

The Kicker Impedance and its Effect on the RCS in J-PARC

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Special thanks to J. Holmes (SNS)

Outline

- The RCS kicker and its impedance.
(Theory & Measurements)
- A strategy to achieve 1MW goal in the serious condition.
 - ◆ Tune manipulation & space charge damping.
- A proposal reducing the kicker impedance.

RCS Parameters

Parameter list(C=348.333m, h=2, Repetition rate=25Hz)

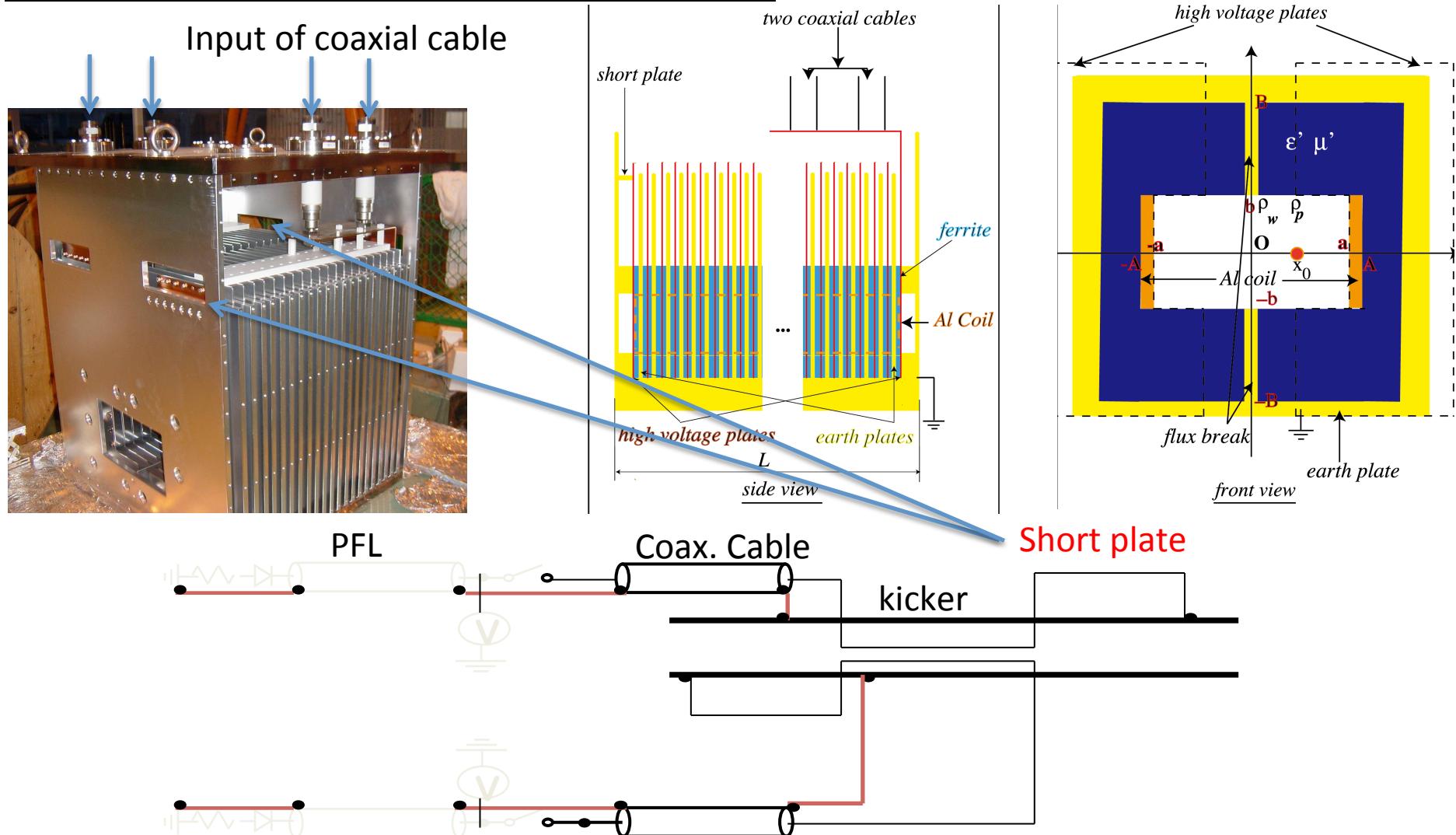
T(Kinetic energy, GeV)	0.4	3
Q_x / Q_y		6.45/6.42
B_f (Av/Peak)	0.47	0.185
N_b (protons/bunch)/ 10^{13}	3.11	3.11
I_c (Average current, A)	6.1	8.3
I_p (peak current, A)	13	46
f_0 (MHz)	0.614	0.84
η (slippage factor)	-0.4791	-0.047
$\Delta p/p(\%)$	0.85	0.38
τ_z (half bunch length, m)	55	20
v_s	0.0058	0.0005

- The RCS utilizes ceramic chambers.
- It is designed so that the impedance is suppressed except the kicker impedance.

Background information

- The impedance for *proto-type* kicker ($\sim 20 \text{ k}\Omega/\text{m}$) is measured by the wire method (**8** are installed).
- It is **10 times larger** than that of SNS kickers, since no impedance reduction cure has been made.
- If we apply the Sacherer's theory (no space charge effect) to the RCS, the kicker impedance should cause beam instabilities around 100 kW.
 - ◆ A significant **gap** exists between the theory and the measurement.
- Precise estimation of the kicker impedance is necessary (a theory is developed [Y.Shobuda *et al* NIMA 691,11,135 & NIMA 713,11,52].).

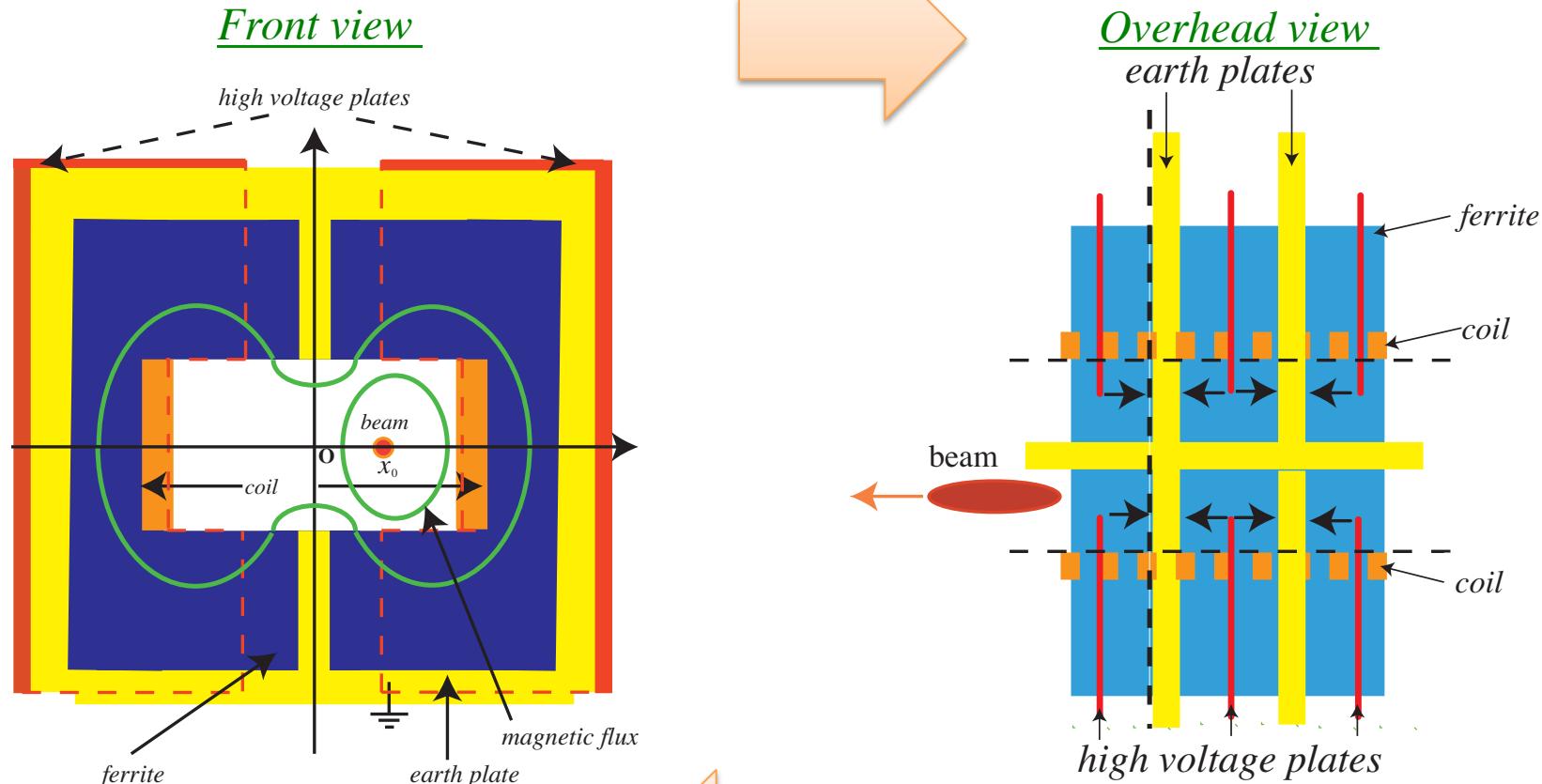
The RCS kicker (distributed type)



- ◆ The short plates double the excitation current by superposing the forward and backward currents, when a beam is extracted from the RCS.

Excitation of the kicker impedance

The Beam and the coils are coupled magnetically. The coils and the high voltage plates are connected electrically.
 Currents flow in the coils.

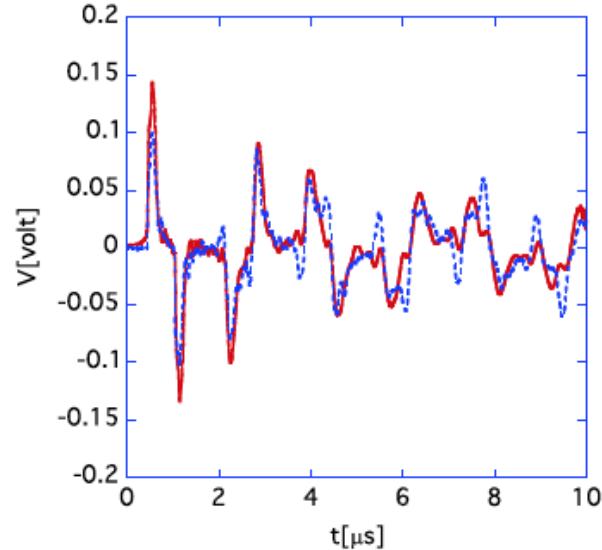
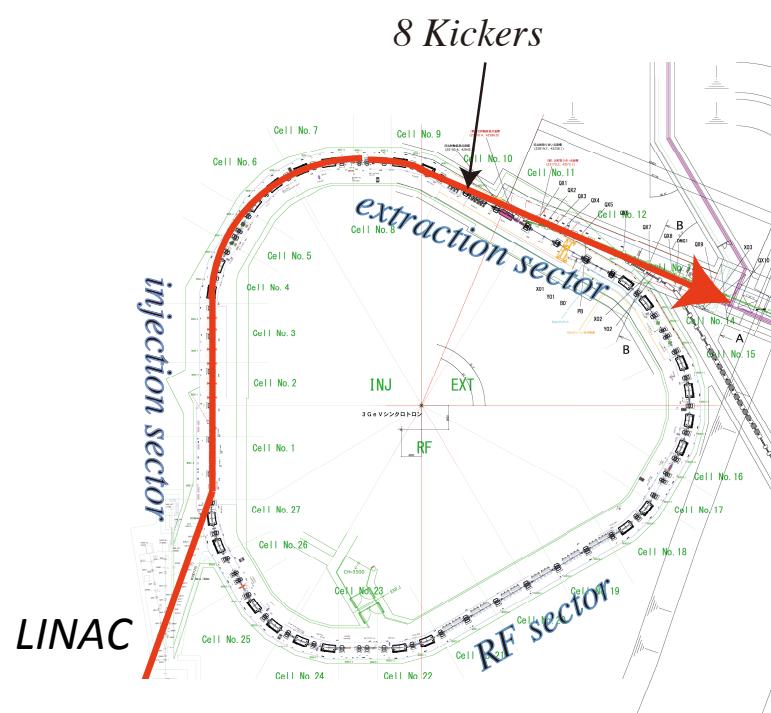


Horizontal impedance is derived by

$$Z_x = \frac{\partial^2 Z_L}{k \partial x_0 \partial x} \Big|_{x=x_0=0}$$

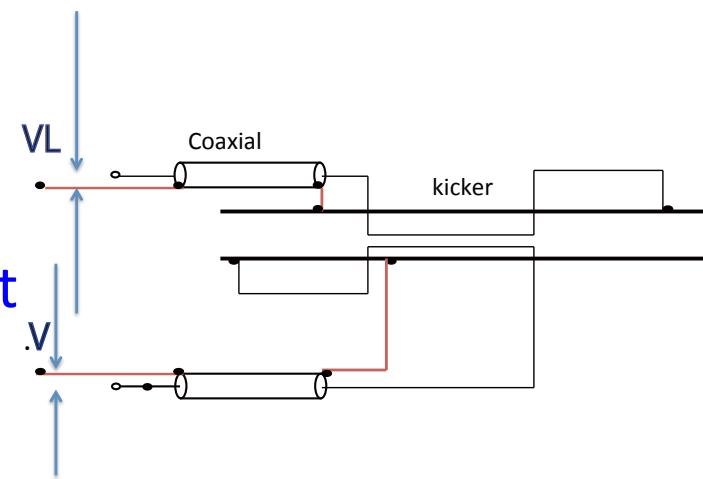
The beam receives longitudinal kicks electrically (Longitudinal impedance Z_L)

Measurement of the beam induced voltage



Red: Theory
Blue: measurement

- Let an injection (pulse) beam from LINAC pass through the kickers once.
- The excited current flows to the ends of the cables.
- Theory predicts the beam induced voltage at the ends of the cables.



The relation between the impedance and the voltages.

*The theory can relate
the measured voltages to the impedances.*

Longitudinal impedance

$$Z_L^{(0)} \simeq -\frac{\theta_1 c \beta}{q\pi} \sqrt{\frac{L_{cable}}{C_{cable}}} \left[\frac{(e^{j\omega(\frac{1}{c\beta} + \theta_1)L} - 1)[-Y_{L,1} + Y_{L,2} - e^{-j\omega\theta_1 L}(-Y_1 + Y_2)]}{(c\beta\theta_1 + 1)(e^{j\omega\theta_1 L} - e^{-j\omega\theta_1 L})} \right. \\ \left. + \frac{(e^{j\omega(\frac{1}{c\beta} - \theta_1)L} - 1)[-Y_{L,1} + Y_{L,2} - e^{j\omega\theta_1 L}(-Y_1 + Y_2)]}{(-c\beta\theta_1 + 1)(e^{j\omega\theta_1 L} - e^{-j\omega\theta_1 L})} \right] \\ \times \sum_{m=1}^{\infty} \frac{(-(-1)^m + 1 + \cos \frac{m\pi(\rho_p+a)}{2a} - \cos \frac{m\pi(-\rho_p+a)}{2a}) \sin \frac{m\pi}{2}}{m \cosh \sqrt{\frac{m^2\pi^2}{4a^2} + \omega^2\theta_1^2 - k^2\beta^2} b},$$

Horizontal impedance

$$Z_x^{(1)} \simeq \frac{\theta_3 c^2 \beta^2}{2\omega q a (e^{j\omega\theta_3 L} - e^{-j\omega\theta_3 L})} \sqrt{\frac{L_{cable}}{C_{cable}}} \\ \times \left[\frac{(e^{j\omega(\frac{1}{c\beta} + \theta_3)L} - 1) \frac{d[-Y_{L,1} + Y_{L,2} + e^{-j\omega\theta_3 L}(-Y_1 + Y_2)]}{dx_0}}{(c\beta\theta_3 + 1)} \Big|_{x_0=0} \right. \\ \left. + \frac{(e^{j\omega(\frac{1}{c\beta} - \theta_3)L} - 1) \frac{d[-Y_{L,1} + Y_{L,2} + e^{j\omega\theta_3 L}(-Y_1 + Y_2)]}{dx_0}}{(-c\beta\theta_3 + 1)} \Big|_{x_0=0} \right],$$

The impedances depend on the induced voltages through the functions $Y_1, Y_2, Y_{L,1}, Y_{L,2}$.

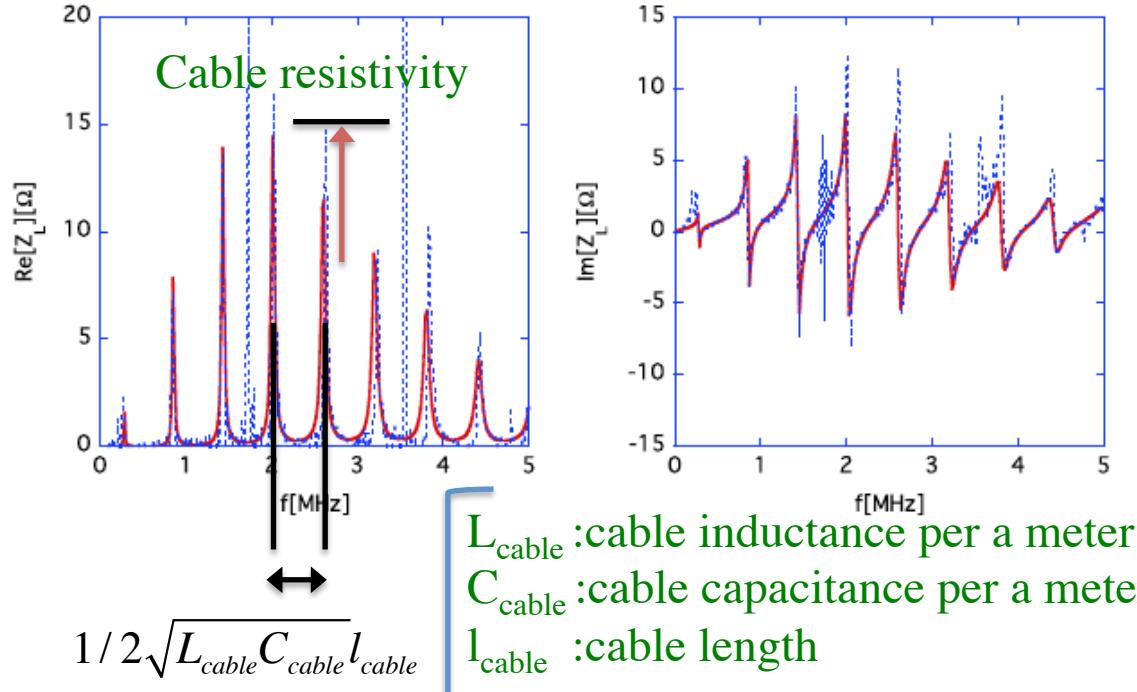
$$Y_1 = \frac{e^{-j\omega\sqrt{C_{cable}L_{cable}}l_{cable}}}{2\rho(\omega)} \left(\frac{1}{R_t(\omega)} - \sqrt{\frac{C_{cable}}{L_{cable}}} \right) \int_{-\infty}^{\infty} dt e^{-j\omega t} V(t),$$

$$Y_2 = \frac{e^{j\omega\sqrt{C_{cable}L_{cable}}l_{cable}}}{2\rho(\omega)} \left(\frac{1}{R_t(\omega)} + \sqrt{\frac{C_{cable}}{L_{cable}}} \right) \int_{-\infty}^{\infty} dt e^{-j\omega t} V(t),$$

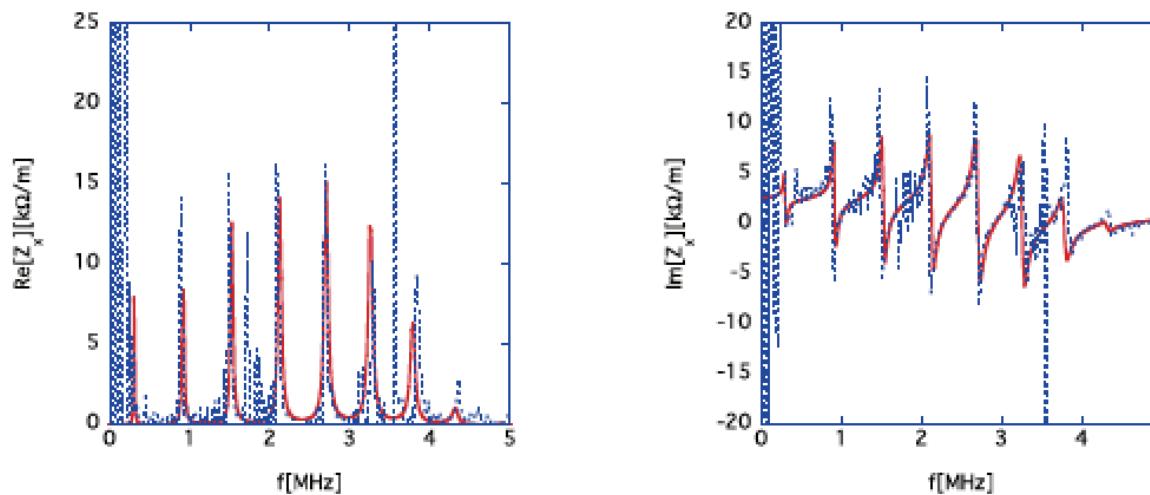
$$Y_{L,1} = \frac{e^{-j\omega\sqrt{C_{cable}L_{cable}}l_{cable}}}{2\rho(\omega)} \left(\frac{1}{R_t(\omega)} - \sqrt{\frac{C_{cable}}{L_{cable}}} \right) \int_{-\infty}^{\infty} dt e^{-j\omega t} V_L(t),$$

$$Y_{L,2} = \frac{e^{j\omega\sqrt{C_{cable}L_{cable}}l_{cable}}}{2\rho(\omega)} \left(\frac{1}{R_t(\omega)} + \sqrt{\frac{C_{cable}}{L_{cable}}} \right) \int_{-\infty}^{\infty} dt e^{-j\omega t} V_L(t),$$

Longitudinal impedance



Horizontal impedance

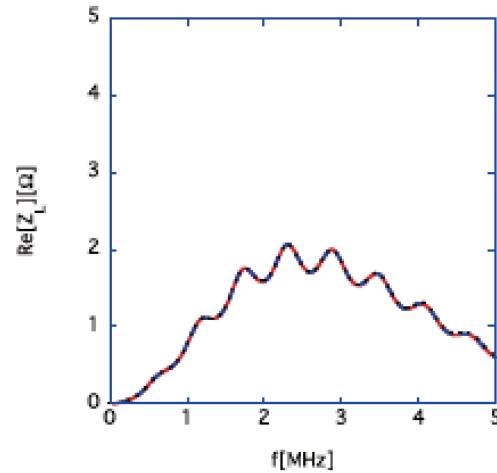


Red: theory
Blue: measurements
Lorentz- $\beta=0.545$

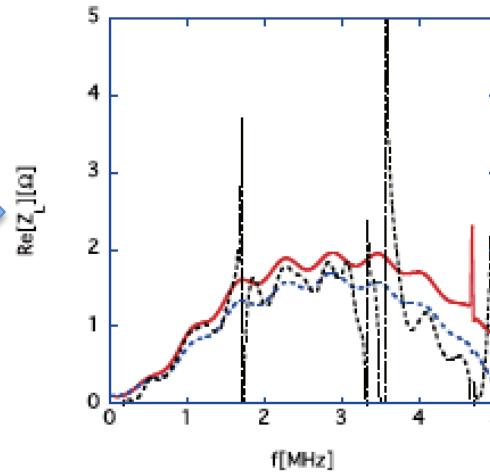
Theoretical and measured results are in good agreement.
 (artificial peaks appear around $f=n/\Delta$, $n=1,2,\dots$
 Δ is the pulse length)

When the terminal is connected to a matched resistor, the Lorentz- β ^{10/27} dependence of the impedance is found.

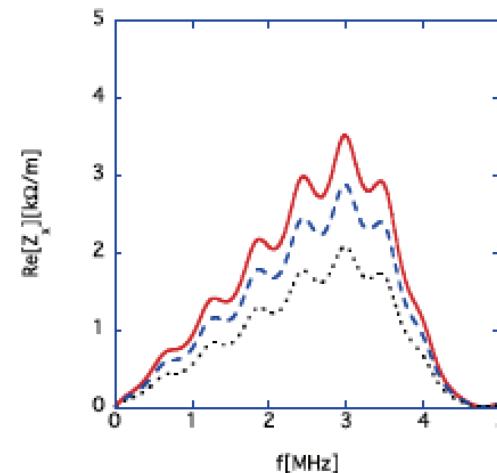
Theory



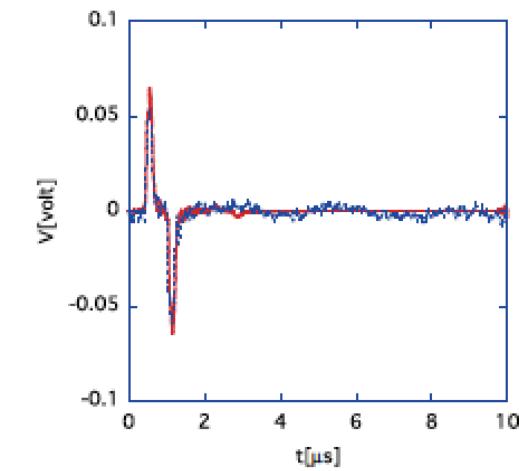
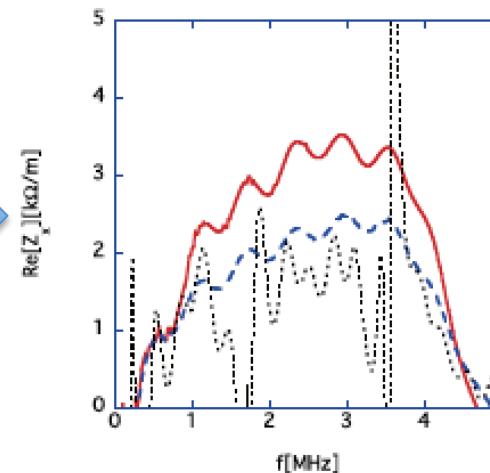
Measured



Theory



Measured



Red: $\beta=0.9$

Blue: $\beta=0.75$

Black: $\beta=0.545$

- Beam induced voltage are successfully converted to the kicker impedance.

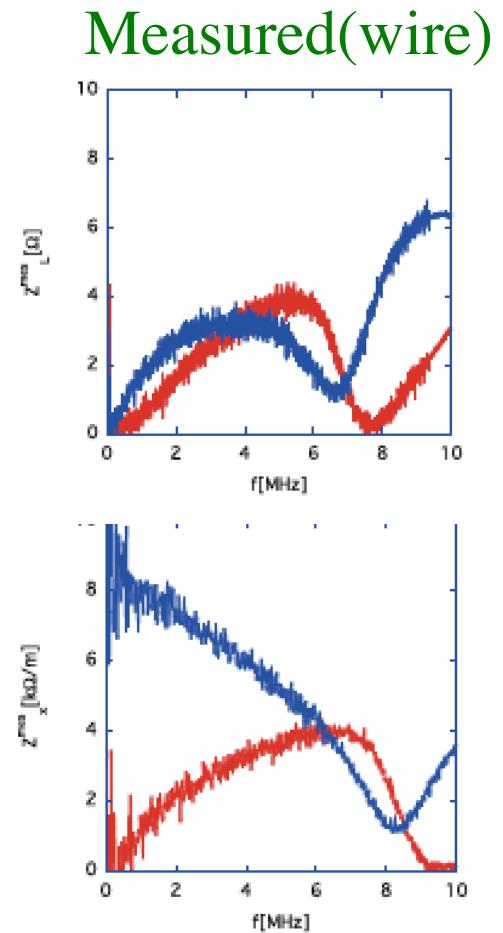
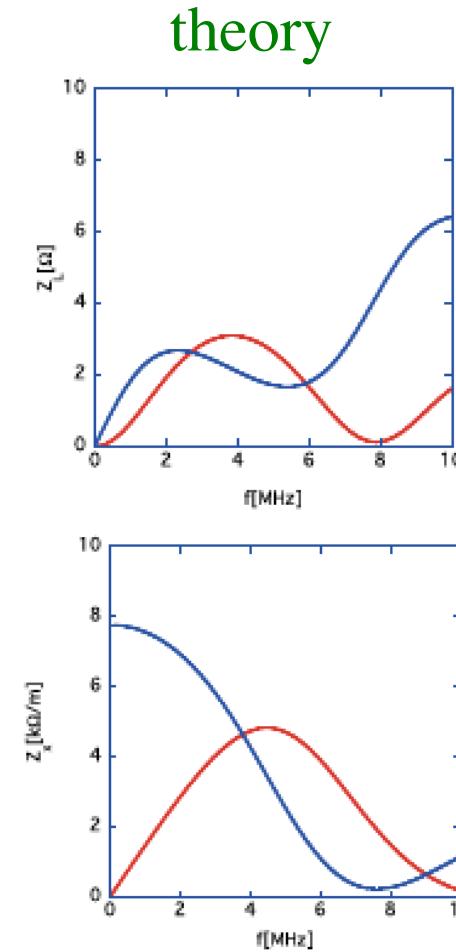
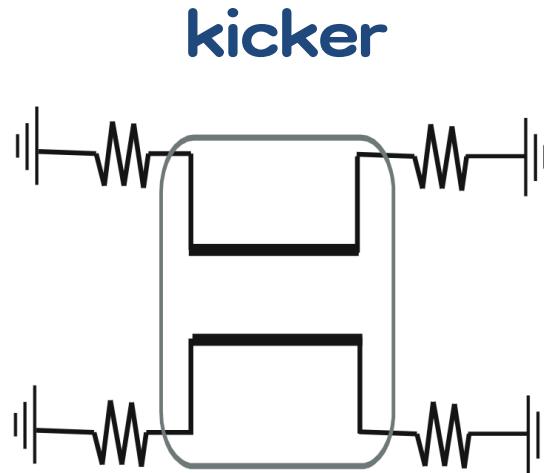
- *Characteristic of impedance*

- The longitudinal impedance has little dependence on the Lorentz factor at low frequency,
- while the transverse impedance is roughly proportional to Lorentz- β factor in the whole frequency region.



- ◆ The non-relativistic beam receives more fluctuating kicks from the wake fields while going through them.
- ◆ The kicks tend to cancel each other in net.
- ◆ However, longitudinal wakes are excited by the beam like cosine function, and they are nearly constant at low frequency during the beam passage.
- ◆ The beam tends to be more unstable horizontally than longitudinally, as it becomes relativistic.

The kicker with simpler termination



The agreements are remarkably important.

because Nassibian proposed the formula
for the kicker impedance with the termination,

the formulae does not satisfy the Hilbert transformation

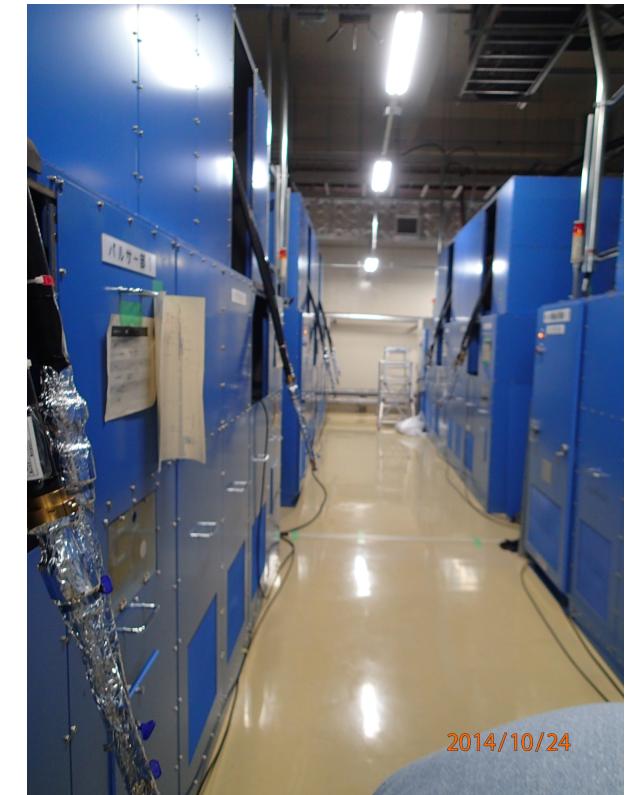
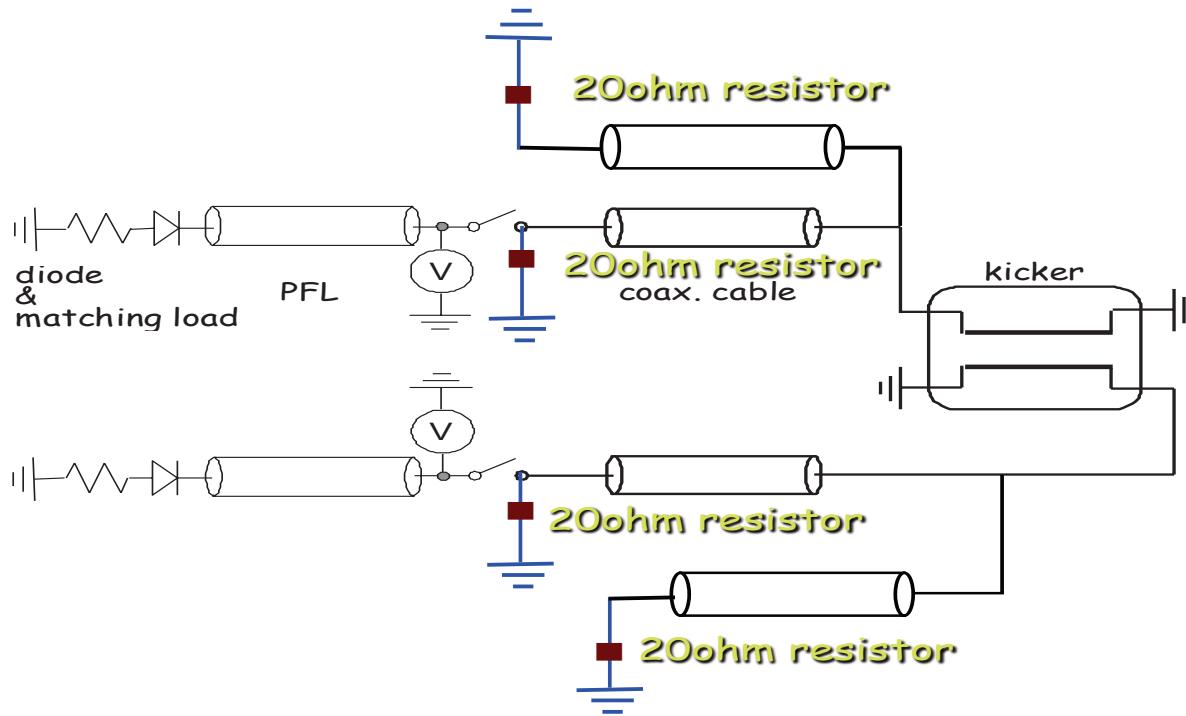
(causality condition), as already pointed out by K.Ng (AIP 184, 472).

$$Z_L = \frac{1}{4} \sqrt{\frac{L_{\text{ind}}}{C}} \left[2 \sin^2 \frac{\omega \sqrt{L_{\text{ind}} C L}}{2} + j(\omega \sqrt{L_{\text{ind}} C L} - \sin \omega \sqrt{L_{\text{ind}} C L}) \right]$$

$$Z_x = \frac{L}{16ab} \sqrt{\frac{L_{\text{ind}}}{C}} \left[\frac{1 - \cos \omega \sqrt{L_{\text{ind}} C L}}{\omega \sqrt{L_{\text{ind}} C L}} + j \left(1 - \frac{\sin \omega \sqrt{L_{\text{ind}} C L}}{\omega \sqrt{L_{\text{ind}} C L}} \right) \right]$$

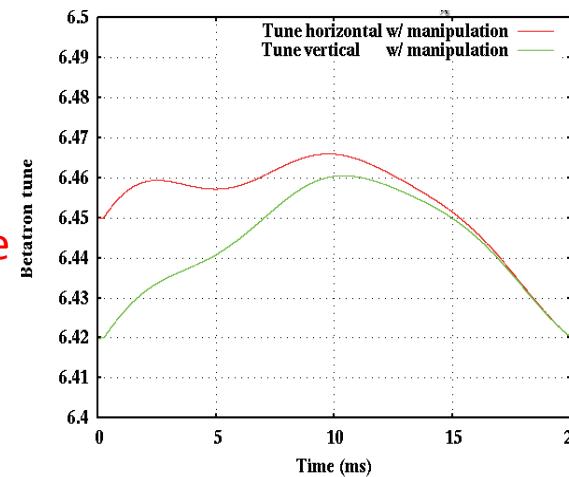
A strategy to achieve one-mega watt goal with the present kicker

- Let us demonstrate that the kicker impedance dominates among the RCS impedance sources by using 750 kW beam.
- The kicker impedance is minimized by connecting matched resistors to all terminals of the cables.



Condition

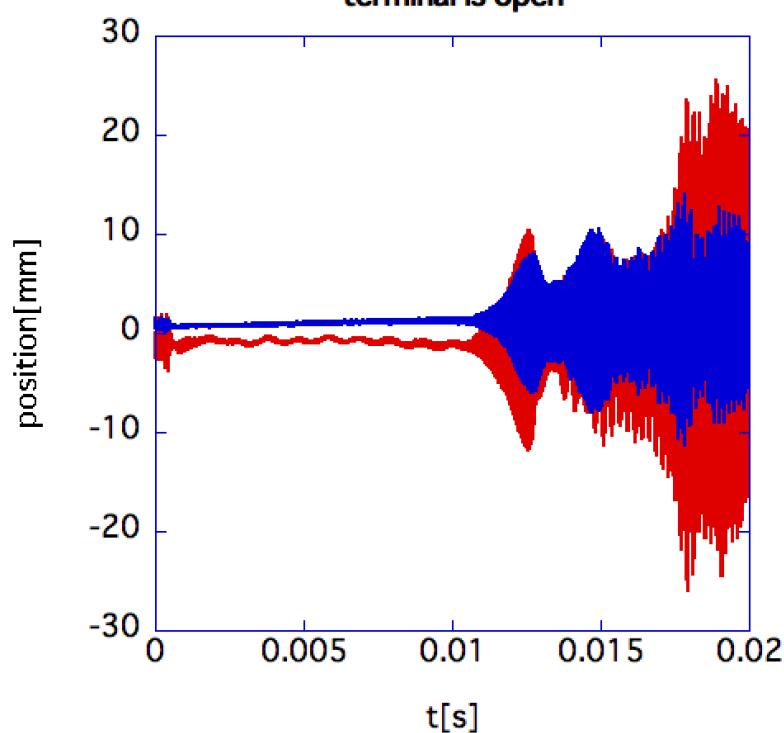
- Chromaticity is fully corrected along the entire energy.
- 750kW beam.

Tune pattern:

horizontal
vertical

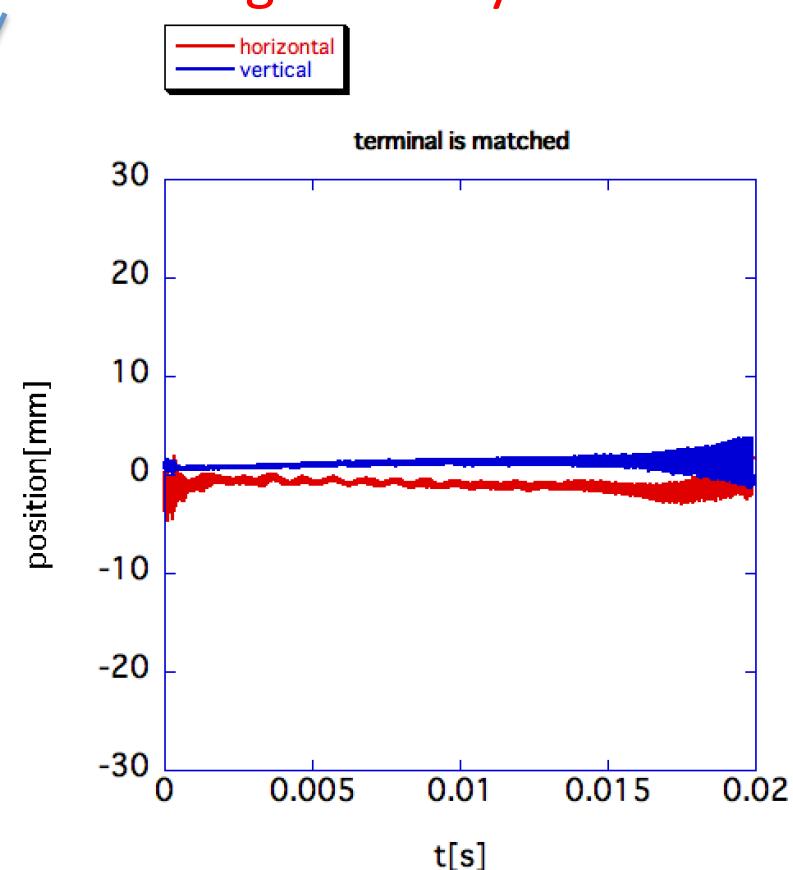
- Vertical motion (blue) becomes unstable accompanied with the horizontal one (red), because the both tunes merge during the acceleration.
- The resistors make the beam growth rate significantly reduced.

terminal is open



Kicker
Impedance
dominates
at the RCS.

terminal is matched



- We demonstrate that the kicker impedance dominates among the RCS impedance sources.
- Only the kicker impedance is sufficient, considering the beam instability at the RCS by simulation codes.

◆ How about simulation study ?

- Simulation studies have been progressing at the RCS.
- Simulation code ORBIT is used at the RCS for special studies about the beam instability.
- ORBIT is originally developed in SNS for storage rings.
 - ◆ In 2013, Dr. J. Holmes visited to J-PARC RCS.
 - ◆ He succeeded to implement the β -dependence of the kicker impedance into the code.

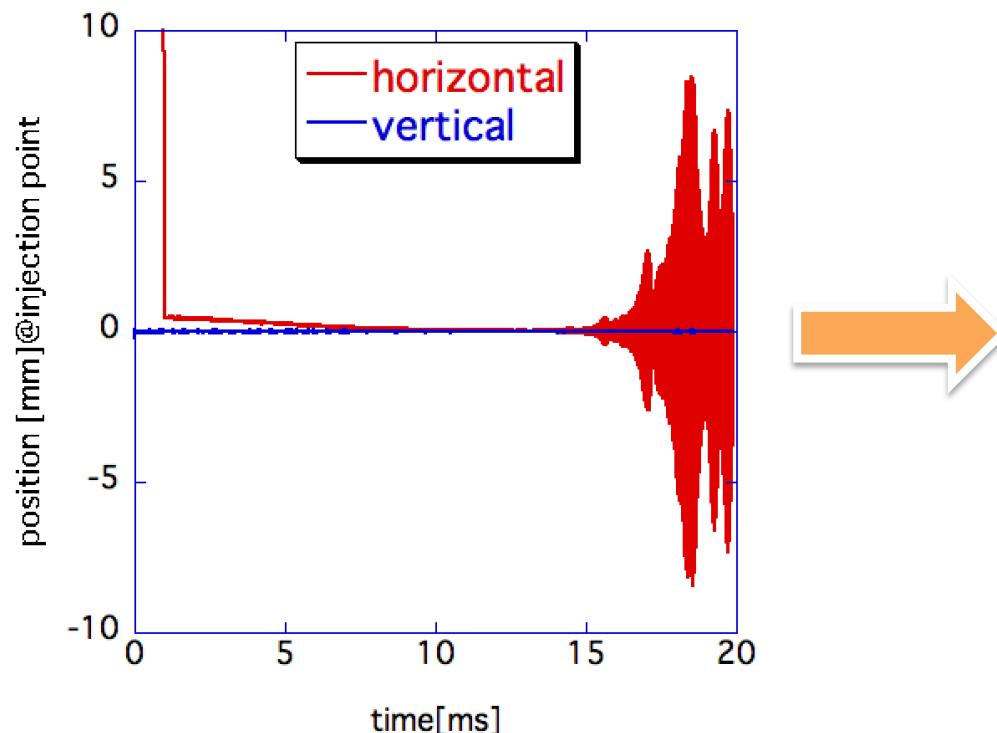
◆ *Benefit of tune manipulation*

- Simulation results for one megawatt beam.

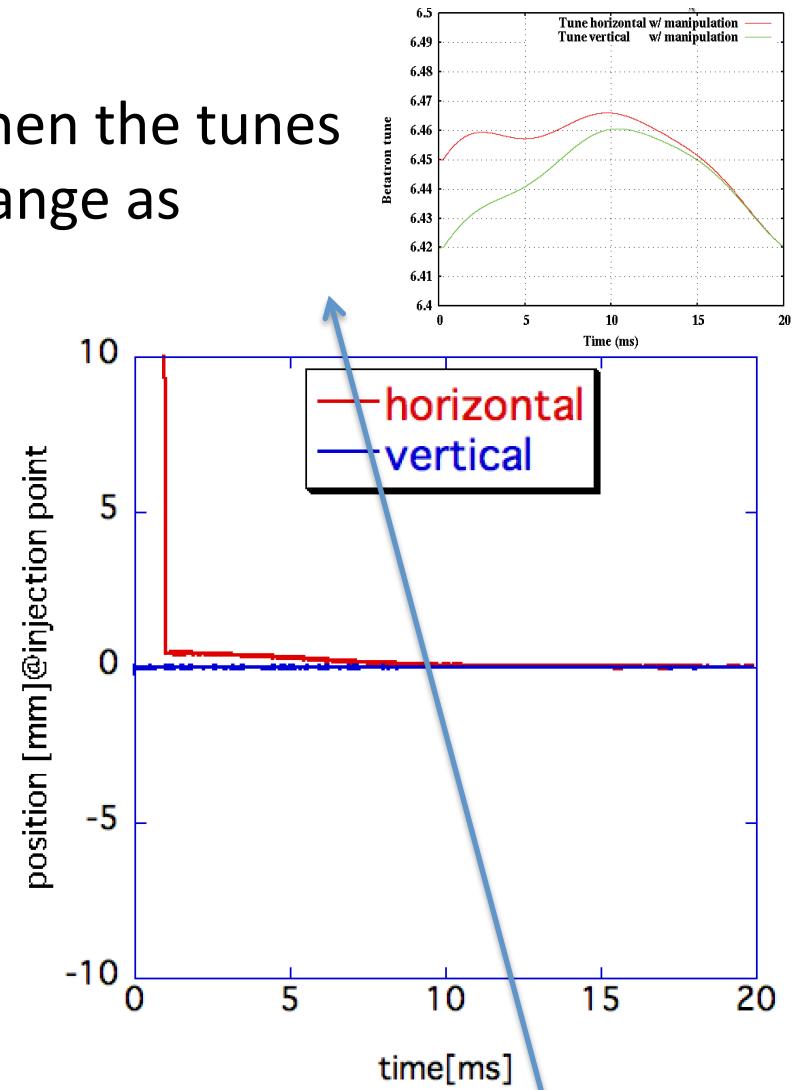
The chromaticity is corrected only at the injection energy.

The tunes are **fixed** during the acceleration time.

$$(v_x=6.45, v_y=6.42)$$



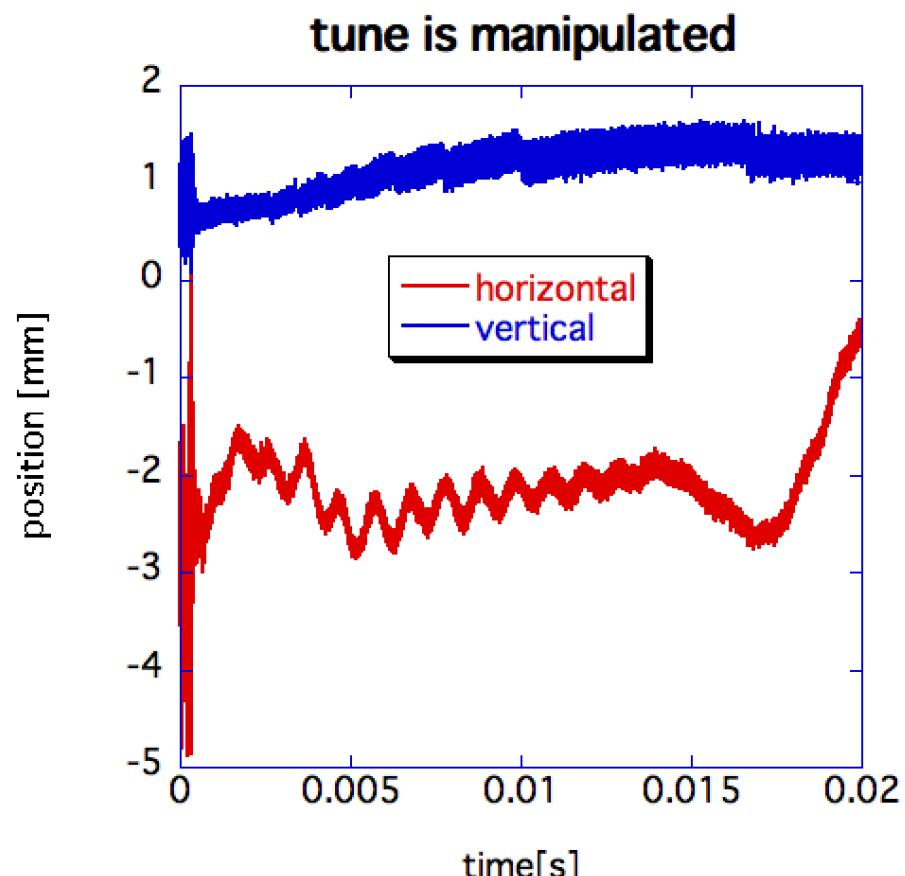
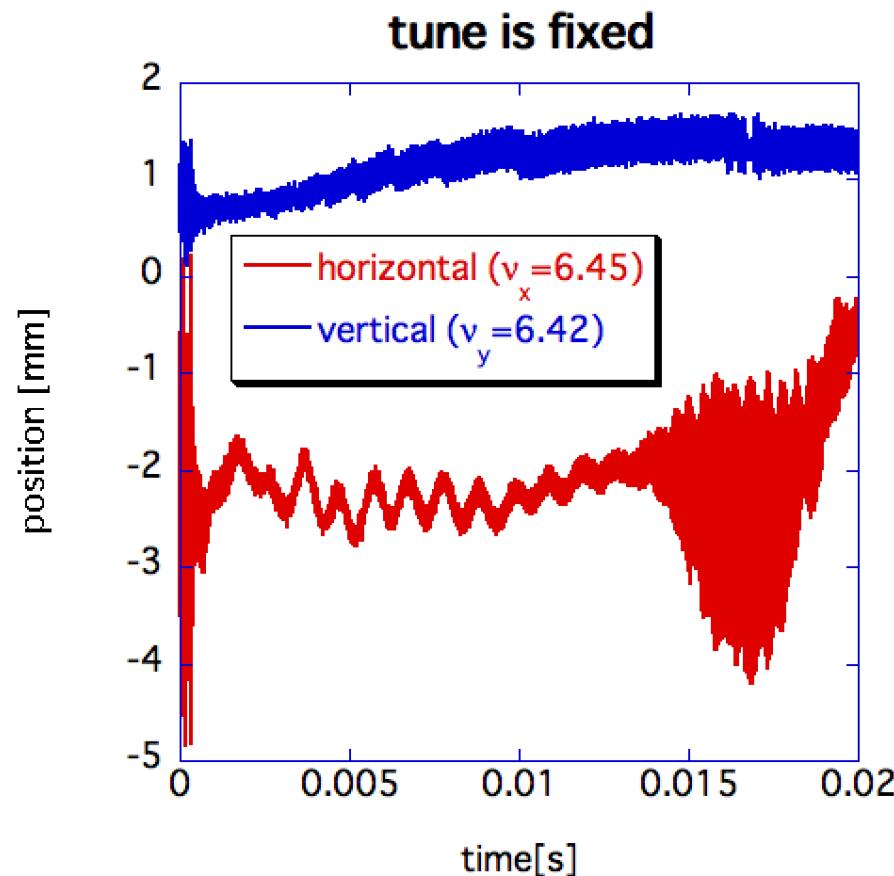
When the tunes change as



The tune manipulation cure the beam instability.

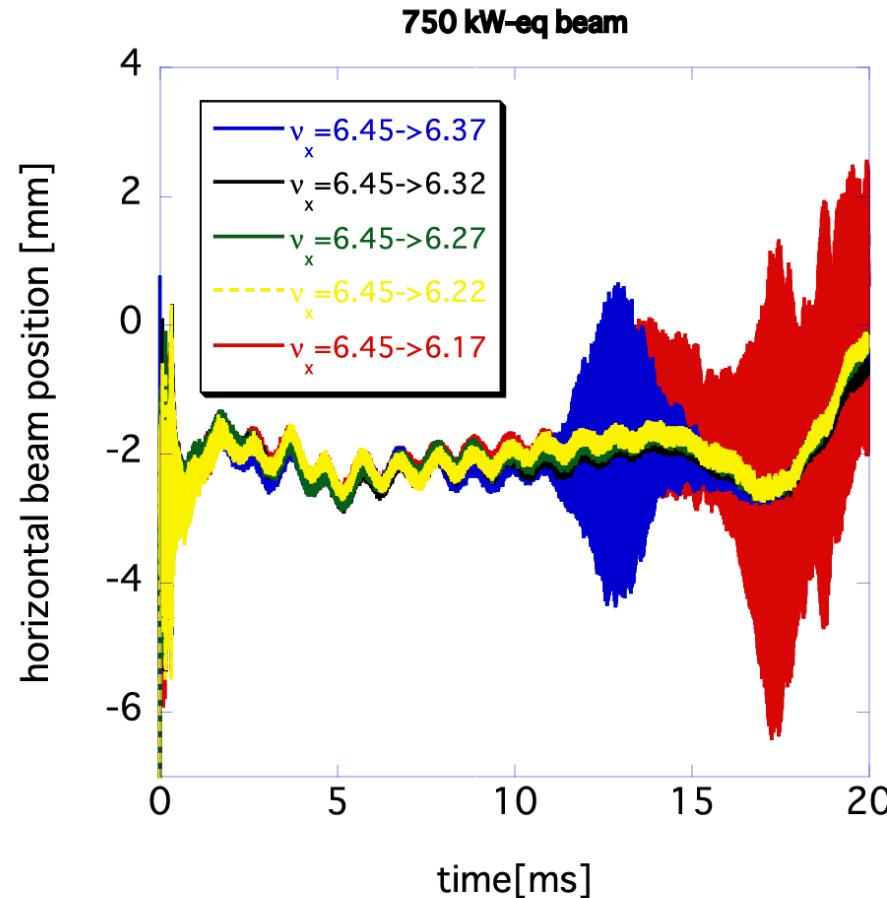
The availability of the procedure is demonstrated by 750 kW beam^{17/28} where the momentum spread of the injection beam $d\mathbf{p}/\mathbf{p}=0.18\%$.

- ◆ The chromaticity is corrected only at the injection energy.



The kicker impedance substantially determines the preferable tune to accomplish the high intensity beam.

This October,
several tune manipulations are experimentally challenged
by gradually decreasing the tunes toward the extraction time.

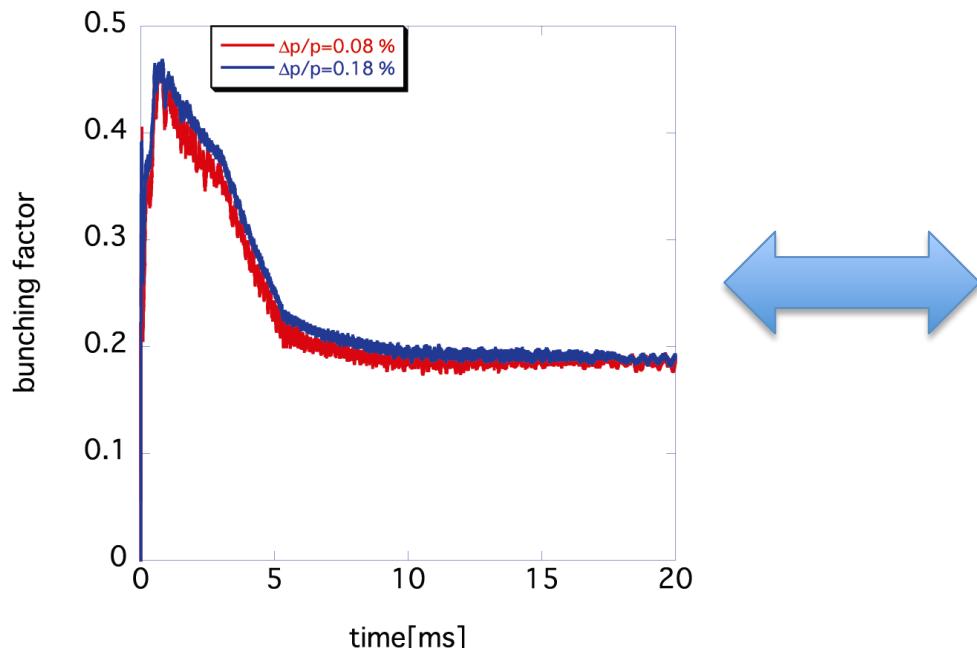


- ◆ Three tracking patterns ($v_x=6.32, 6.27$ and 6.22 at the extraction time) seem promising to achieve the high intensity goal.

◆ Benefit of space charge damping

19/29

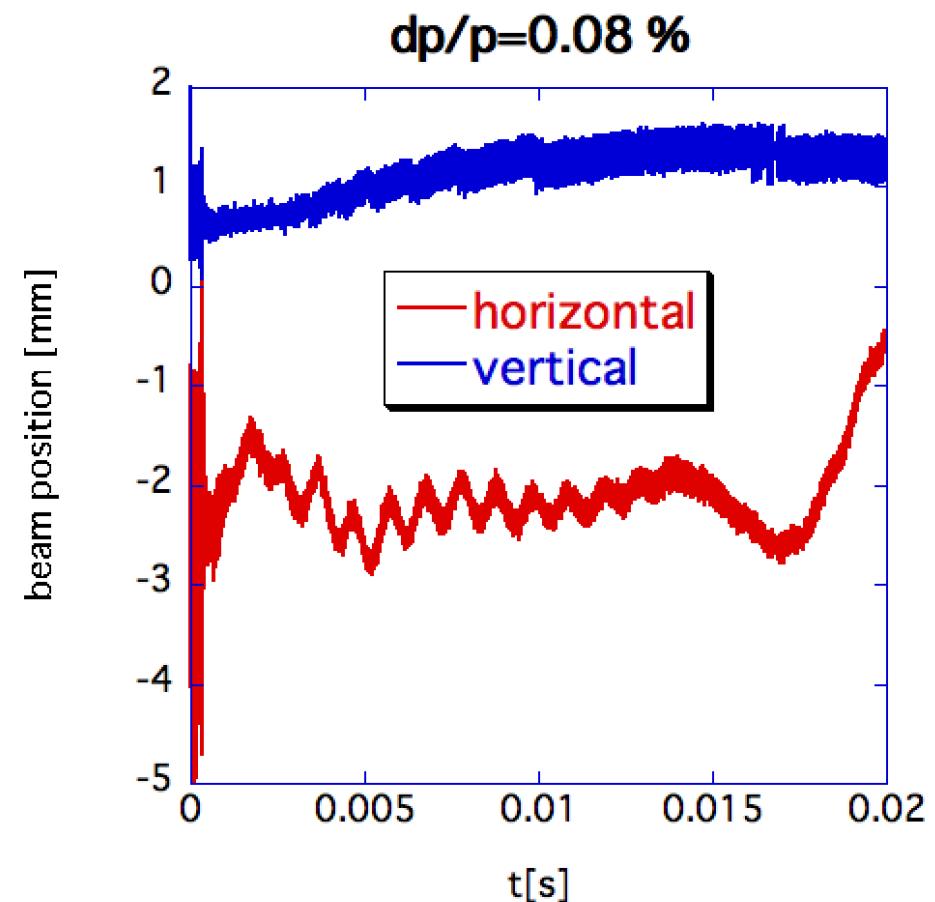
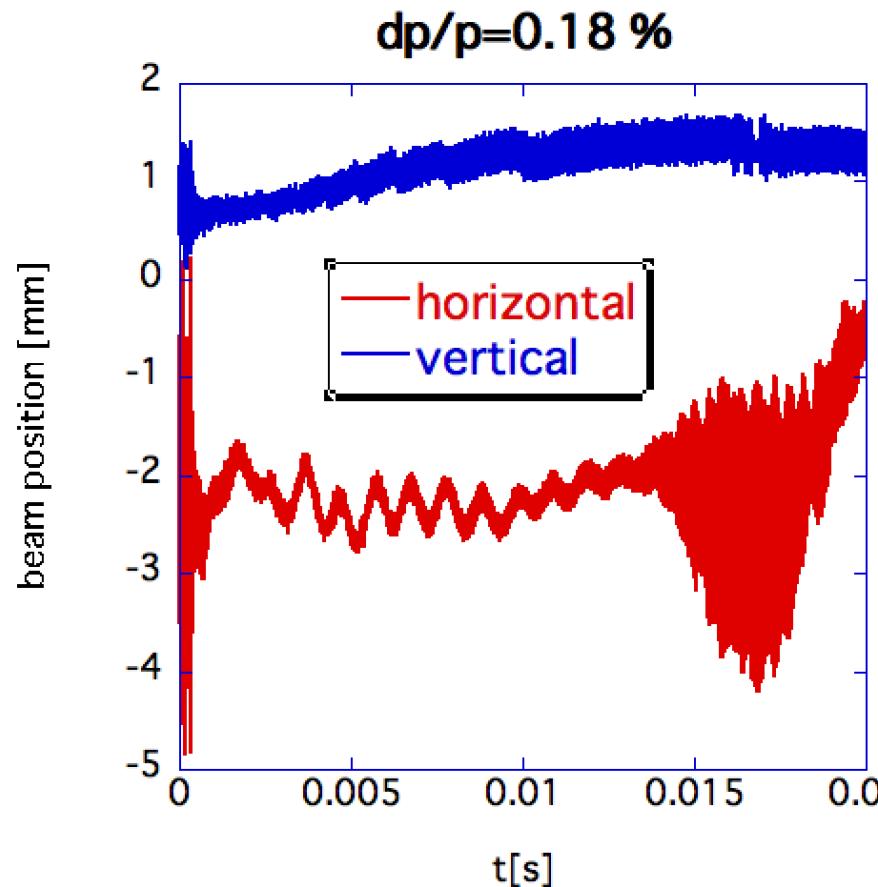
- In the accelerator covering the intermediate energy region such as the RCS, the smaller bunching factor (average current/peak current) especially around the low energy region causes beam stabilizations by expanding the tune spread.
[Y. Shobuda *et al* IPAC2011,MOPS004]
- We expect the effect by making the RCS beam accumulating the injection beam with smaller momentum spread.



The injection beam with the smaller momentum spread creates the RCS beam with the smaller bunching factors.

Measurement results(750kW)

Chromaticity is corrected only at the injection energy.



- The beam with the smaller bunching factor is stabilized.
- The space charge effect suppress the beam growth.

- In 1 MW operation, it is planned that the sextupole magnets will be turned off.
- The voltage with the second harmonic RF as well as the one with the fundamental harmonic RF is excited during the injection period, in the routine operation of RCS.
- In order to mitigate the space charge effect, the longitudinal painting is performed
 - by applying the phase sweep of the second harmonic voltage (-100 degree) relative to the phase of the fundamental one,
 - by adequately superposing the voltage with second harmonic to the one with the fundamental harmonic in order that the injection beam feels momentum offset (-0.2 %) relative to the center of the RF-bucket.

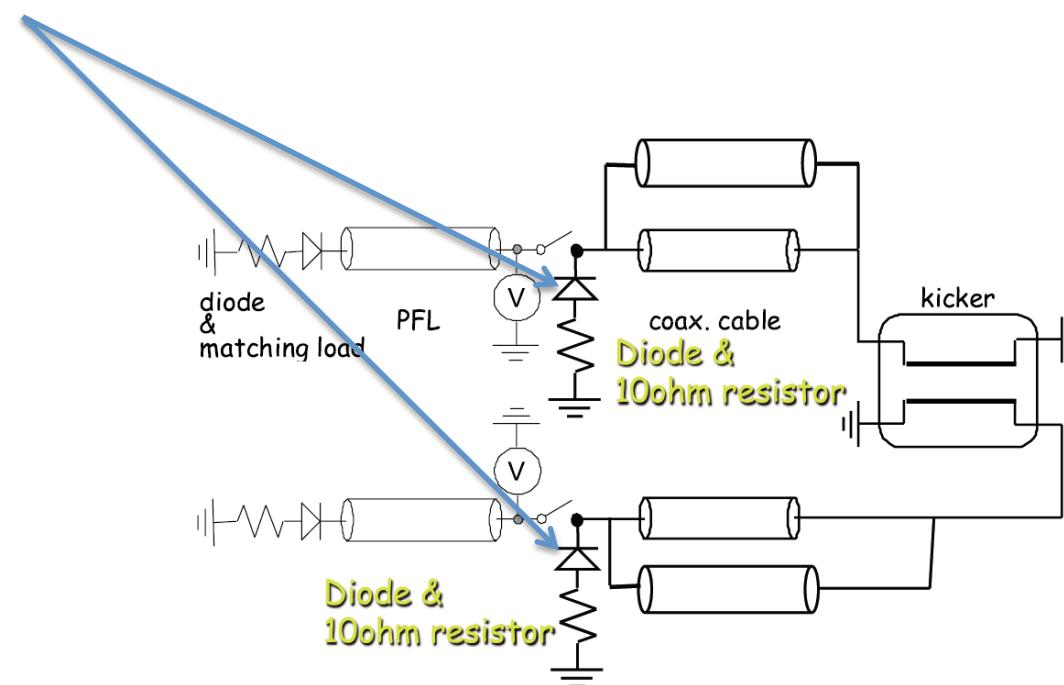
On the other hand,

- Present strategy to achieve one mega-watt beam is
 - to make maximum use of the adequate tune manipulation combined with the space charge damping effect.
 - When the damping effect is insufficient, the bunching factor will be made lowered by activating the second harmonic voltage without the phase sweep, neither the momentum offset during the injection period.
- ◆ *In order to pursue the higher intensity beam, there is no way except reducing the kicker impedance itself.*

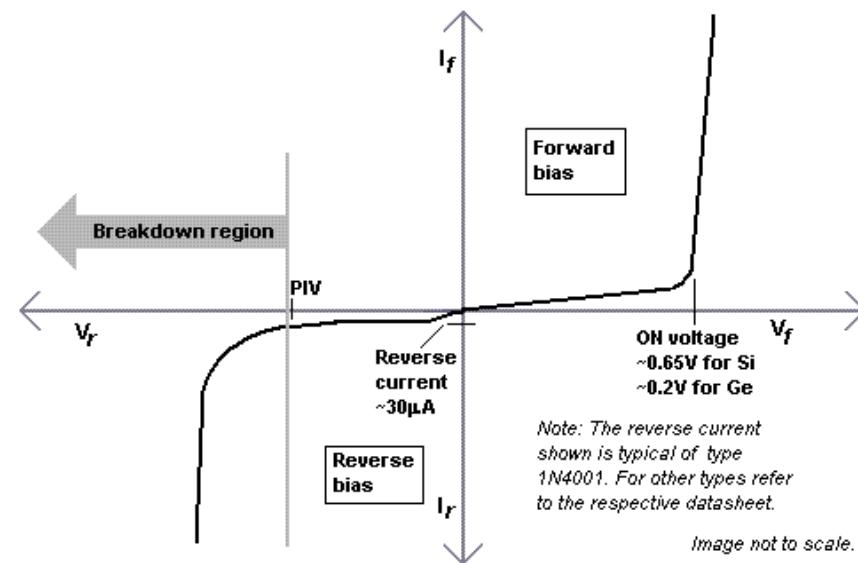
A reduction scheme of the kicker impedance

■ In order to reduce the impedance, a resistor with matched should be inserted between the coaxial cable and PFN.

- The resistor has to be isolated from PFN, but needs to be seen by a beam.
- We need a mechanism to isolate the damping resistor from pulse current from the PFN.
- From a mechanical point of view, the easiest way is to insert a diode in front of the resistor.



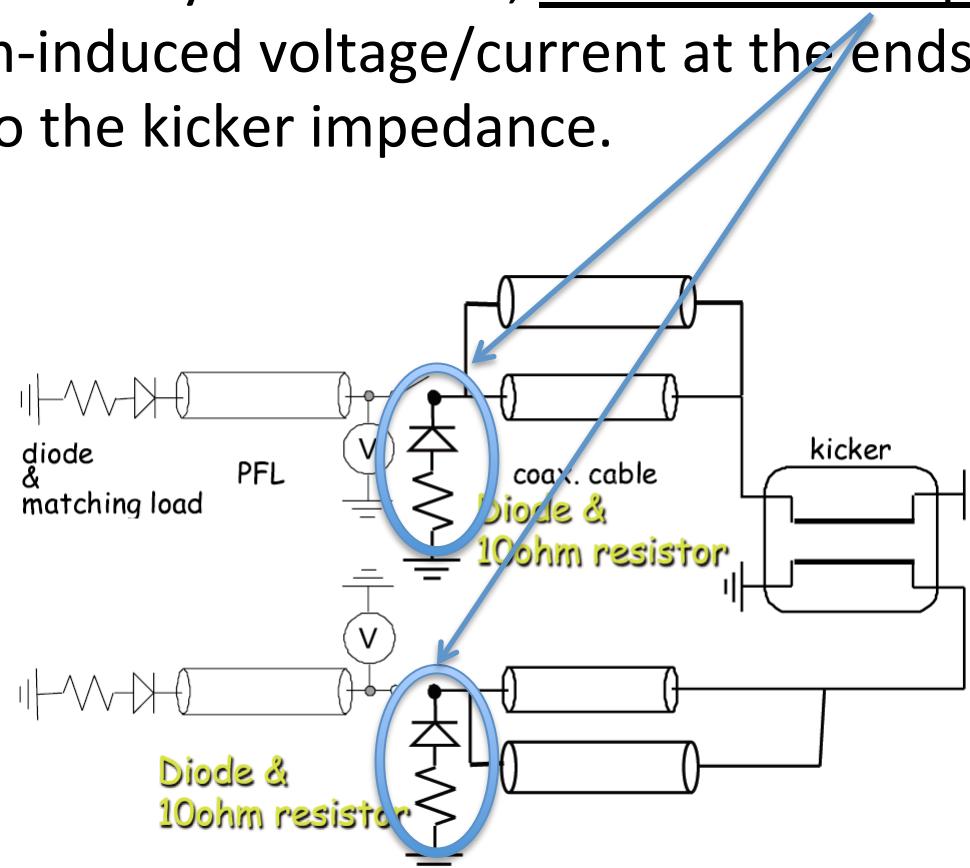
- In practical point of view, the diode must have the high reverse voltage V_R (the resistor has to be isolated from PFN when the kicker is fired)
- Requirement to the actual diode: the V_R must have at least 40kV or higher.

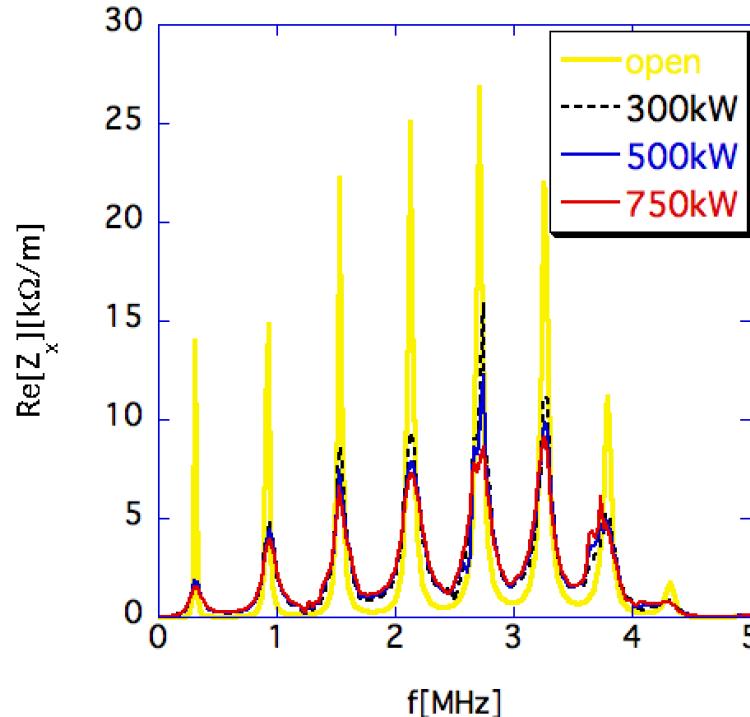


- The most significant concern is whether the beam-induced current flows the diode having the such high reverse voltage.

◆ Let us measure the kicker impedance.

- The conventional wire method cannot measure the impedance of the kicker with the diodes, because the measurement is basically done in frequency domain by using weak currents with Network Analyzer.
- Applying our theory to the case, the terminal impedance (measured by the beam-induced voltage/current at the ends of the cable) can be converted to the kicker impedance.





- because the diode becomes more conductive for higher current, which means that the terminal impedance (diode+resistor) approaches the characteristic impedance of the kicker.
- The scheme successfully makes the present kicker impedance halved or less.

Issue:

- ◆ We do not sufficiently study whether the kicker equipped with the diodes and resistors extracts beams from the RCS, yet.

Summary

- The measured beam-induced voltage at the ends of the kicker cables is successfully transformed to the kicker impedance.
- The measurement enhances the reliability of the estimation of the kicker impedance, so that it is incorporated into the input of ORBIT.
- In order to achieve high intensity beams, it is effective to utilize tune manipulations and the space charge damping effect.
 - It is preferable that the momentum spread of the injection beam is as small as possible.
- The measurements of the terminal impedance at the ends of the kicker cables by using the beam-induced voltage/current demonstrate that the kicker impedance can be halved or less by attaching the resistors combined with diodes there.