^{\sigma}}{\cdots}$$

…ulation (right)

Practically difficult



計算曲線形状品 ($K(z) = Ko(1-Z/L)^{2.63}$

One **exponential** coupler BPM was installed for
the horizontal and vertical intra-bunch feedback systems
In J-PARC MR

Taper electrodes should be bent down toward its tips
to keep Zc constant

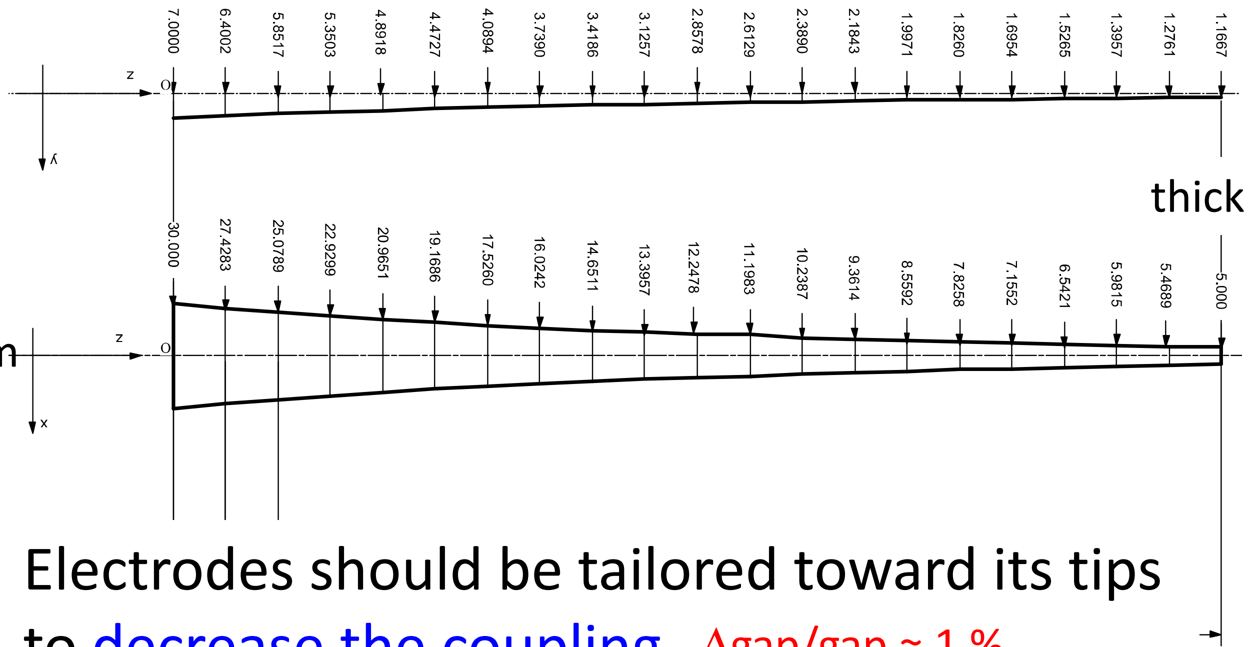
gap ~ 7.0 mm

gap ~1.7mm

thickness = 1.0 mm

width ~30 mm

width ~5 mm



Electrodes should be tailored toward its tips
to decrease the coupling

$\Delta gap/gap \approx 1\ \%$

$\Delta Z_C \approx 0.5\ \Omega$

keep mechanical strength and stability

One **exponential** coupler BPM was installed for the horizontal and vertical intra-bunch feedback systems In J-PARC MR

Taper electrodes should be bent down toward its tips to keep Zc constant

gap ~ 7.0 mm

gap ~1.7mm

ness = 1.0 mm

width ~30 mm

width ~5 mm

Practically difficult

Ele

to

$\Delta Z_C \approx 0.5\ \Omega$

keep mechanical strength and stability

Are there
more accurate, easier, efficient methods?

(1) Simpler electrode shape

Y. Shobuda et al., PRAB, 19, 021003 (2016)

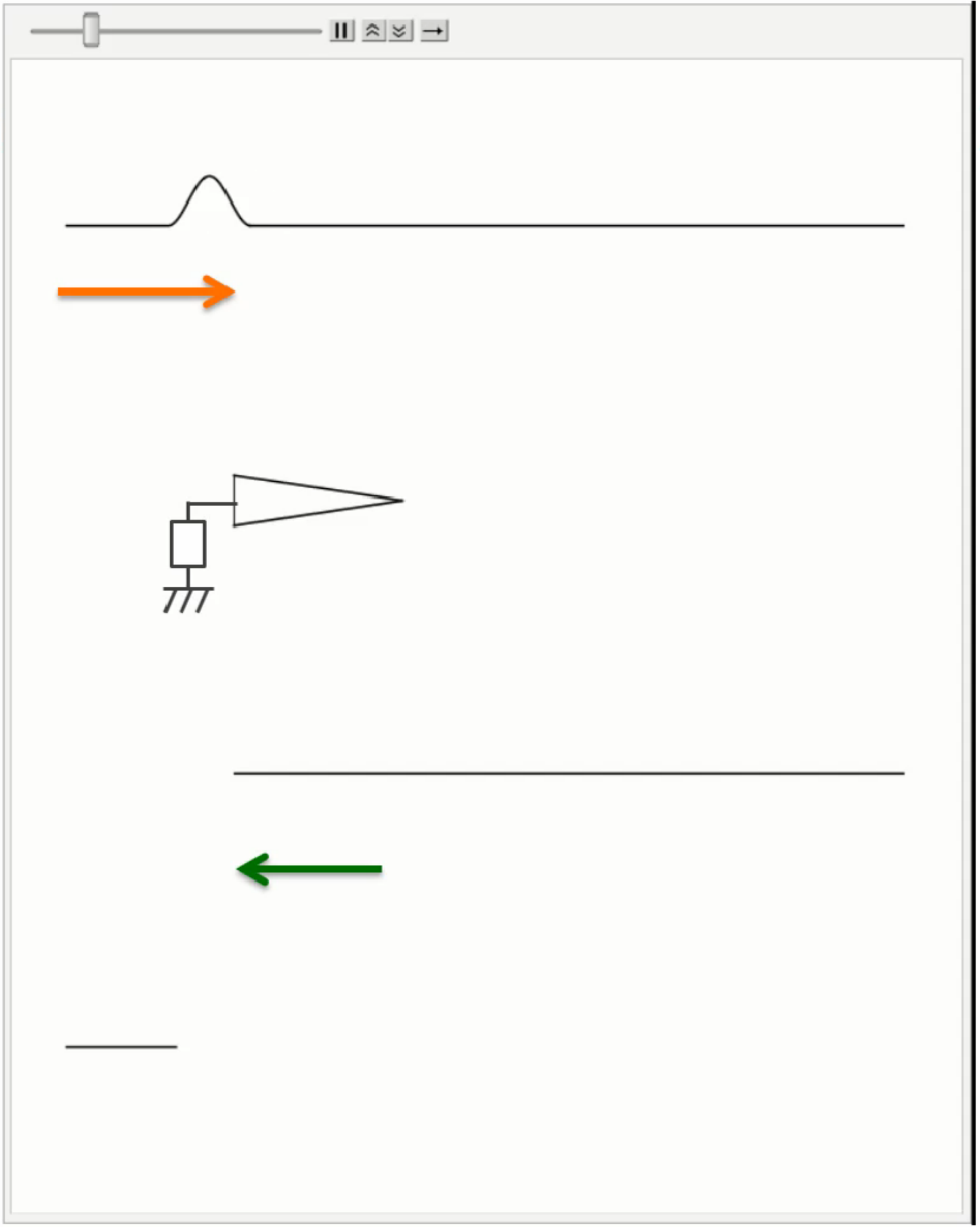
Stripline (Linear/triangle)

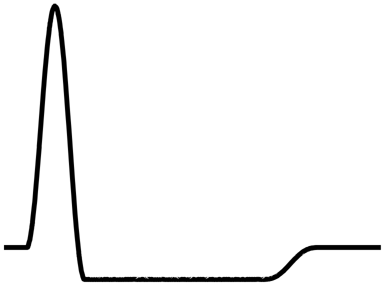
Beam

Stripline

Signal transmission

Signal observed at the upstream terminal





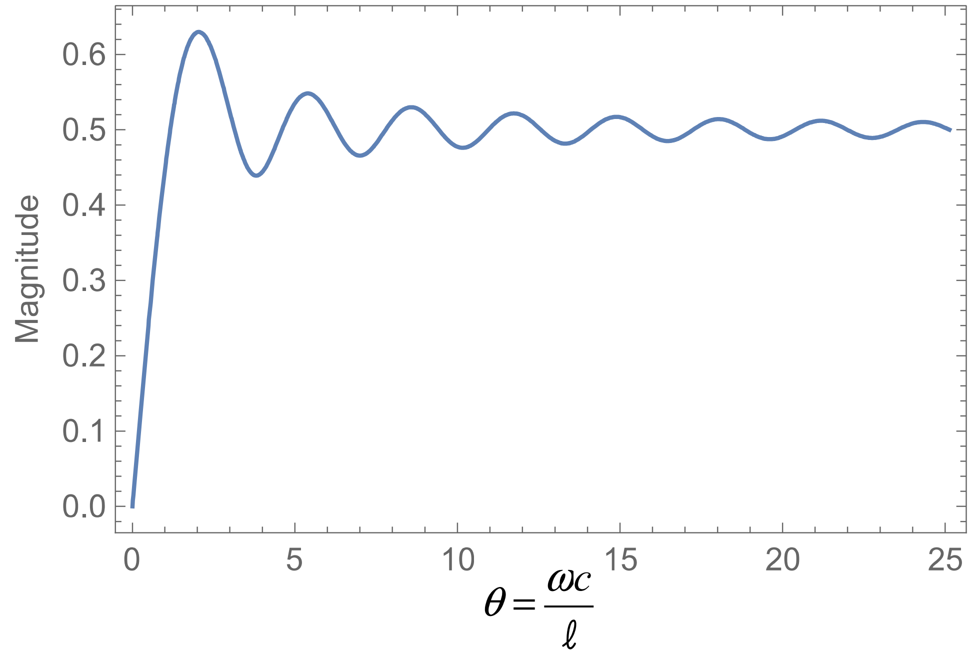
Stripline (linear/triangle)

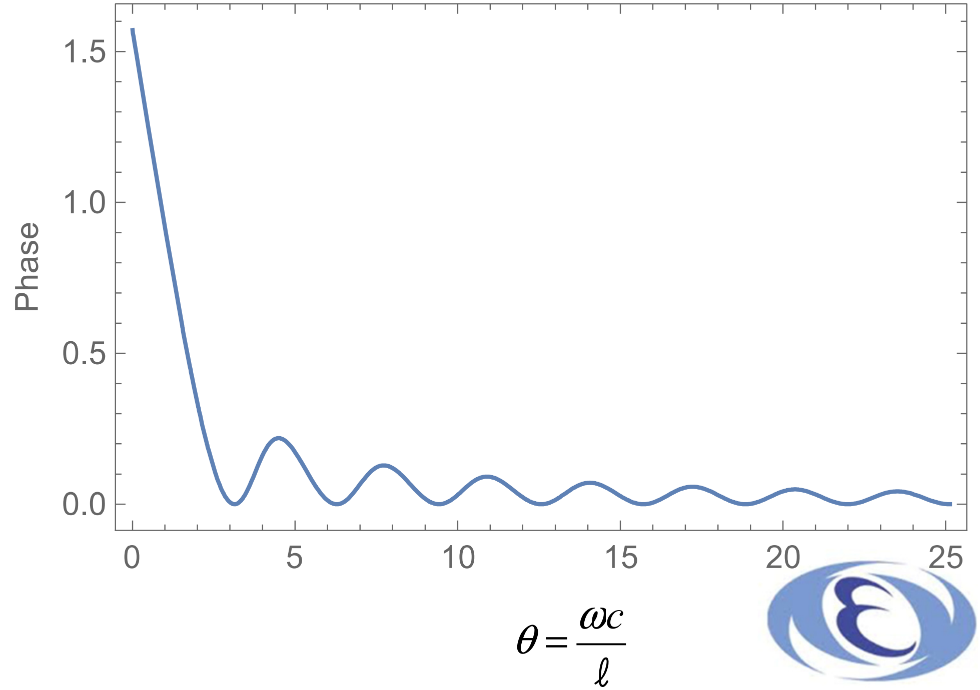
coupling constant

$$k_{triangle}(z) = k_0 \frac{(l - z)}{l}$$

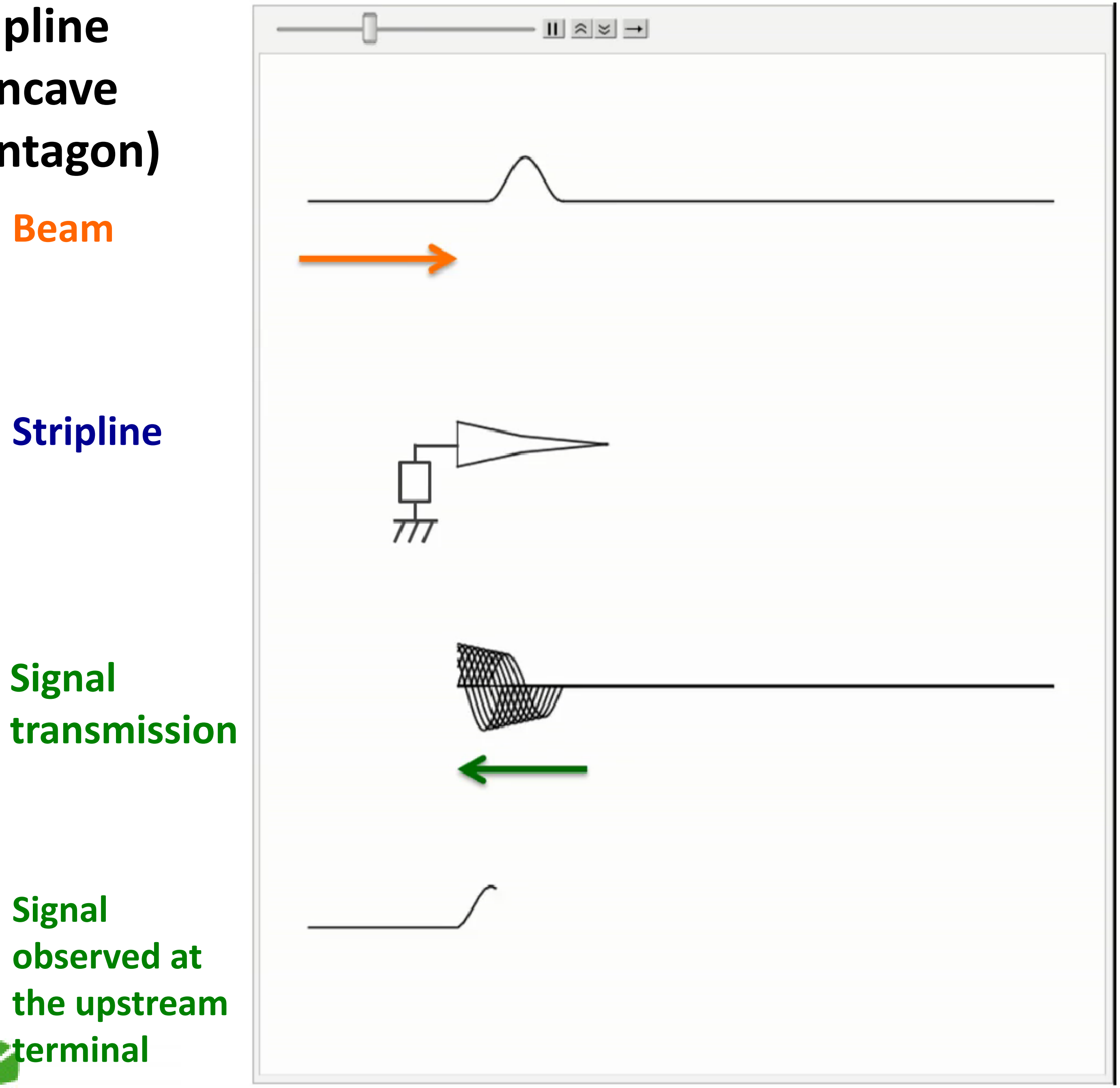
Frequency response

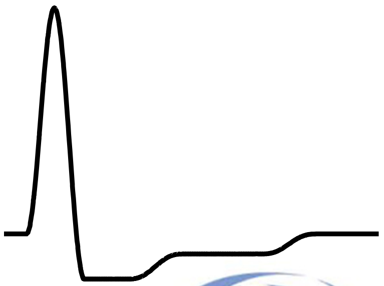
$$F(\omega) = \frac{k_0}{2} \frac{i(1 - i\frac{2\omega l}{c} - e^{-i\frac{2\omega l}{c}})}{\frac{2\omega l}{c}}$$





Stripline (concave pentagon)





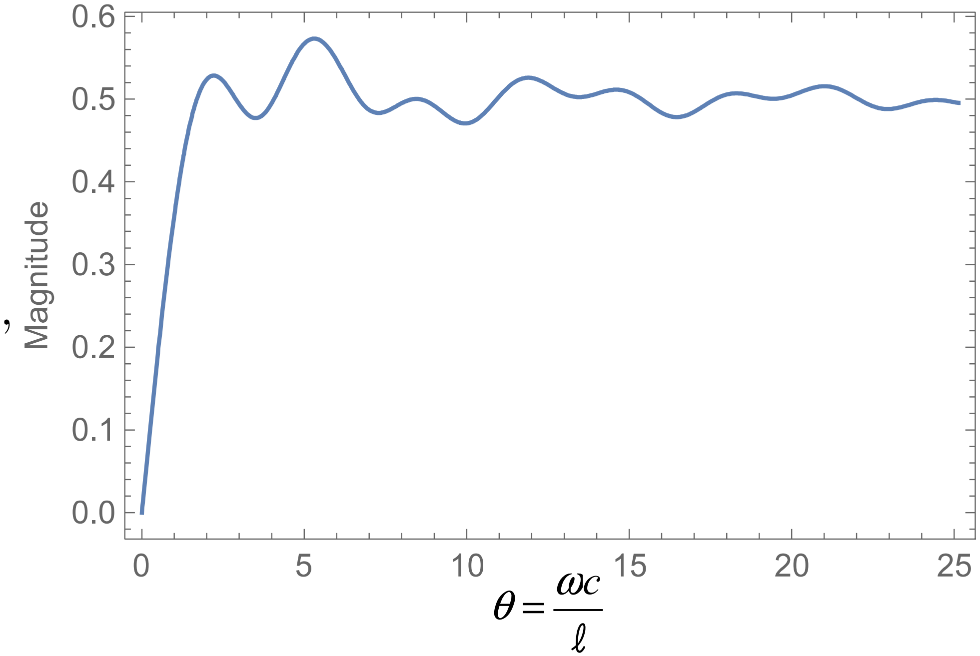
Stripline
(Concave pentagon)

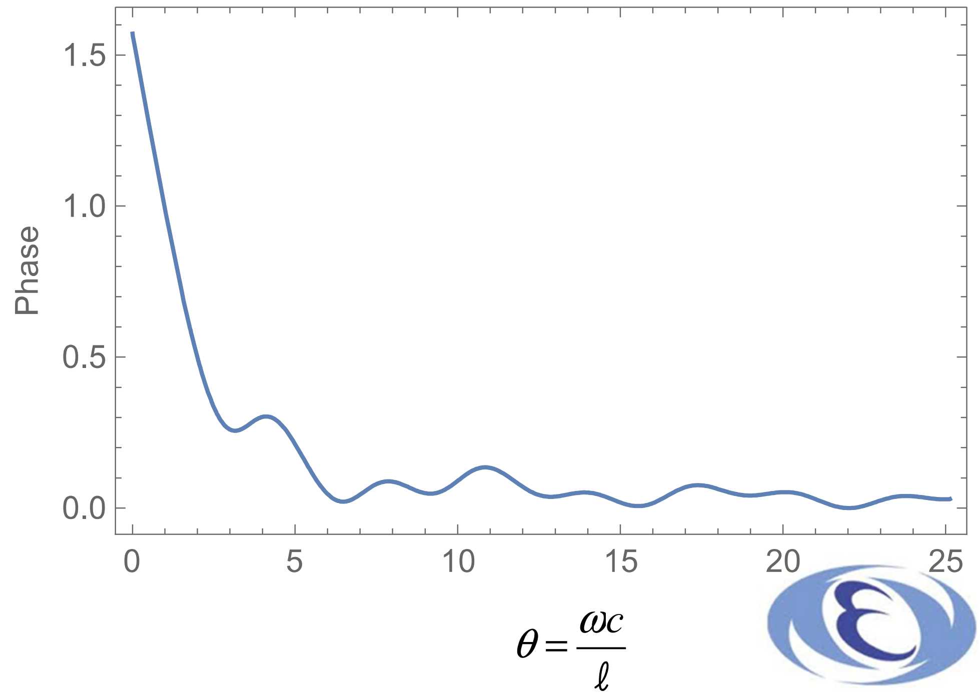
coupling constant

$$k_{pentagon}(z) = \begin{cases} k_0(1 - \frac{(1-y_0)z}{x_0}), \text{for } z \le x_0, \\ -k_0\frac{y_0(z-l)}{(l-x_0)}, \text{for } z > x_0, \end{cases}$$

Optimum parameter

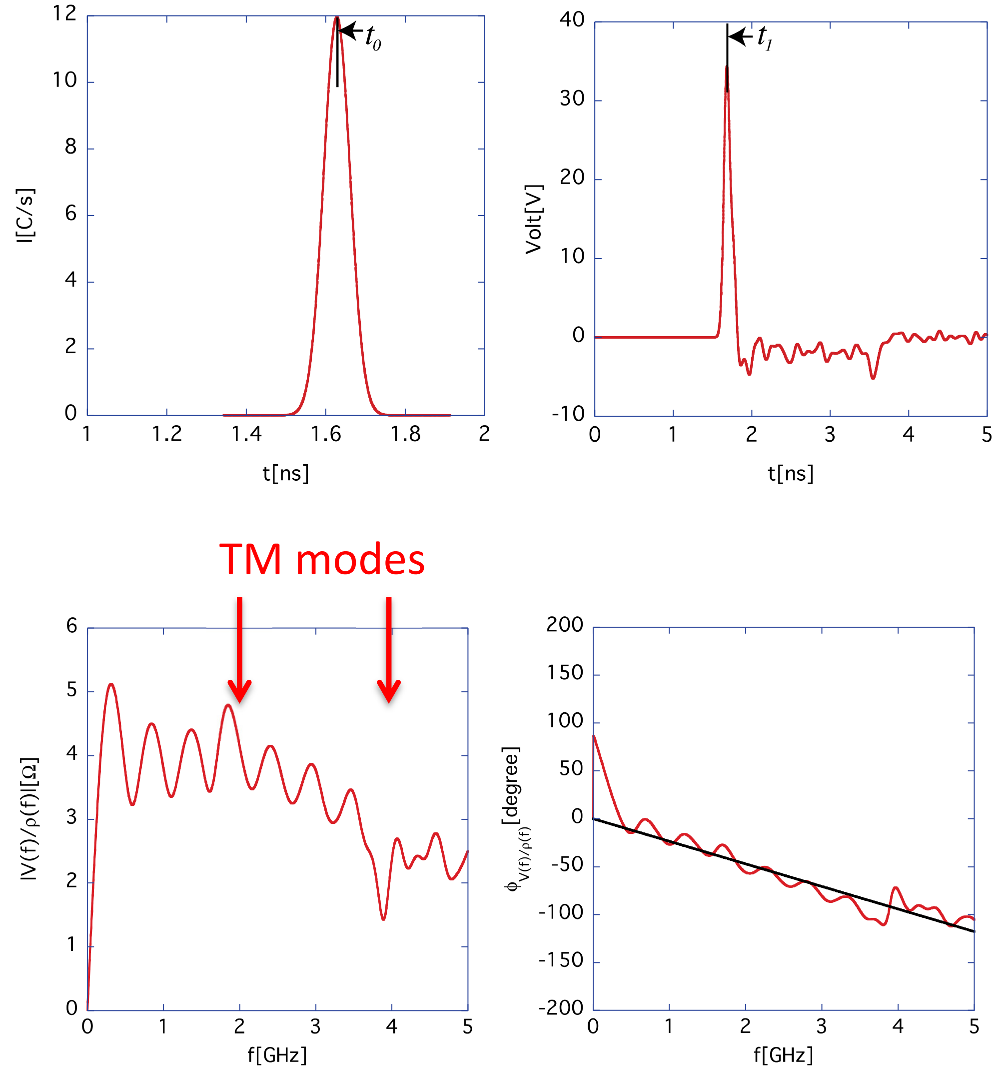
$$x_0 = \frac{8.5}{20}l, y_0 = \frac{7.5}{20}$$





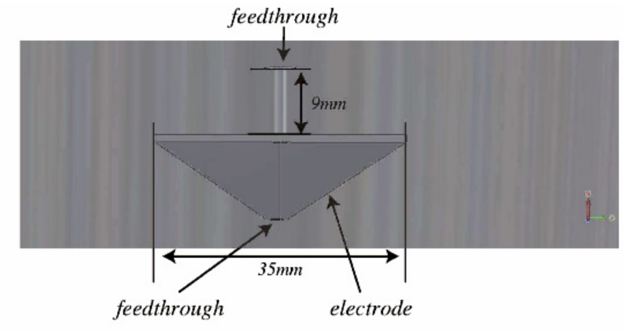
CST simulation

Triangle electrode

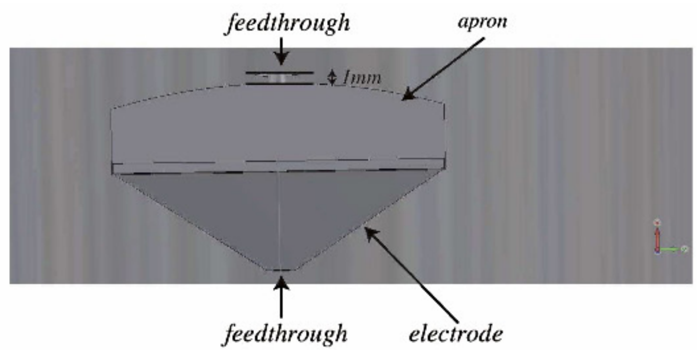


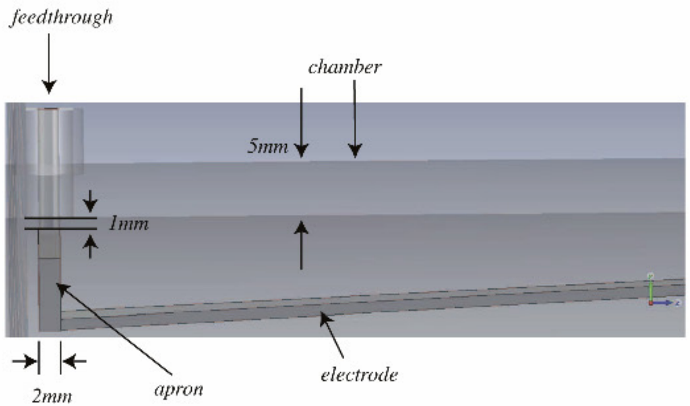
(pipe I.D. = 130 mm)

Conventional connection



With "apron"





Simulation

The **"Apron"** improves the frequency response up yo 4 GHz

(pipe I.D. = 130 mm)

Triangle

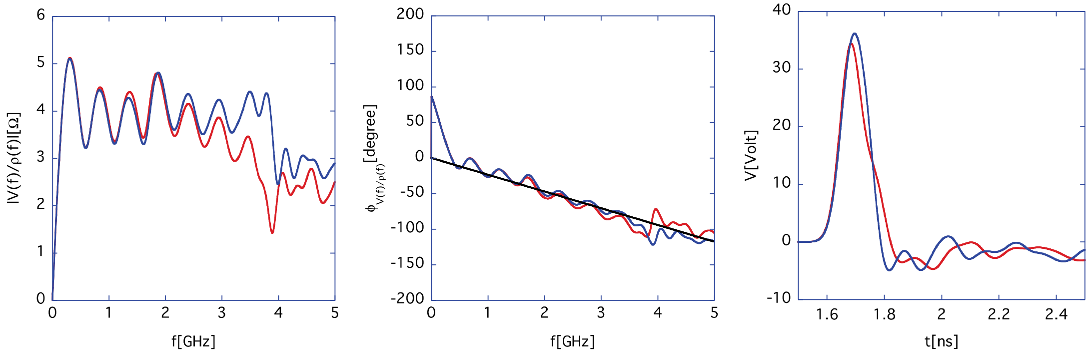


FIG. 11. The simulation results for the triangle electrode with (blue) and without (red) apron.

Concave Pentagon

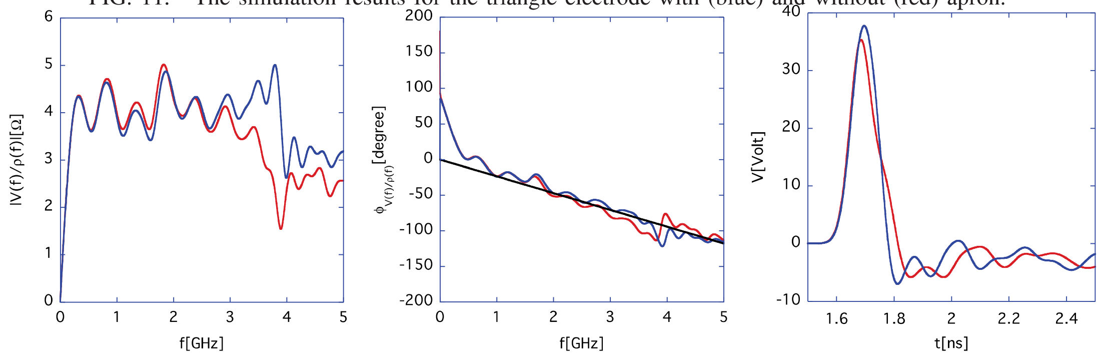
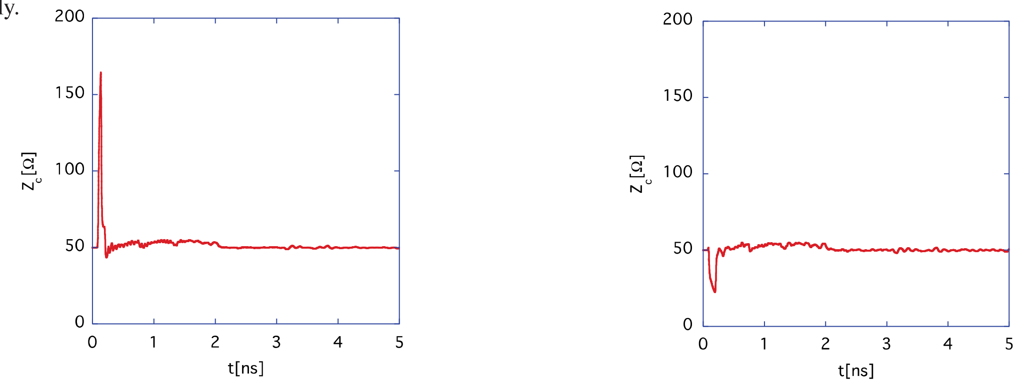


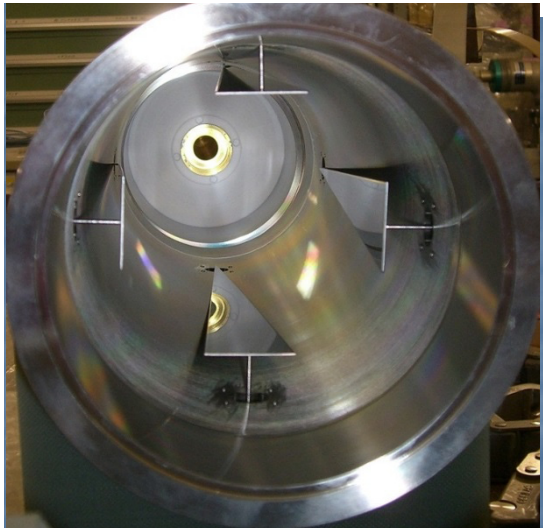
FIG. 17. The simulation result of the concave pentagon electrode. The blue and the red lines show the results with and without apron, respectively.



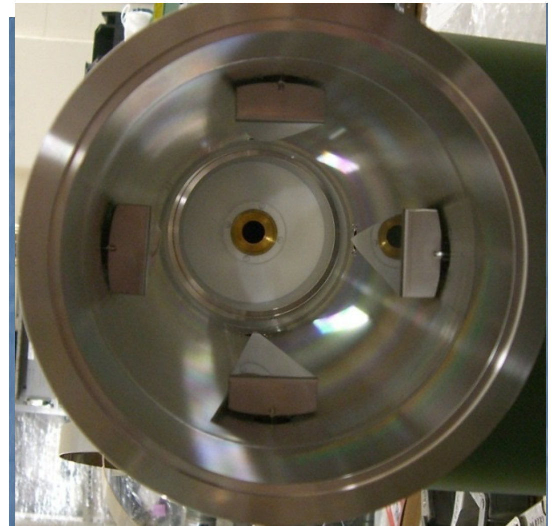
The **characteristic impedance along the electrode** is significantly improved (triangle electrode)

Prototype

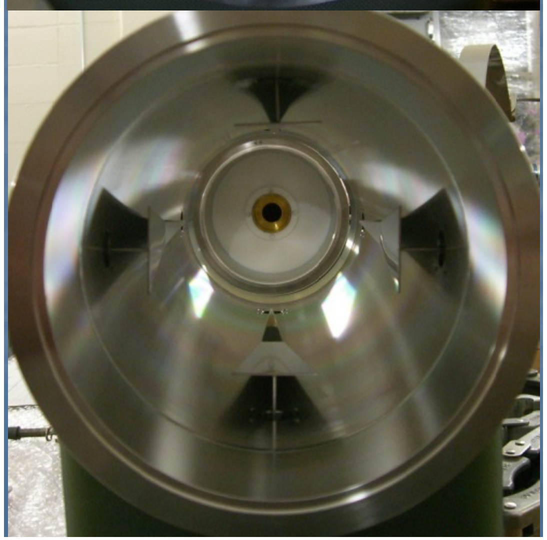
Triangle
w/o "aplon"



Triangle
with "aplon"



Pentagon
w/o "aplon"



Pentagon
with "aplon"

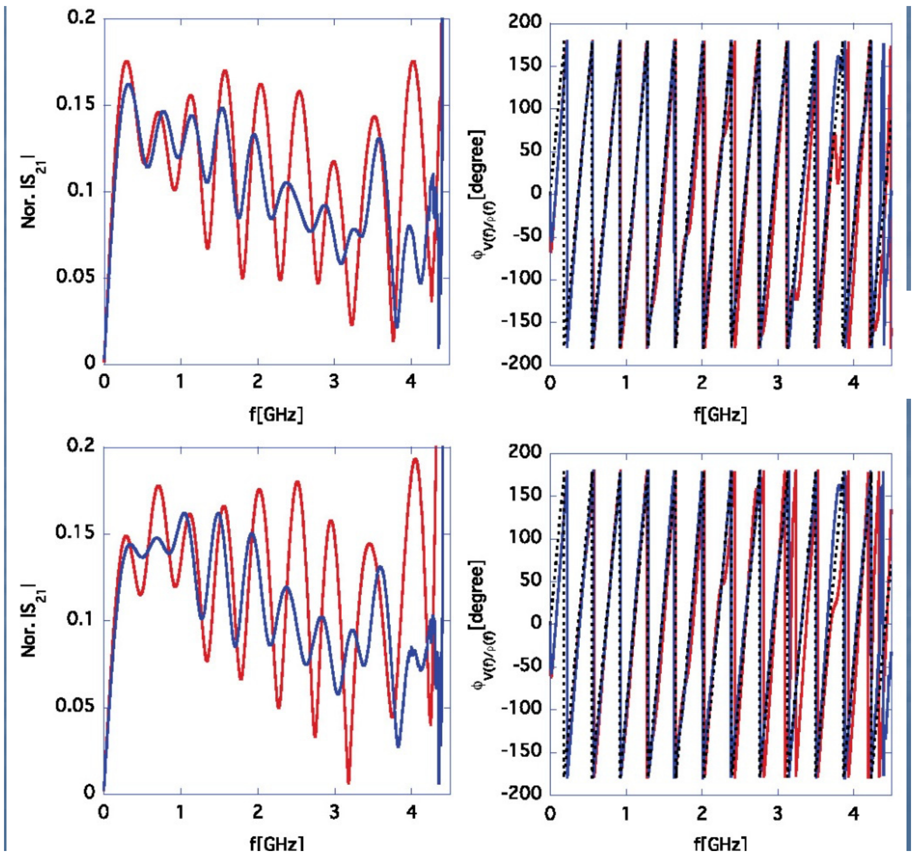
Measurement

Using taper pipe to keep 50 Ω impedance of the transmission line
Measure S21 with the network analyzer

Not as good as the simulation
Concave pentagon is better in frequency response

Triangle
Red: w/o "apron"
Blue: with "apron"

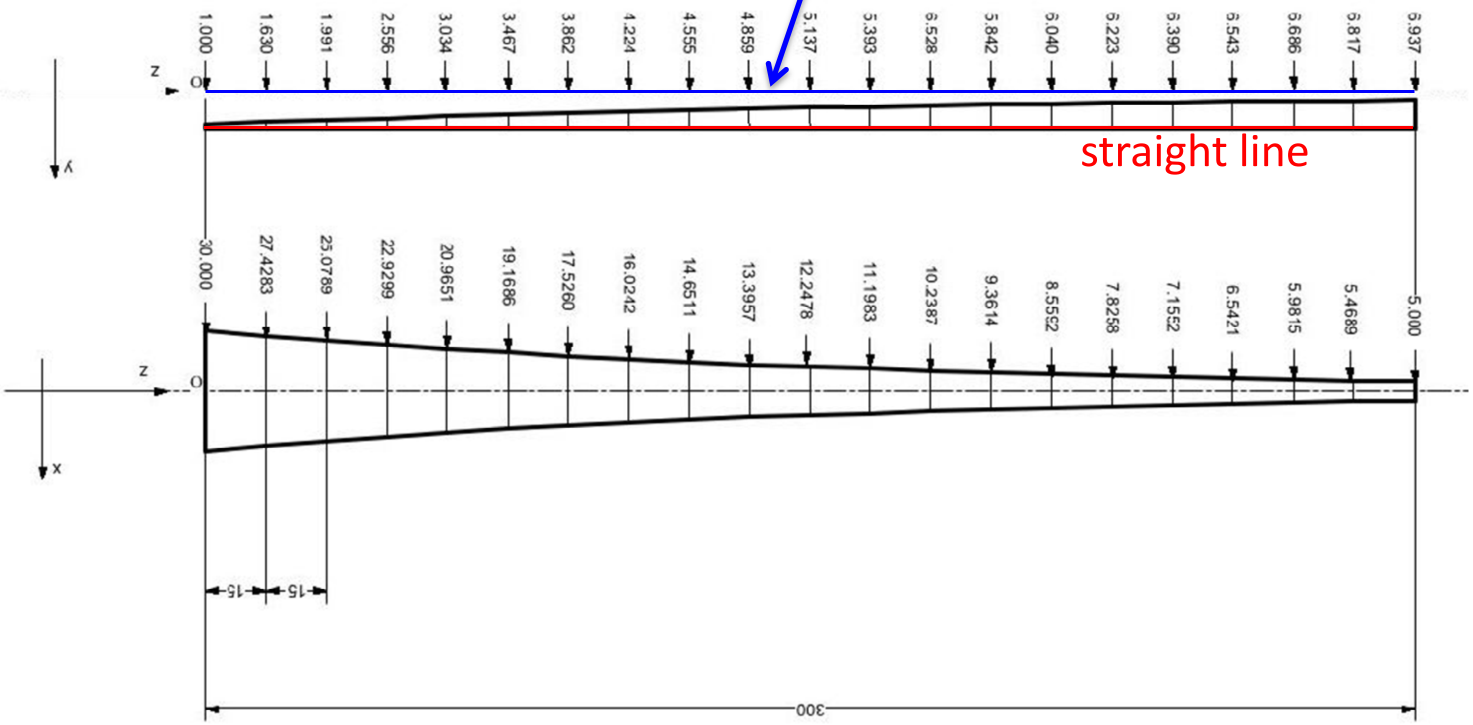
Concave pentagon
Red: w/o "apron"
Blue: with "apron"



Are there
more accurate, easier, efficient methods?

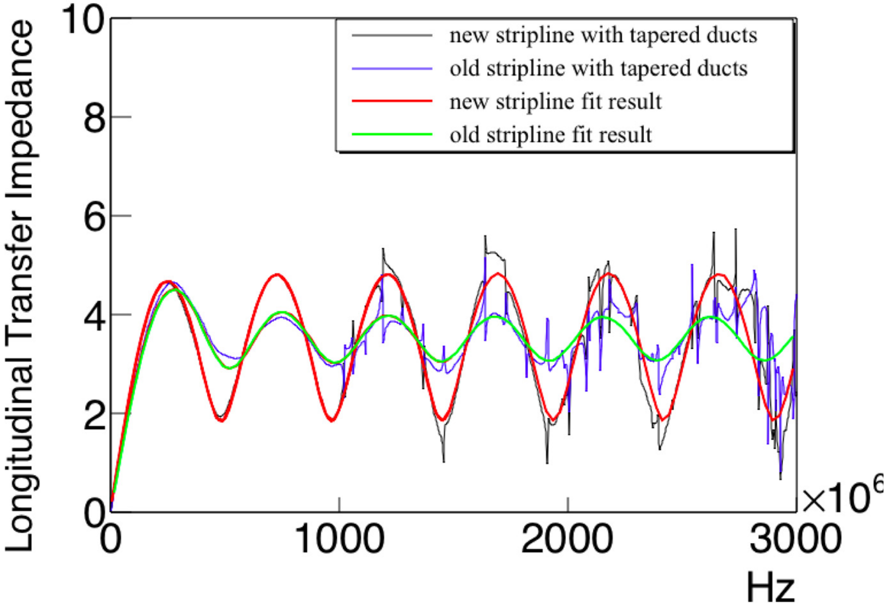
(2) 3D shape: not plate but more solid

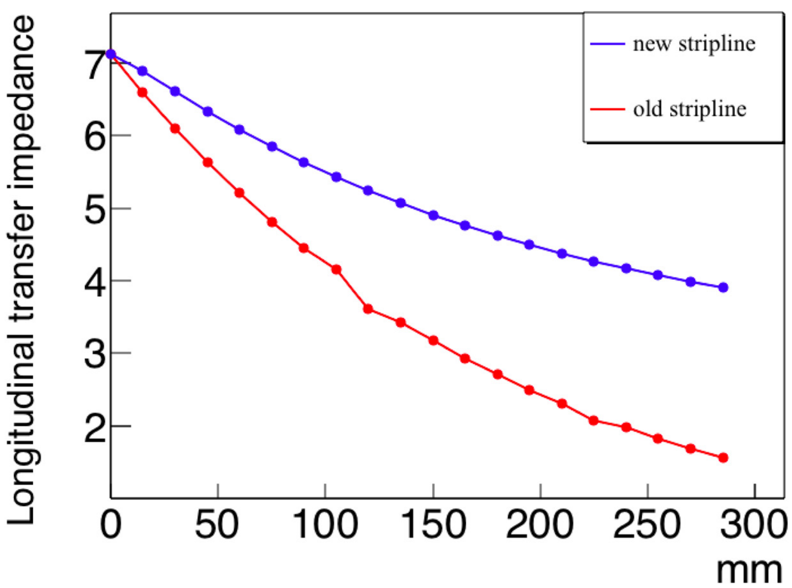
Gap size between the electrode and the pipe wall exponentially decreasing!



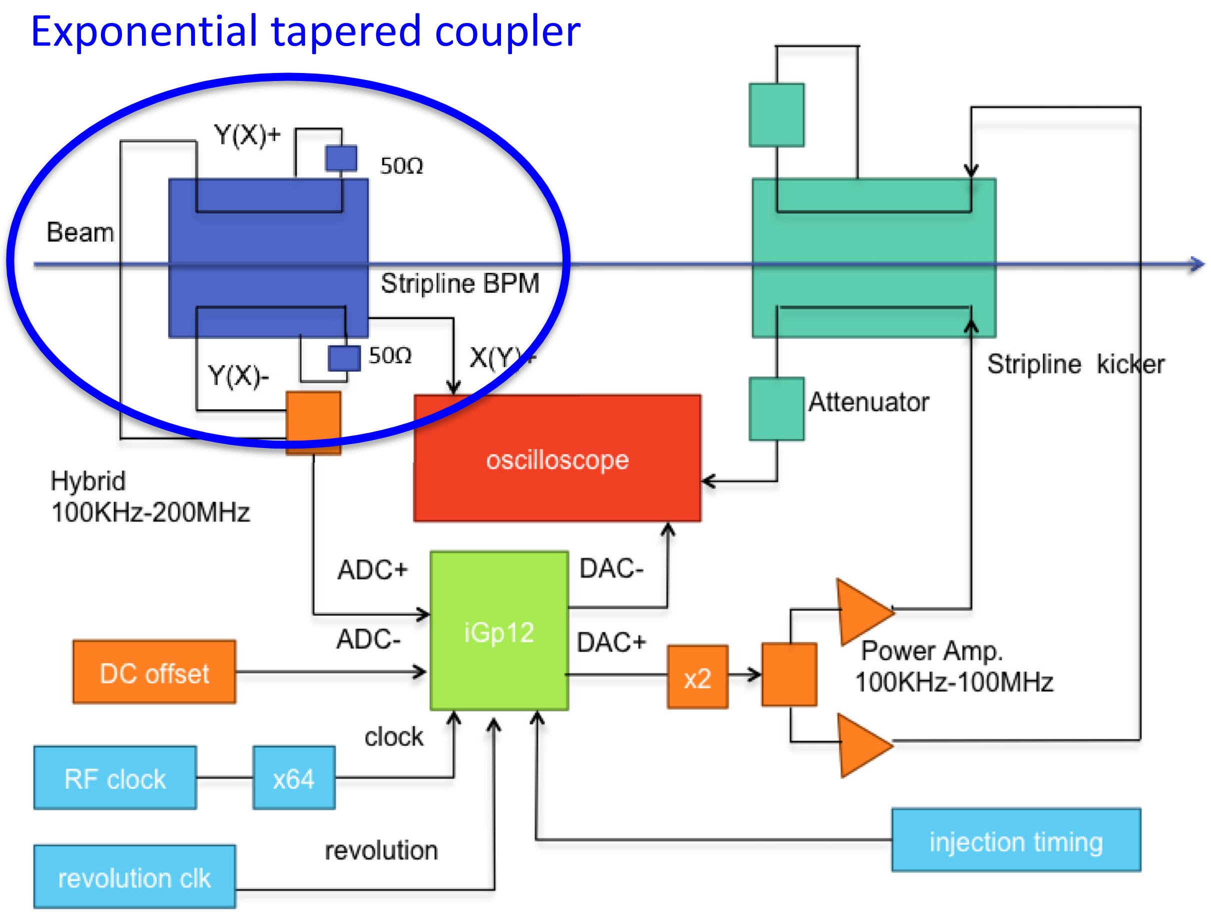
K. Nakamura et al., Proceedings of IPAC2015, Richmond, VA, USA MOPTY001, p.937.

Using taper pipe to keep 50 Ω impedance of the transmission line
Measure S21 with the network analyzer

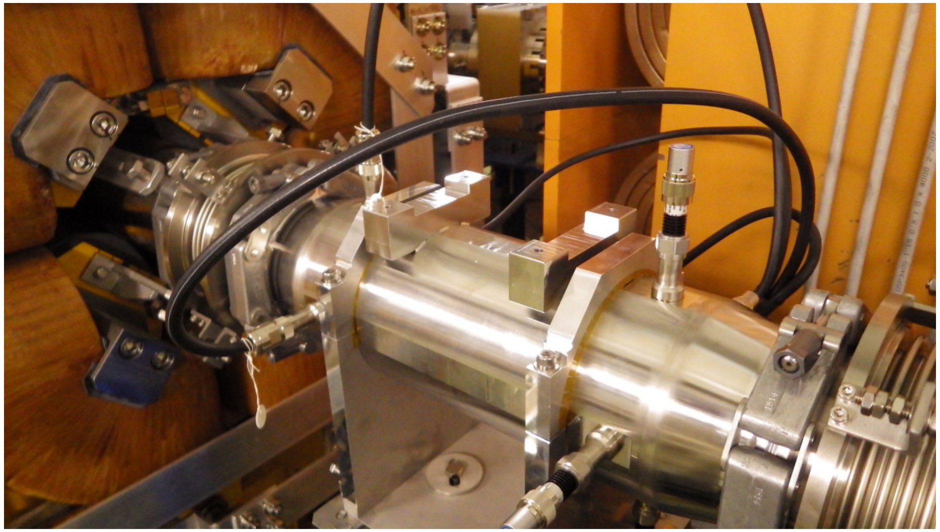


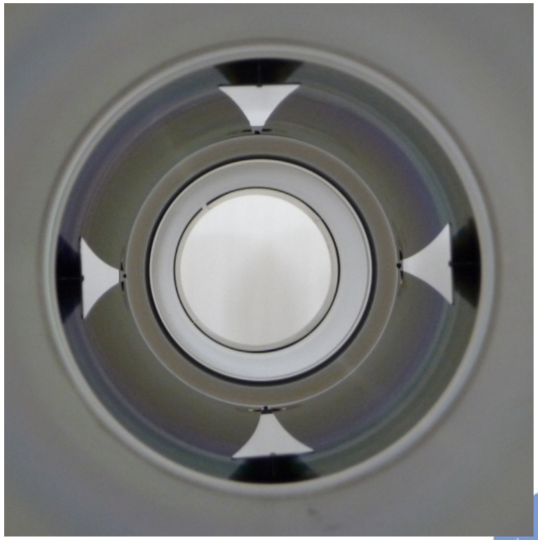


Intra-bunch feedback in the J-PARC MR



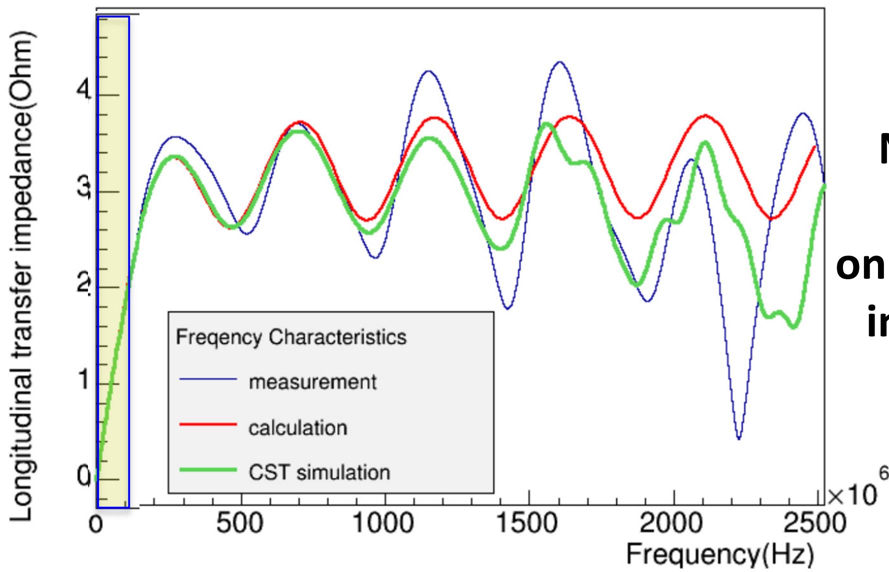
Sensor for the intra-bunch feedback in the J-PAC MR





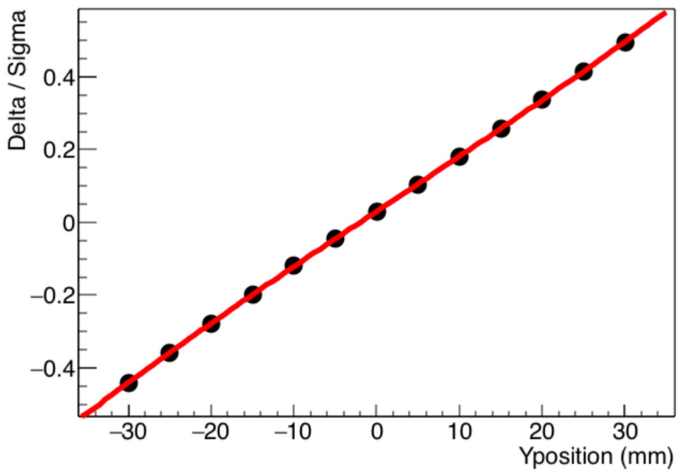
Present system covers f = 100k – 110 MHz

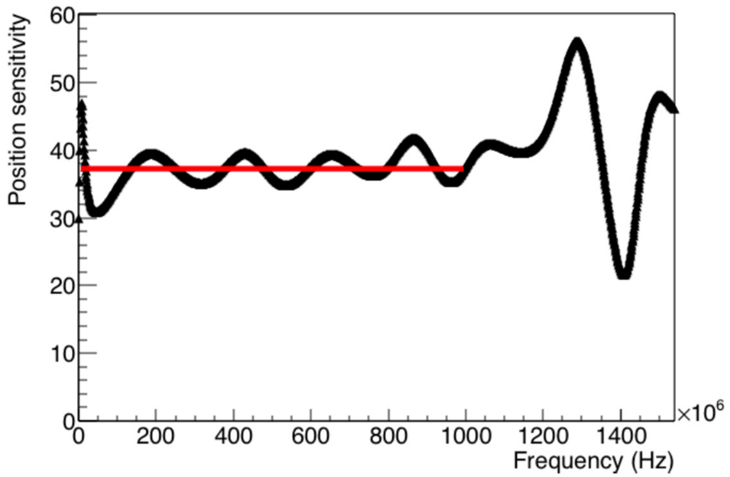
Longitudinal response



Numerical integration is done on a bunch-by-bunch basis in the processing circuit (iGp12)

Position sensitivity





For wider feedback, gain & phase variation of the BPM should be compensated as well as the cable attenuation and delay.

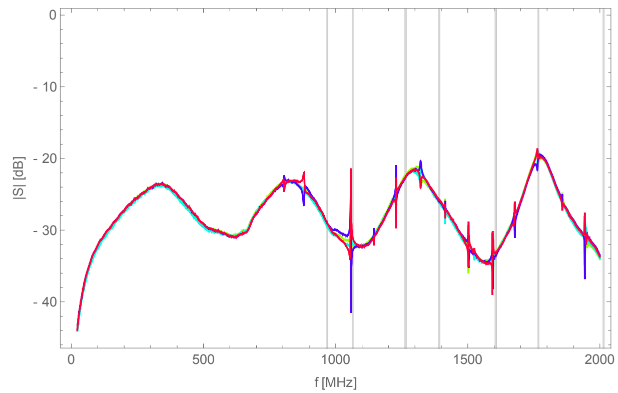
Triangle electrode → installed for **instability observation etc.**

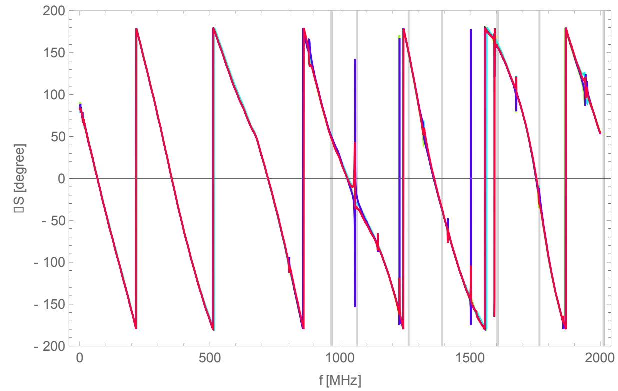
Preliminary

Longitudinal response

Bench measurement by 50 Ω taper coaxial pipe

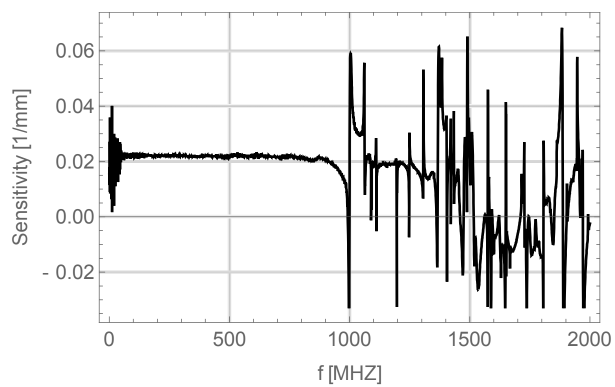
HOMs

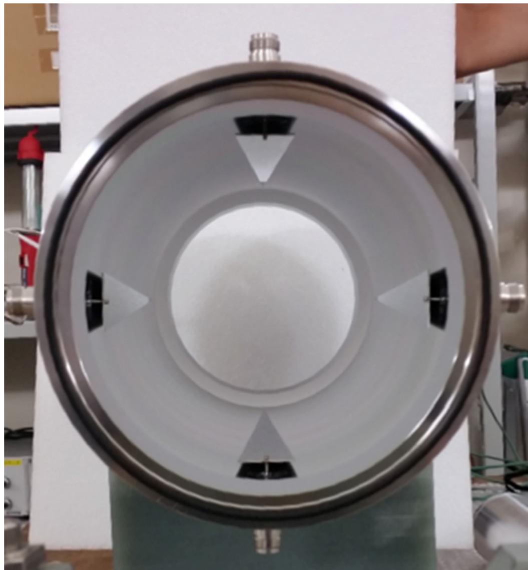




Position sensitivity

Bench measurement with thin stretched wire with resistors at both ends





Y. Nakanishi et al., WECL03 using this device

Conclusion

- The several shape of the stripline electrodes have been studied
  Triangle, Convex pentagon, 3D exponential
  Convex pentagon looks promising

- Counter measure against HOMs are important
  present work: "apron"
  Linnecar: ferrite beads

- Precise fabrication is still necessary

Thank you for your attention!

OLD

NEW

J-PARC