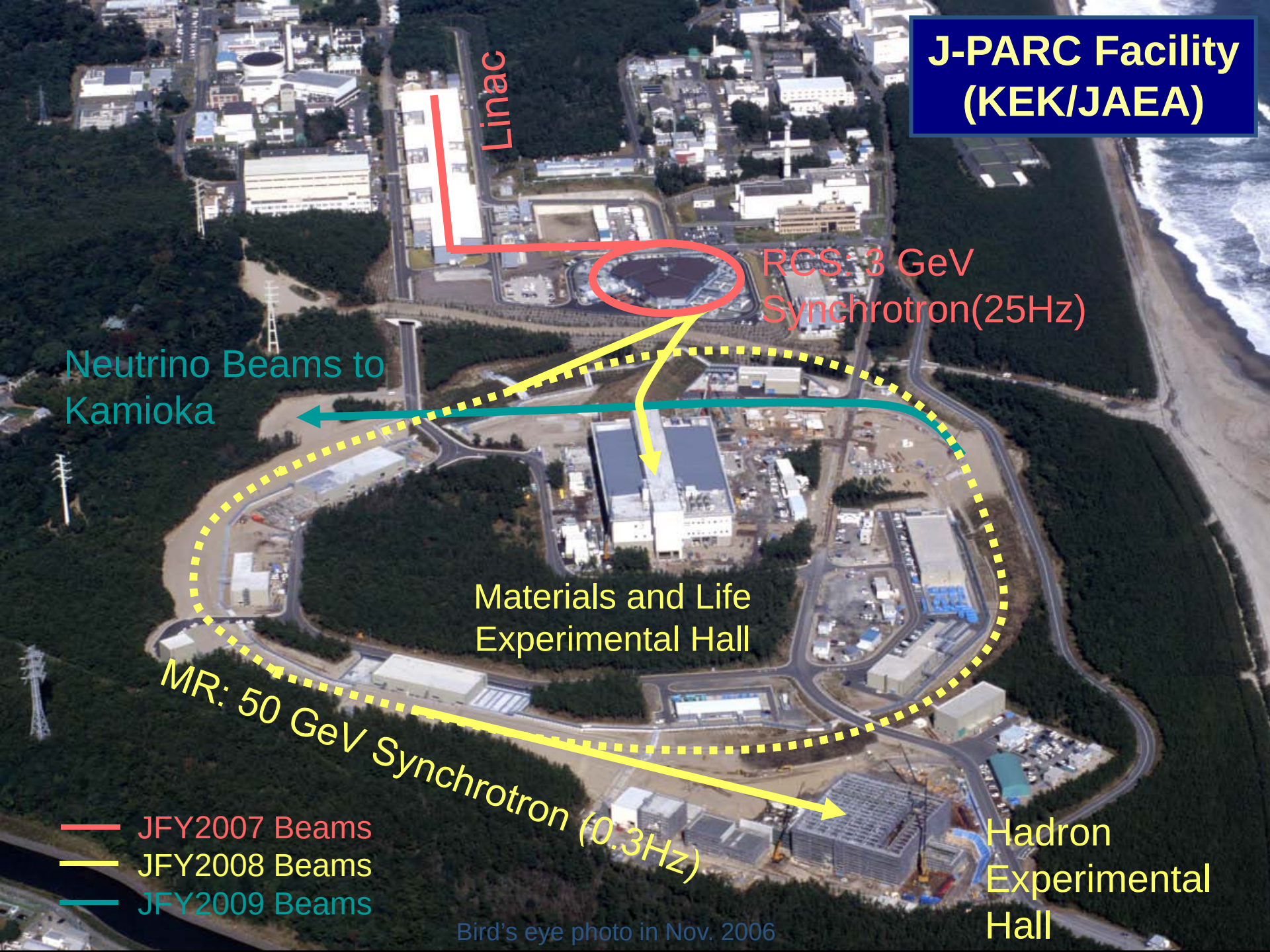
Impedance and Beam Instabilities Issues at J-PARC Rings

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Y. Shobuda and J. Kamiya (JAEA),
ICFA-HB2008
Nashville, TN

Outline

- The Important Remark at First:
  - Since the beam intensities at both J-PARC rings are still small, no beam instabilities have been observed up to date.
- J-PARC Rings at a Glance
- Issues of Concern
  - Kicker impedances
    - How to reduce them
  - Stainless-steel chamber impedance at Main Ring (MR).
  - RF shields of ceramic breaks at MR.
- Summary.


J-PARC Facility
(KEK/JAEA)
Linac
RCS: 3 GeV
Synchrotron(25Hz)
Neutrino Beams to
Kamioka
Materials and Life
Experimental Hall
MR: 50 GeV Synchrotron (0.3Hz)
Hadron
Experimental
Hall
JFY2007 Beams
JFY2008 Beams
JFY2009 Beams
Bird's eye photo in Nov. 2006

Rapid Cycling Synchrotron (RCS)

- Parameter list (C=348.3m, h=2, Rep=25Hz)

T (Kinetic energy, GeV)	0.181	0.4	3
f_0 (MHz)	0.47	0.614	0.84
η (Slippage factor)	-0.69	-0.48	-0.047
Q_x/Q_y		6.68/6.27	
B_f (Bunching factor)	0.374	0.371	0.185
N_b (Protons/bunch)/10^{13}	2.49	4.15	4.15
I_c (Average current, A)	3.74	8.15	11.1
I_p (Peak current, A)	10	22	60
$\Delta p/p$ (%)	0.85	0.85	0.38
τ_z (Half bunch length, m)	55	55	20
ν_s	0.0058	0.0058	0.0005

Main Ring (MR)

- Parameter list (C=1567.5m, h=9, Rep=0.3Hz)

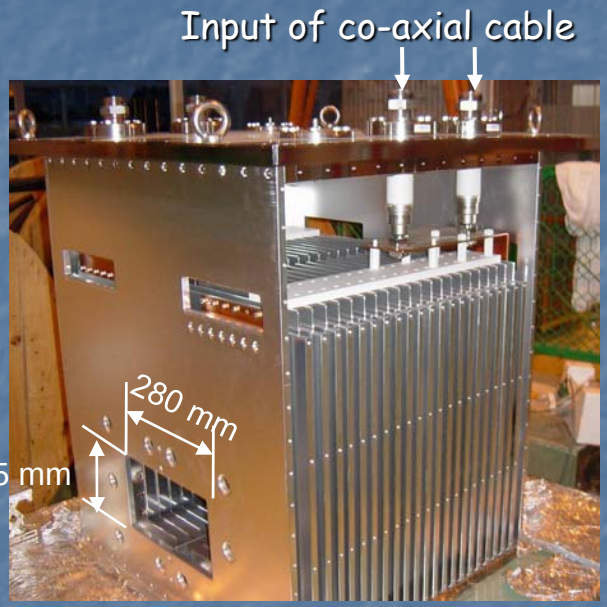
T (Kinetic energy, GeV)	3	50
f_0 (MHz)	0.186	0.191
η (Slippage factor)	-0.058	-0.0013
Q_x/Q_y	22.33/22.28	
B_f (Bunching factor)	0.336	0.056
N_b (Protons/bunch)/10^{13}	4.15	4.15
I_c (Average current, A)	9.86	10.2
I_p (Ppeak current, A)	29.3	182
$\Delta p/p$ (%)	0.85	0.25
τ_z (Half bunch length, m)	41	8
ν_s	0.0025	0.0001

Issues of Concerns

- At both rings, sharp impedances of kickers are estimated to cause beam instabilities at the beam power of around a few 100kW or possibly less.
  - We are studying and testing several damping methods of kicker impedances.
- At MR, the resistive-wall impedance of the stainless-steel chamber is another dominant source for the transverse beam instabilities.
  - Precise estimate of chamber impedance and beam instability assessments.
  - Development of dampers
- RF shields for ceramic breaks at MR.

Kicker Impedance

- Measurement set-up for RCS Kickers (Distributed Constant Type)

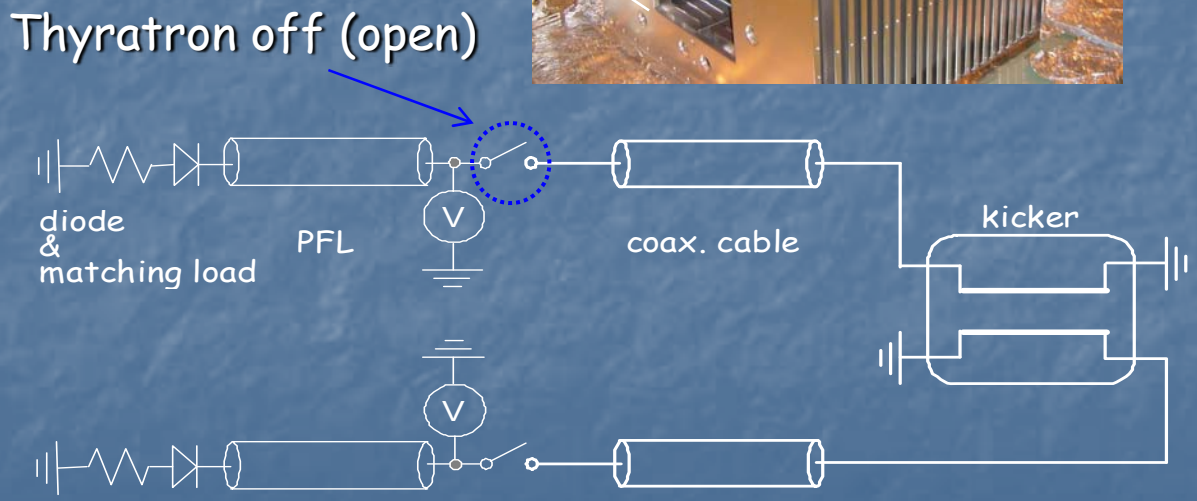


Kicker parameters (prototype)

Z_c=10 Ω
L=1.459 μH/m
C=15.04 nF/m
v=0.0225 c
Effective length = 634 mm
Aperture height = 165 mm

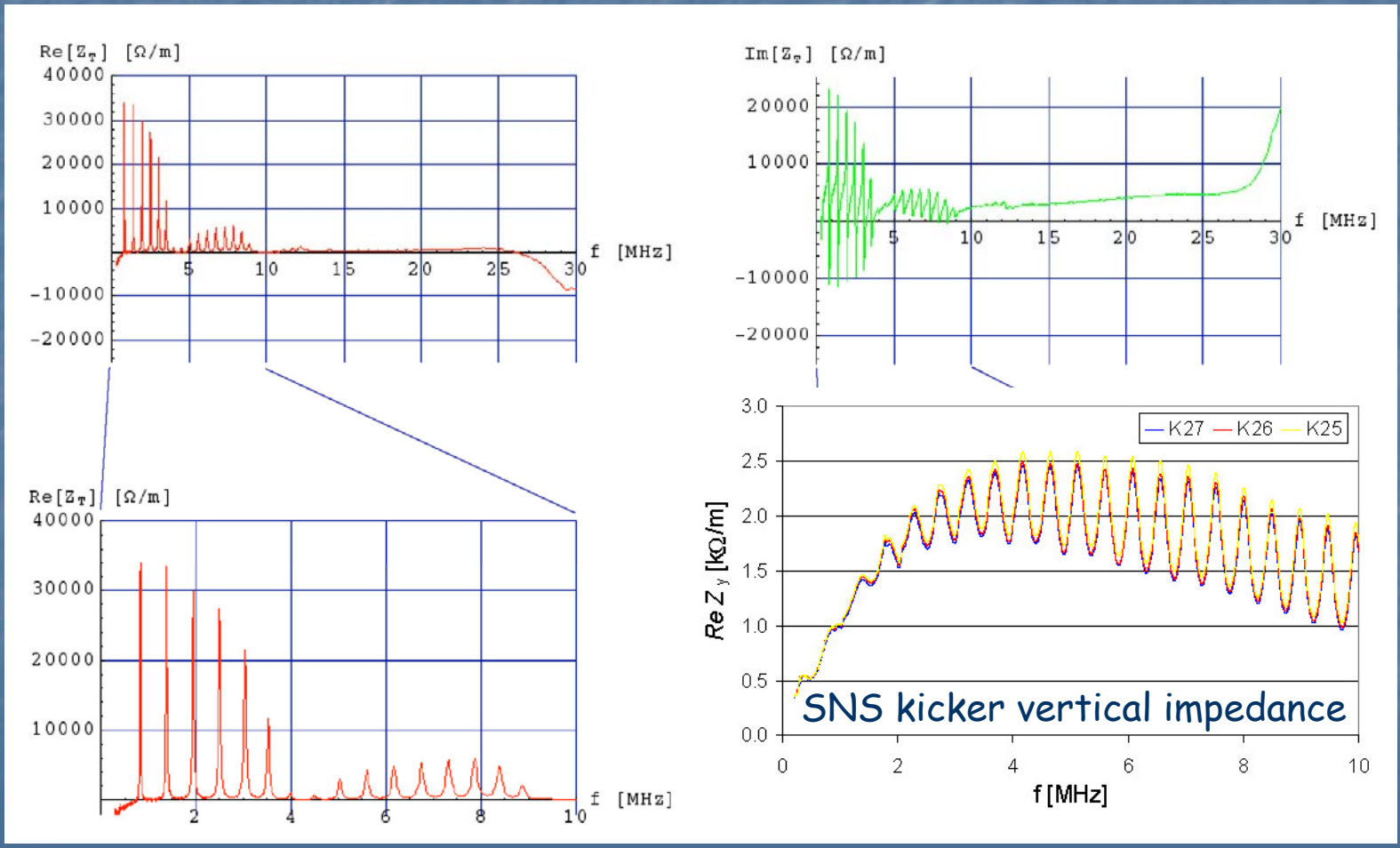
Cable length = 140 m

reflection $\Delta f \sim n \times 600$ kHz



Transverse Impedance of a RCS Kicker

- They are ~10 times larger than those of SNS kickers.



SNS Kicker (Lumped Constant Type)

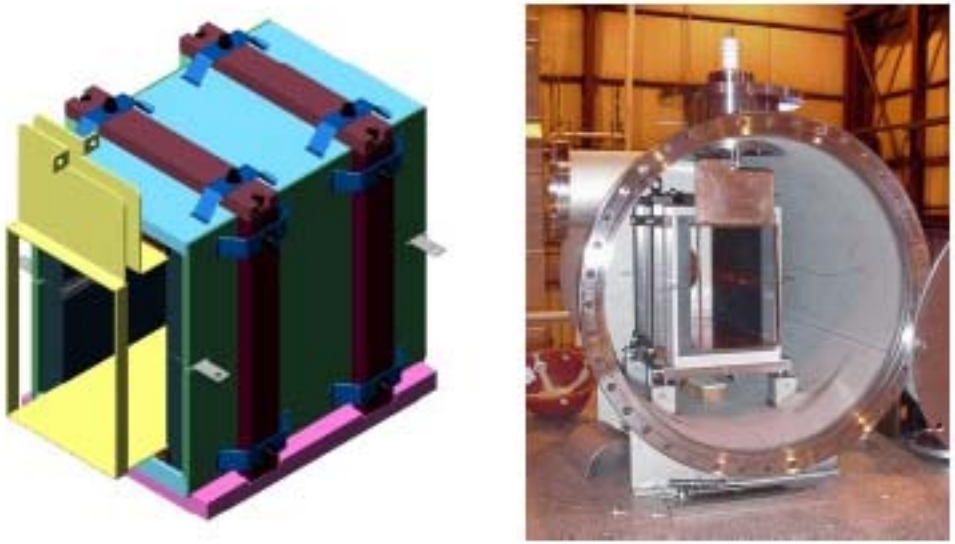


Fig. 1. The SNS extraction kicker: schematic view (left), the kicker in the vessel used for the measurement (right).

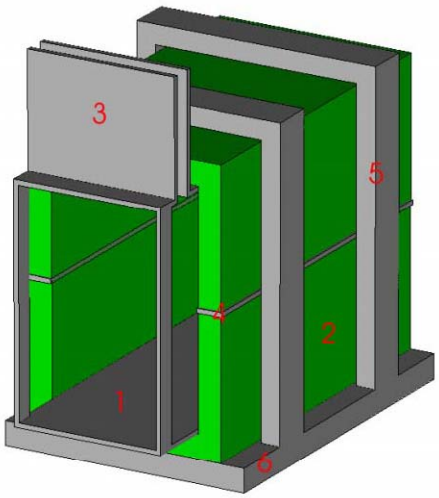


Figure 1: Schematic view of the SNS kicker where it is possible to observe the busbar (1), the ferrite (2), the end-plates of the busbar (3), the strips (4), a frame (5) and a base (6).

Why J-PARC Kicker Impedances So High Compared to SNS Kickers?

- SNS kickers use saturable inductors to damp cable resonances:
  - The saturable inductor behaves as low impedance for high-current pulses from the modulator, but as high impedance for the resonant current induced by a beam, and lets this current flow thru the resistor.

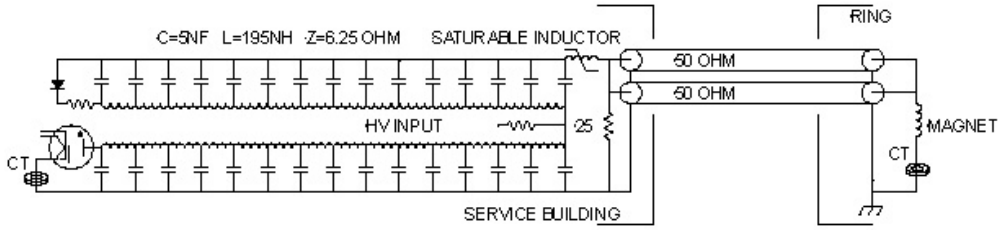


Figure 2: Simplified schematic diagram of modulator.

Can We Use the Same Scheme?

- Yes, for MR, where all existing kickers will be renewed to the lumped constant type.
  - The study is under way.
- No, for RCS, where the existing distributed constant type kickers will be continuously used.

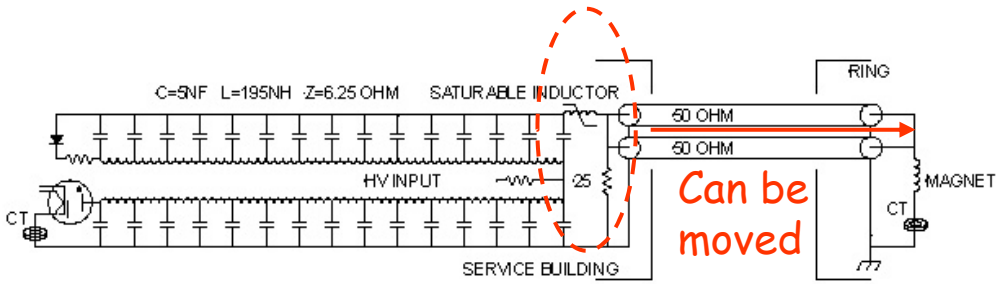
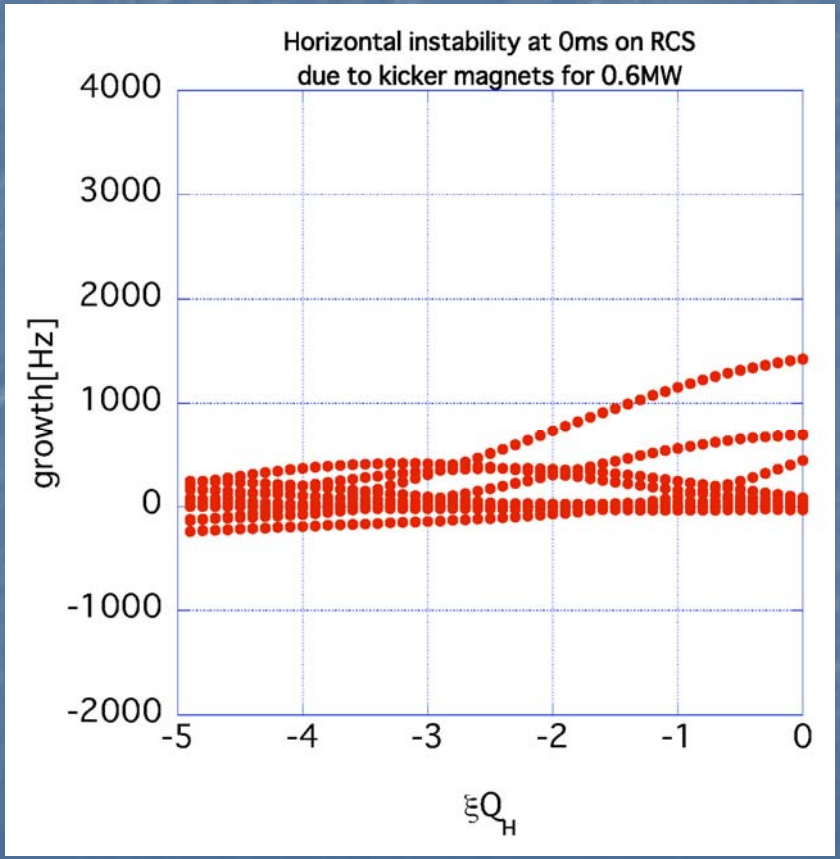
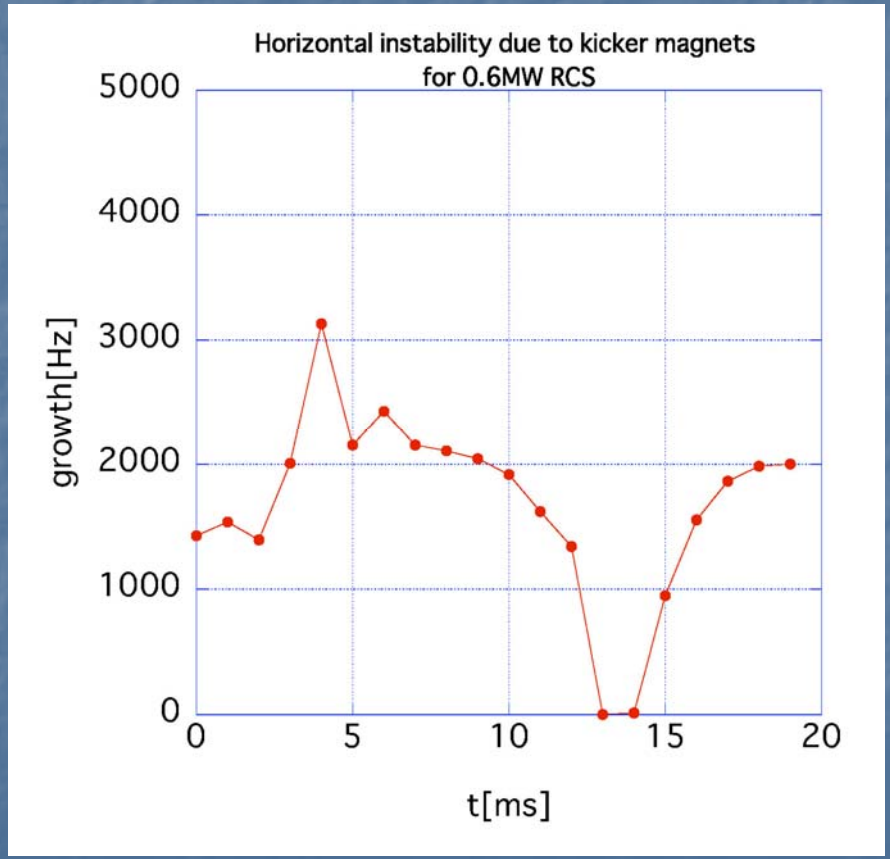


Figure 2: Simplified schematic diagram of modulator.

RCS Beam Instabilities due to Kickers 1

- Beam power=600kW, injection energy=181MeV case.

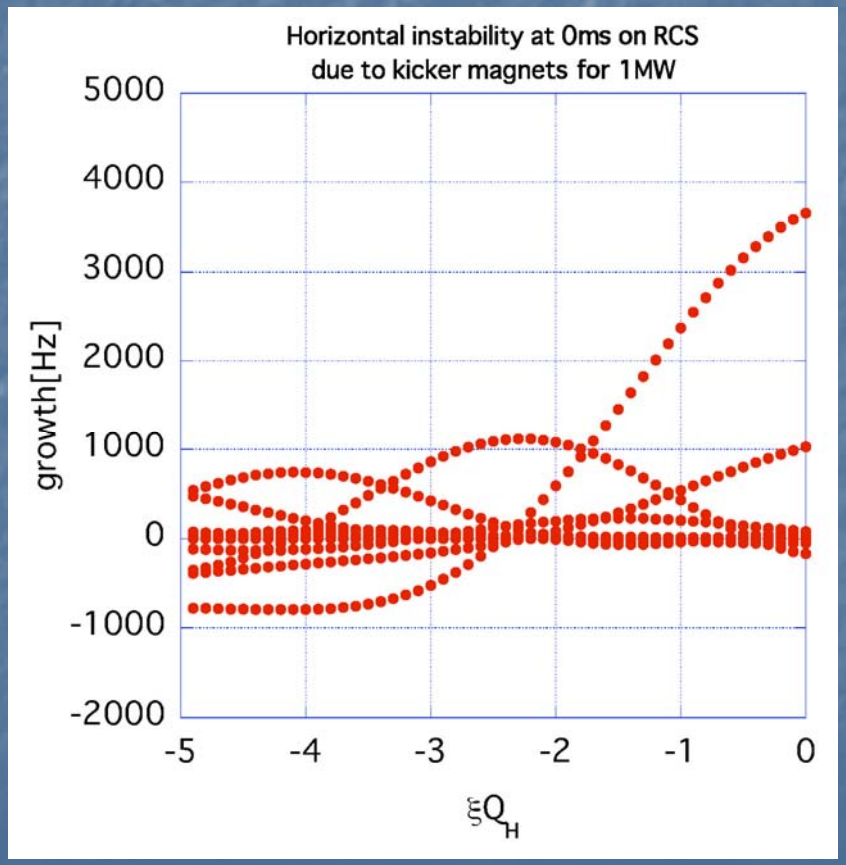


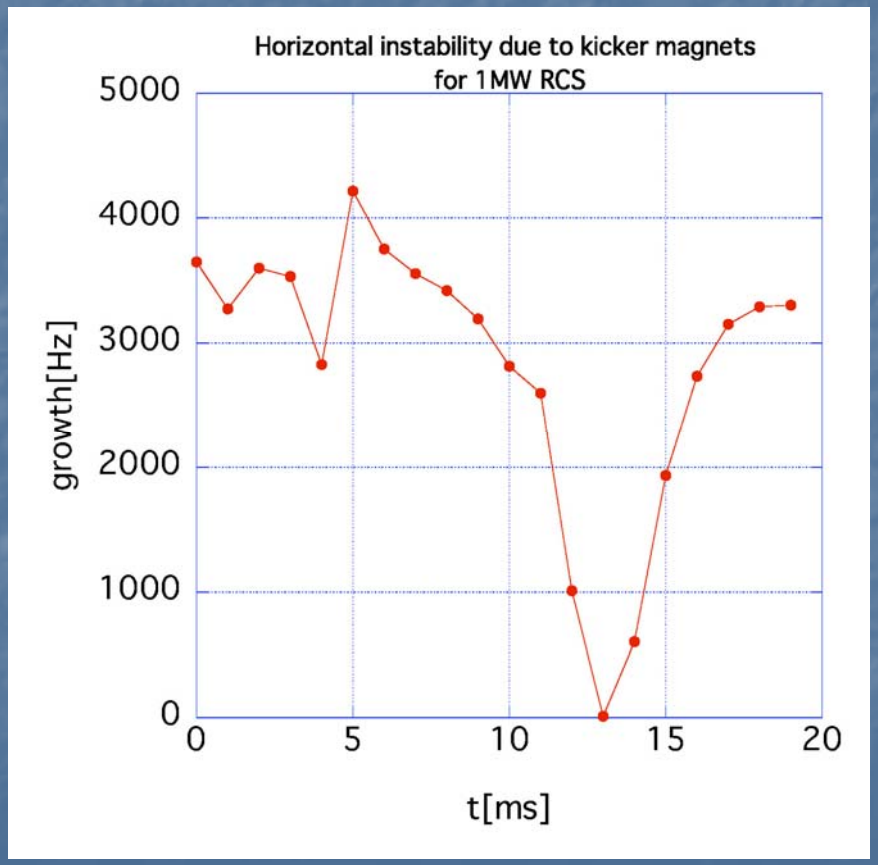


Chromaticity=0

RCS Beam Instabilities due to Kickers 2

- Beam power=1MW, injection energy=400MeV case

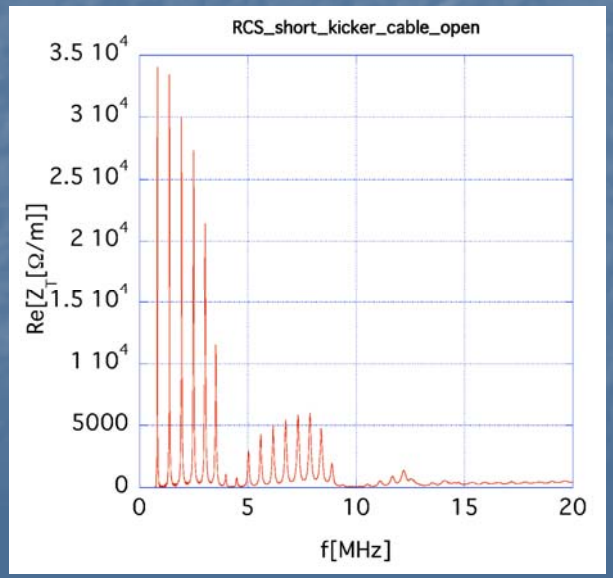


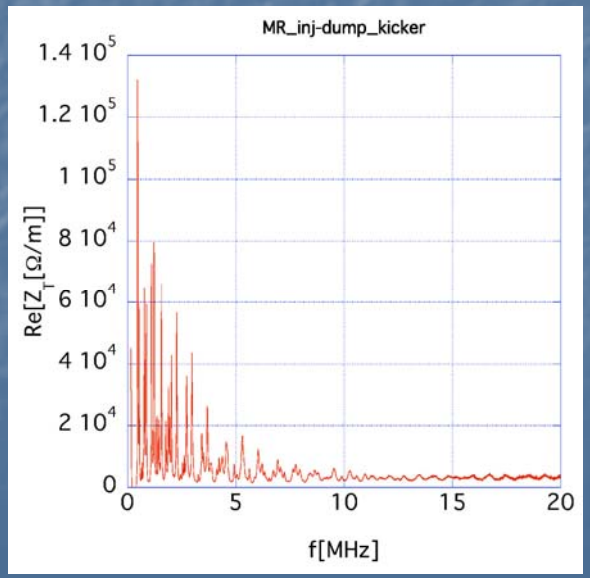


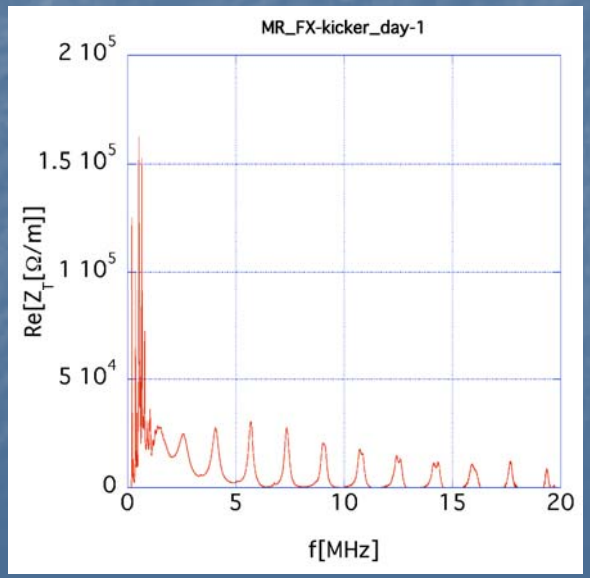
Chromaticity=0

Transverse Impedances of MR Kickers

- MR kicker impedances have been measured as well and they are similar to those of RCS:
  - Injection kickers (3) – distributed constant type
  - Injection dump kickers (3) – lumped constant type
  - Fast extraction kickers (5) - lumped constant type

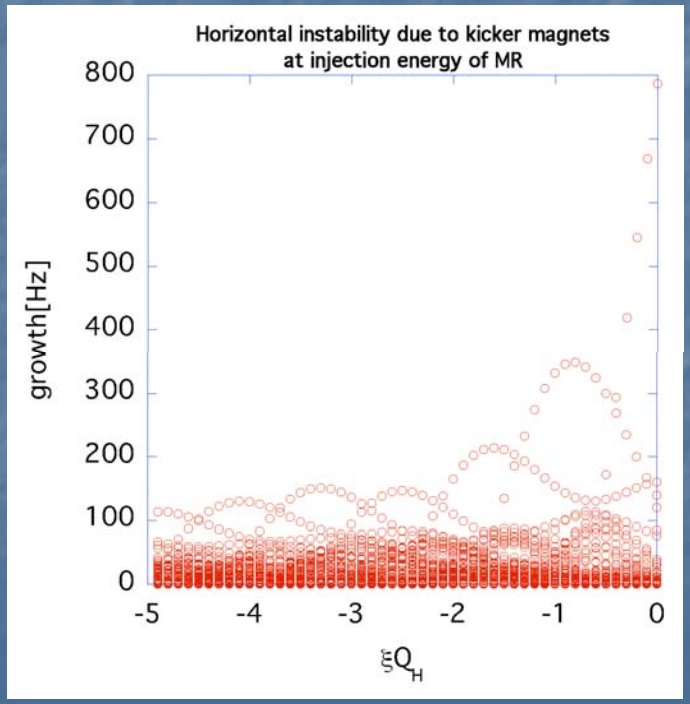


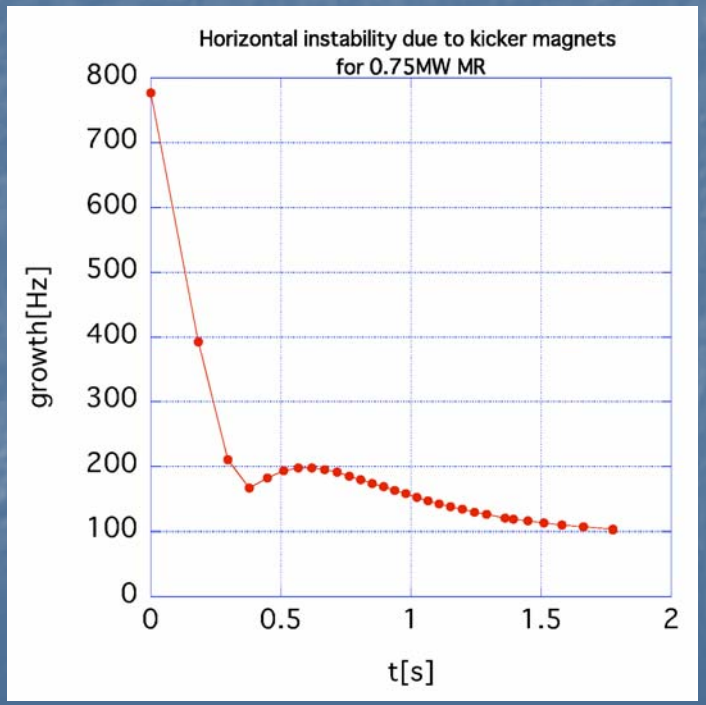




MR Beam Instabilities due to Kickers

- Transverse beam instabilities due to kickers may be very serious (though maybe less serious than due to stainless-steel chambers as described later), and the impedance resonances in the cable need to be damped.





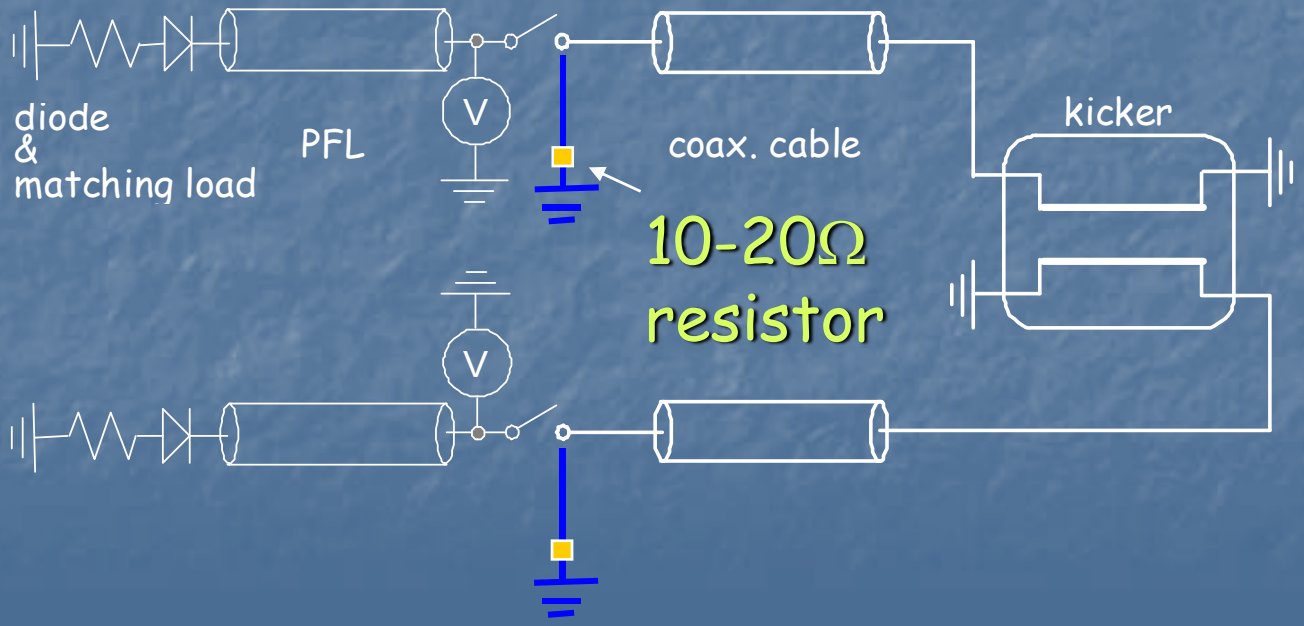
Chromaticity=0

Remarks

- These calculation results of beam instability growth rates are based on the linear theory where
  - No damping due to non-linear effects (revolution frequency slippage factor, betatron tune spread, synchrotron tune spread, and so on) are considered.
- For more accurate estimates, we need to carry out beam instability simulations using realistic simulation codes such as ORBIT.
  - The ORBIT code and many templates for input files have been installed to both the KEK and JEAE parallel computers, thanks to Andrei Shishlo of ORNL.
  - But, we are still under preparation for actual runs.

Damping of the Cable Resonances

- The experiment was done to show that
  - The sharp peaks in impedance are really due to cable resonances.
  - They can be damped in principle using resistors.



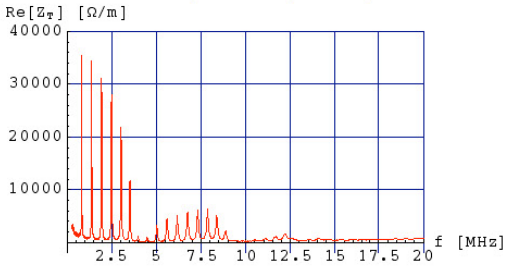
Measurement Results with Resistor

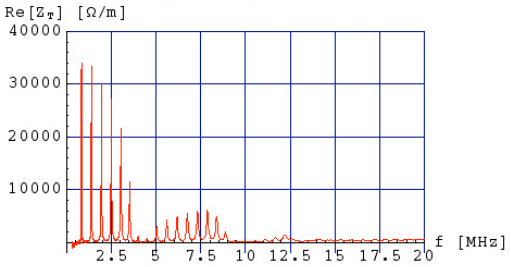
Kickerの終端を変えた

Beam port = open / open

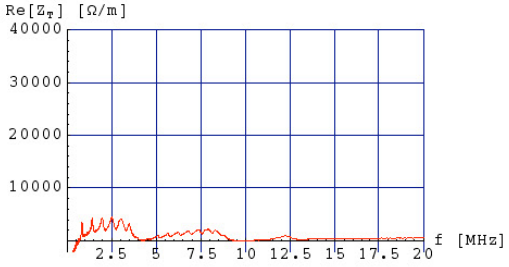
Beam port = open / closed

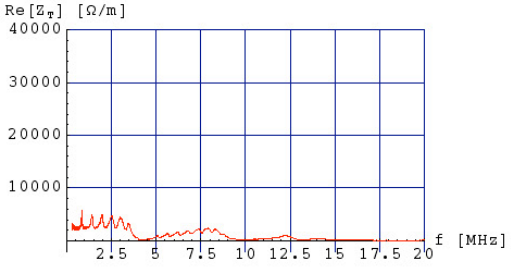
① kicker 終端
short
cable - open (Thyratron ON)



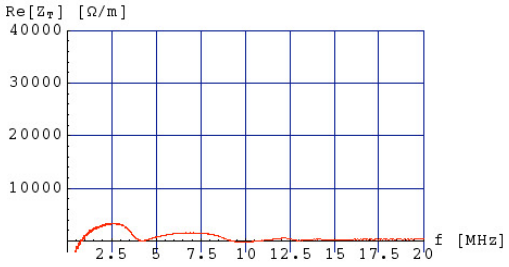


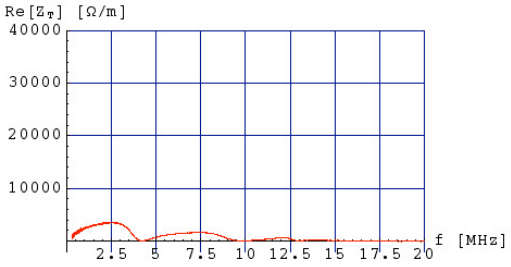
② kicker 終端
short
cable - 20 Ω/cable → 10 Ω





③ kicker 終端
short
cable撤去, kicker本体に10 Ω

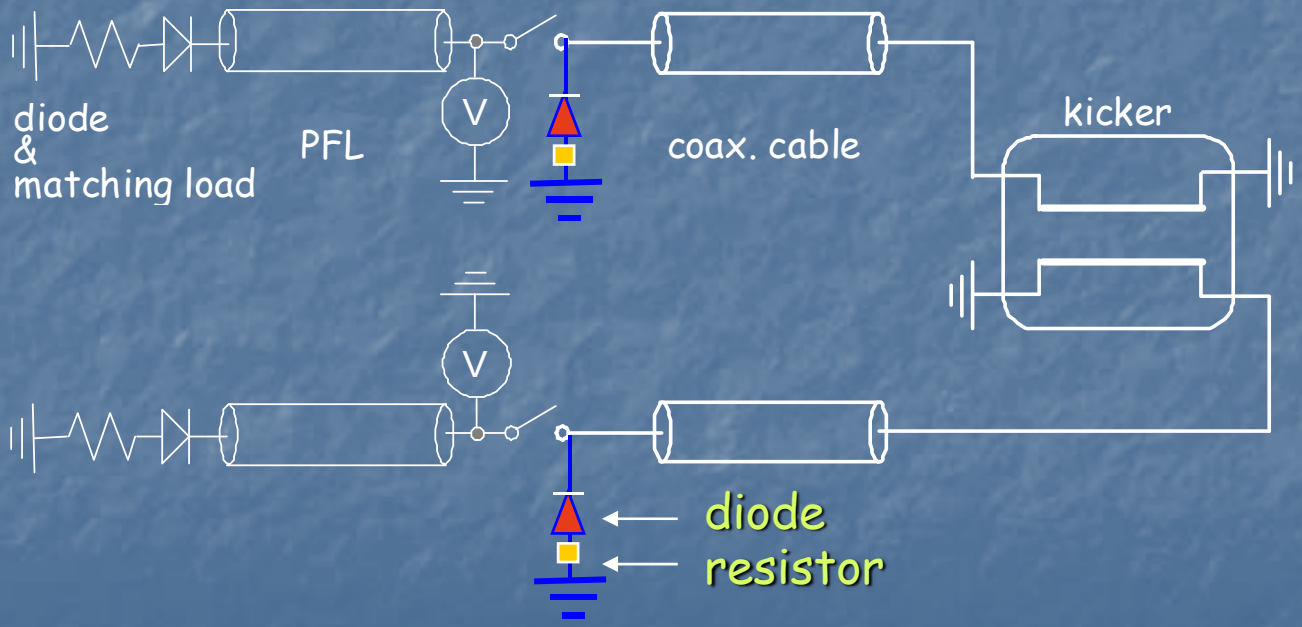




How to Switch the Two Currents?

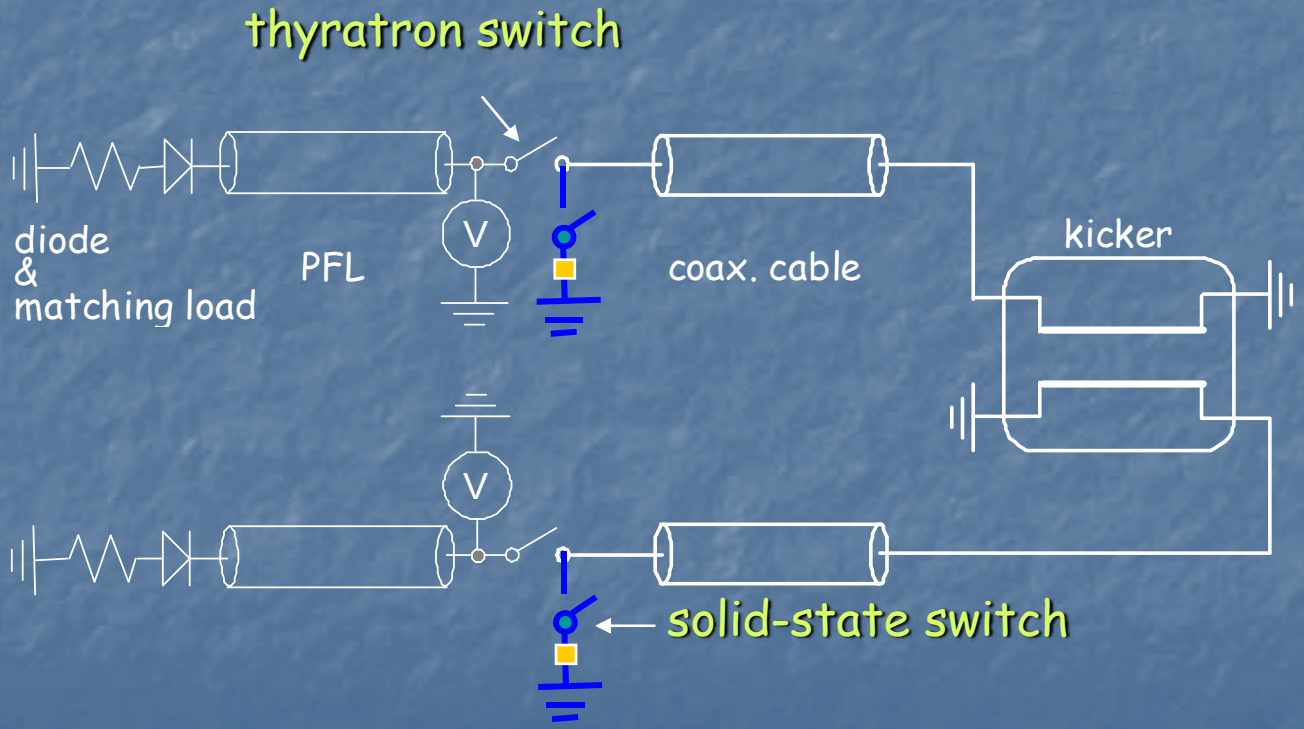
- We need a mechanism to isolate the damping resistor from pulse current from the modulator to the kickers.

Possibility 1 with Diode



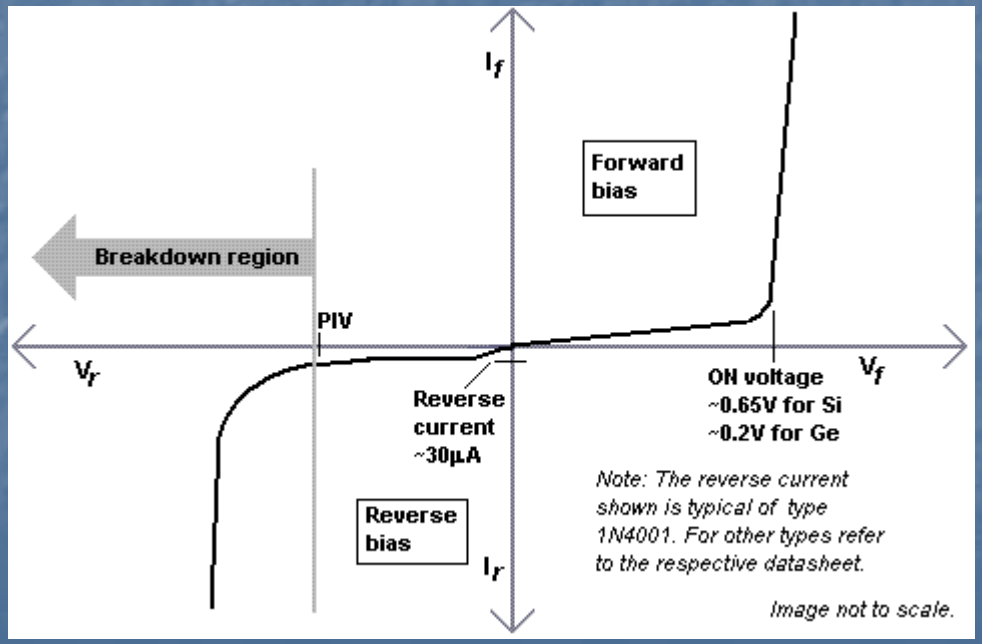
Possibility 2 with Another Switch

- We can insert another switch before the resistor which is unsynchronized with the thyratron switch.



Problem with Diode

- Diode
  - No diode is available with a large dynamic range of working voltage from a few 100V (induced by a beam) to 60kV (pulse from the modulator).



Problems with Solid-State Switch

- Series-parallel assembly of solid-state switches for 60kV blocking voltage is costly.
- Need to develop a gate driver circuit for solid-state switches that will synchronize with the timing of kicker operation.

Examples of Some Pulsed Power Switch Assemblies supplied by ABB Switzerland Ltd, Semiconductors

(Techn. Data can vary depending on application)



5SPR-08F45-16-WC
Reverse Conducting Switch Assembly
(Thyratron Replacement)

Blocking voltage:	70 kV
Reverse Blocking:	0 V
Vdc max cont.:	40 kV
I-pulse:	up to 5 kA
di/dt:	up to 2.0 kA/µs
t-pulse:	≤ 10 µs
Puls rep. rate:	50 Hz
Clamping force:	20 kN
Cooling:	De-Ionized Water
Triggering:	Optical
Supply:	Current Source PS
Semiconductors:	16 x 5SPR 08F4500

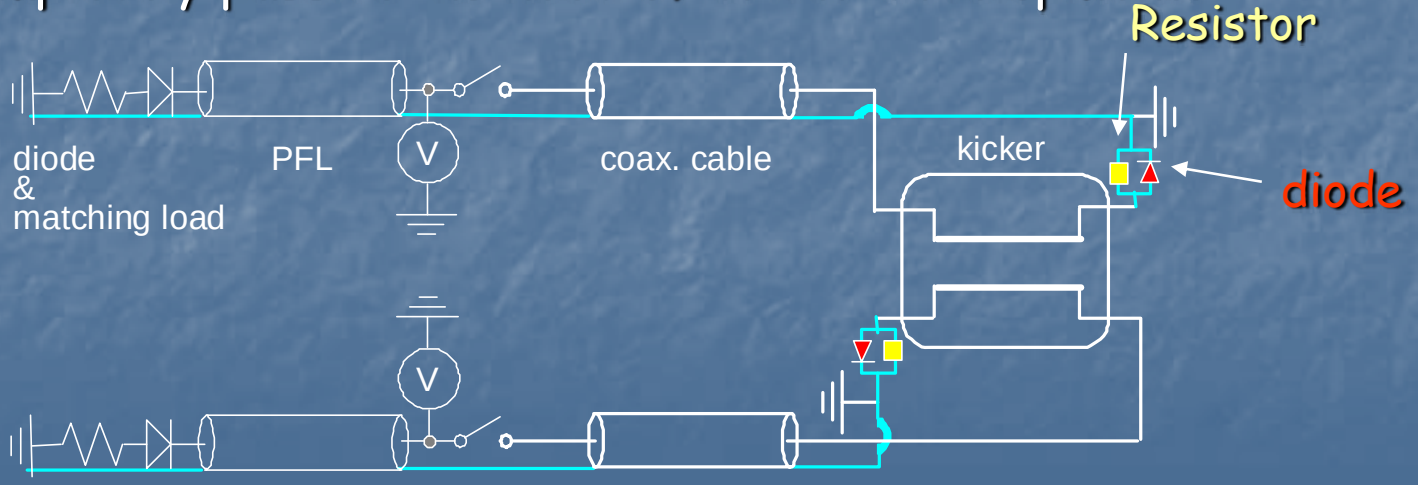


5SNA-20H25-8-WC
IGBT Switch Assembly

Blocking voltage:	20 kV
Vdc max. cont.:	15 kV
I-pulse:	up to 3 kA
t-pulse:	≤ 100 µs
di/dt:	up to 1.5 kA/µs
Pulse rep. rate:	up to 800 Hz
Clamping system:	Glassfiber Epoxy
Clamping force:	70 kN
Cooling:	De-Ionized Water
Triggering:	Optical
Supply:	Current Source PS
Semiconductors:	8 x 5NA 2000H2500 IGBT Press Pack

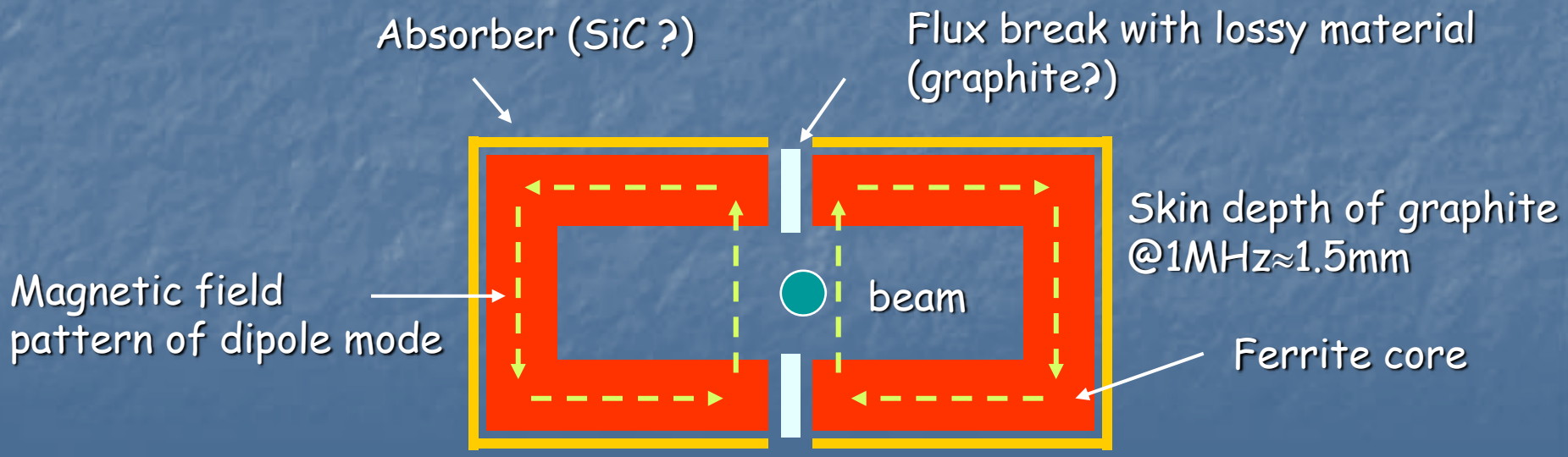
Different Configuration with Diodes

- We can insert a pair of diode and resistor just before the reflection plate where pulses from the modulator become low voltage.
  - The diode is operated at a few kA but only at a few 100V when pulses from the modulator go through.
  - It reduces the impedance resonances induced by a beam by blocking the current flow in cable in the reversed direction.
  - Completely passive: no need of driver development.



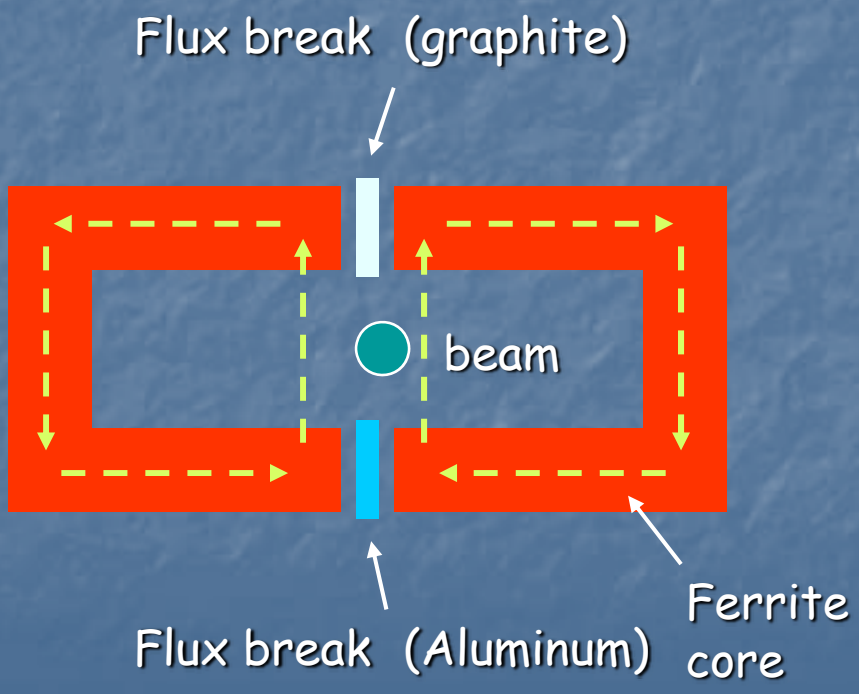
More Direct Approach: Absorbers in the Kickers

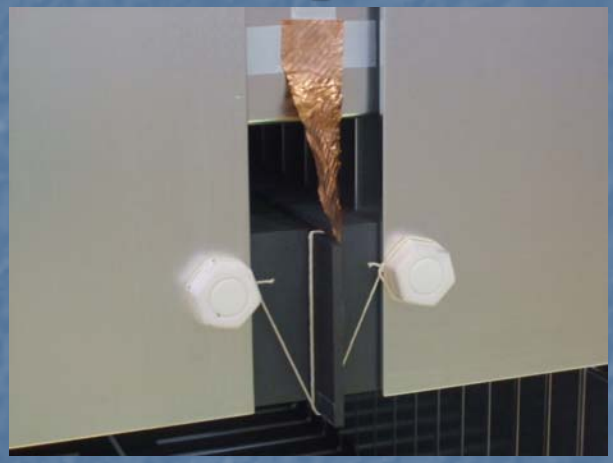
- 1. Use lossy material such as graphite (the bulk conductivity=$10^5/\Omega m$) for the flux break.
- 2. Wrap up (or cover interior of) the ferrite with absorbers such as SiC.
  - Absorbers do not affect the magnetic field inside the ferrite core but damp the electric wakefields.

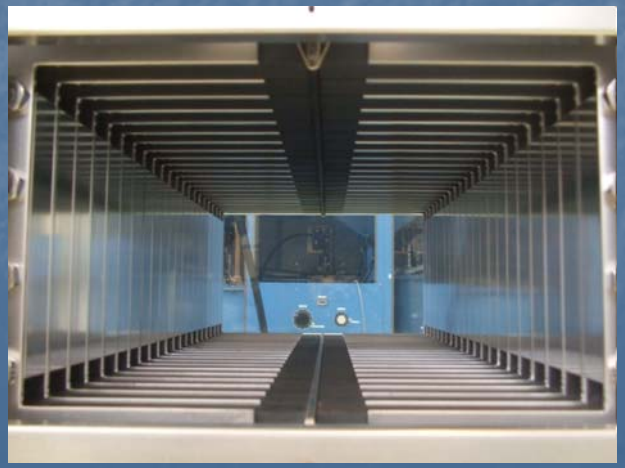


Test of Principle

- We replaced the upper flux break of the RCS kicker by a graphite plate and measured both longitudinal and transverse impedances.

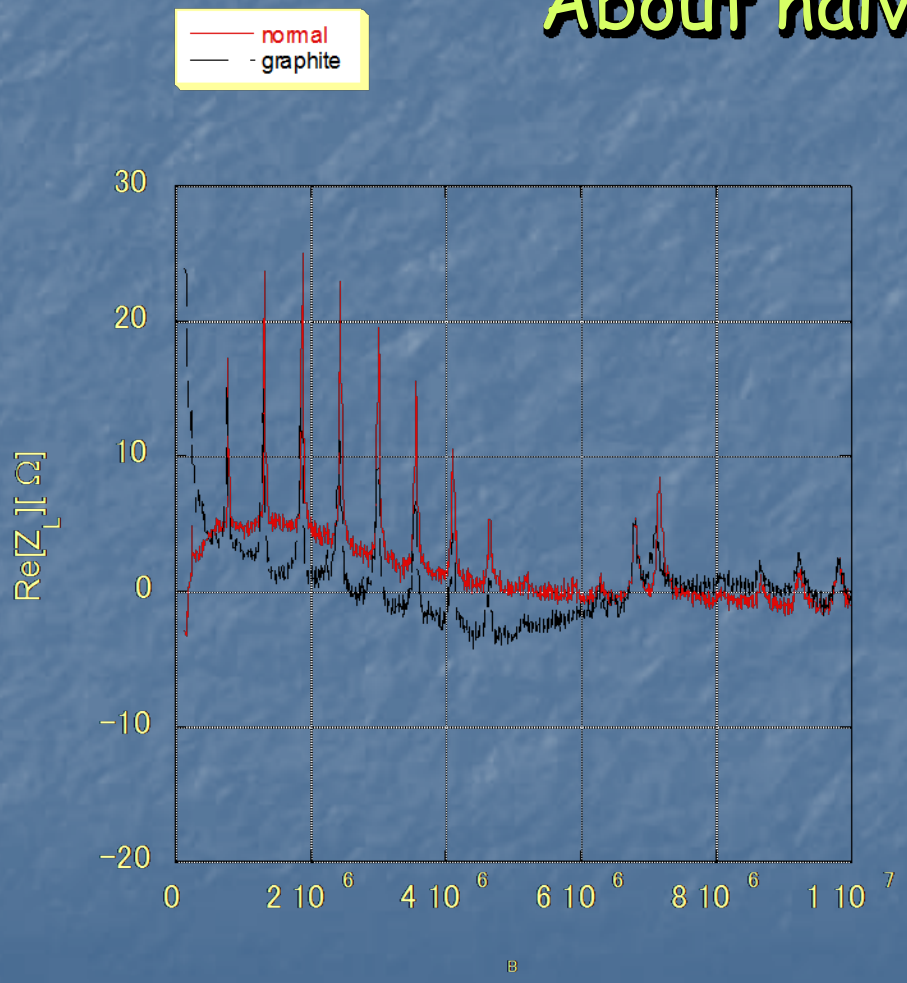


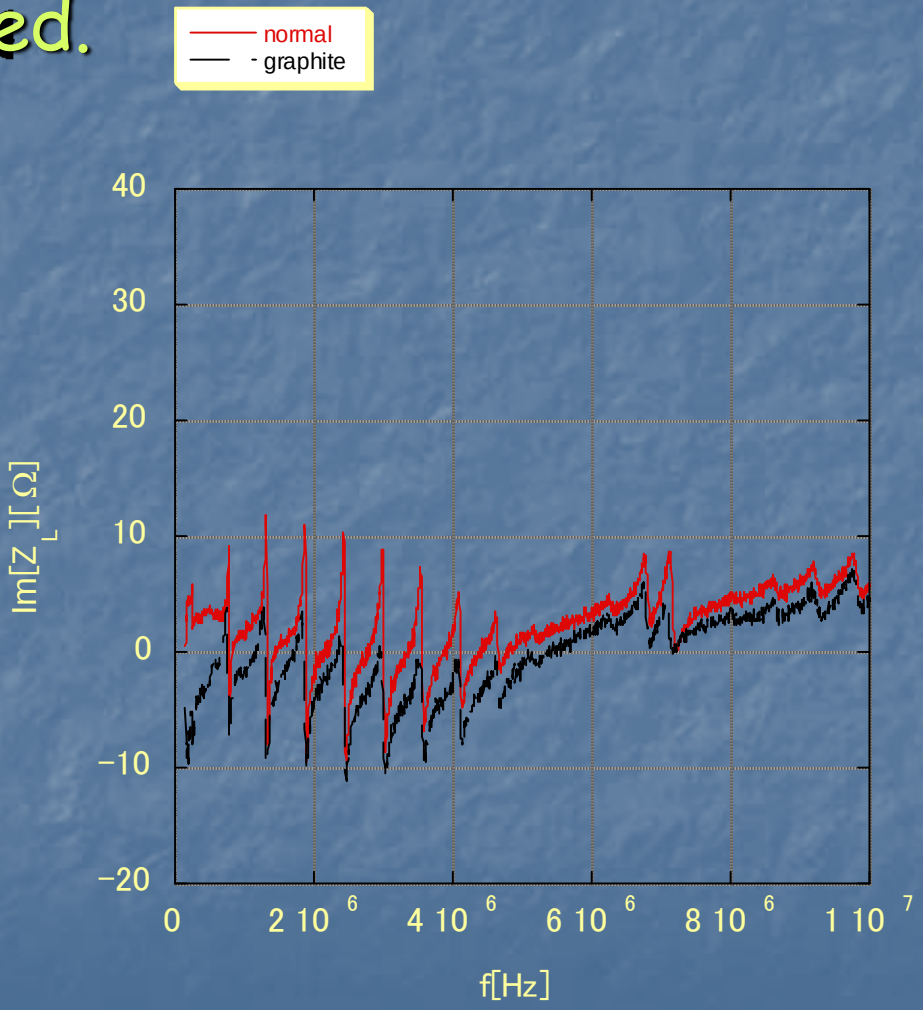




Longitudinal Impedance

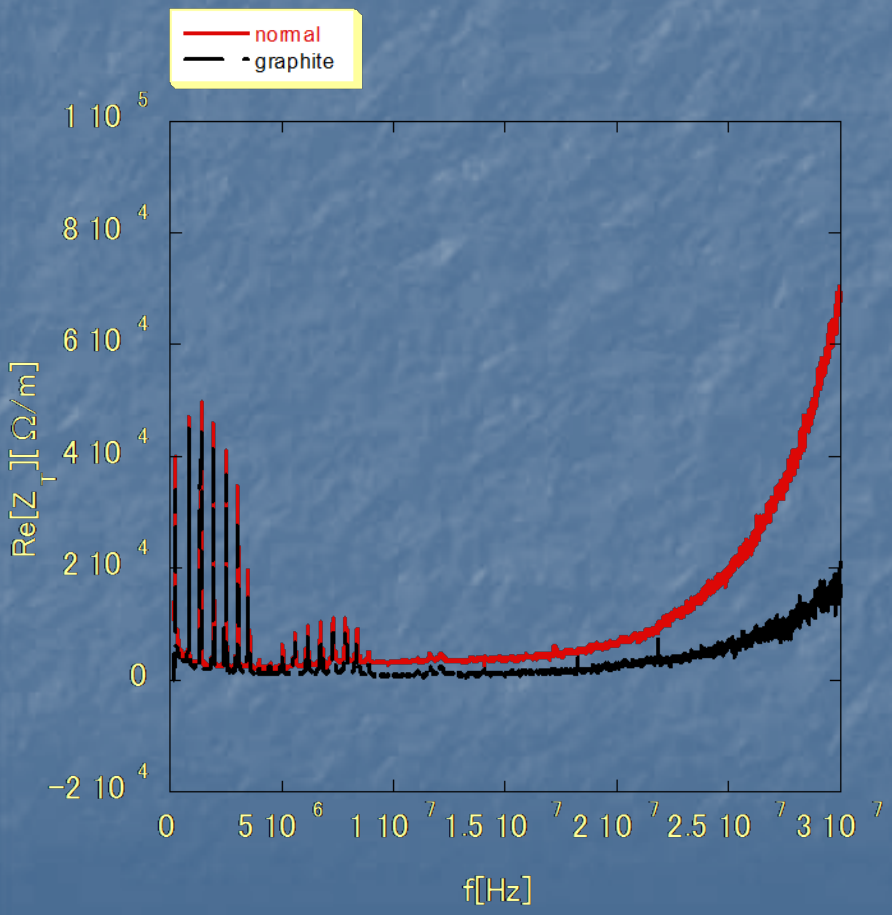
About halved.

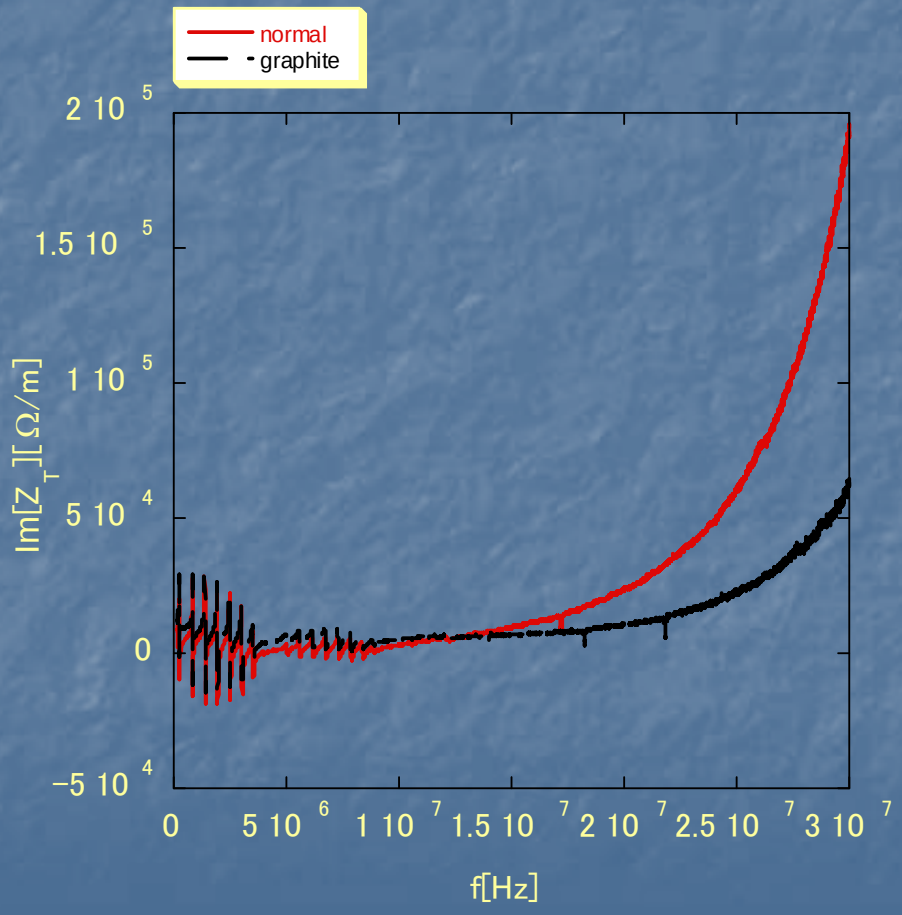




Transverse Impedance

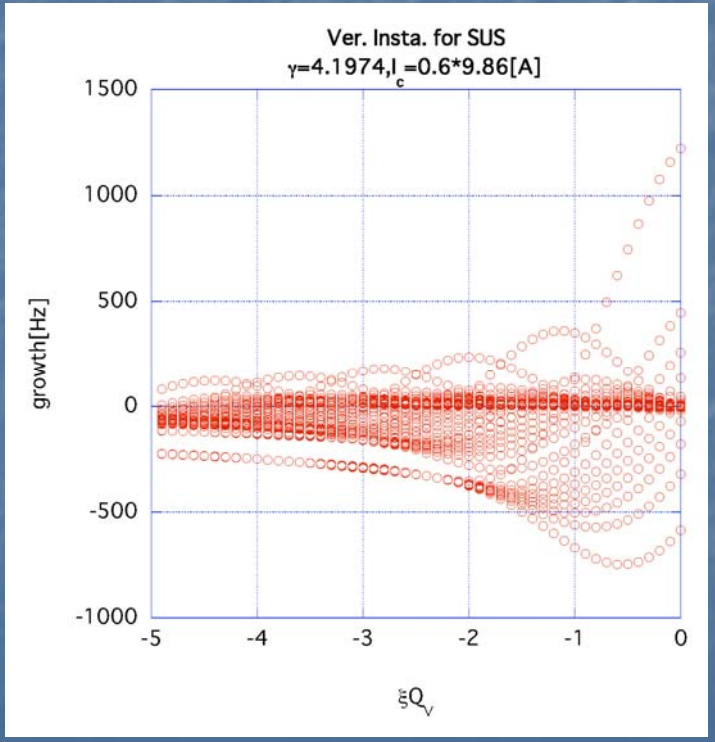
No Big Change.

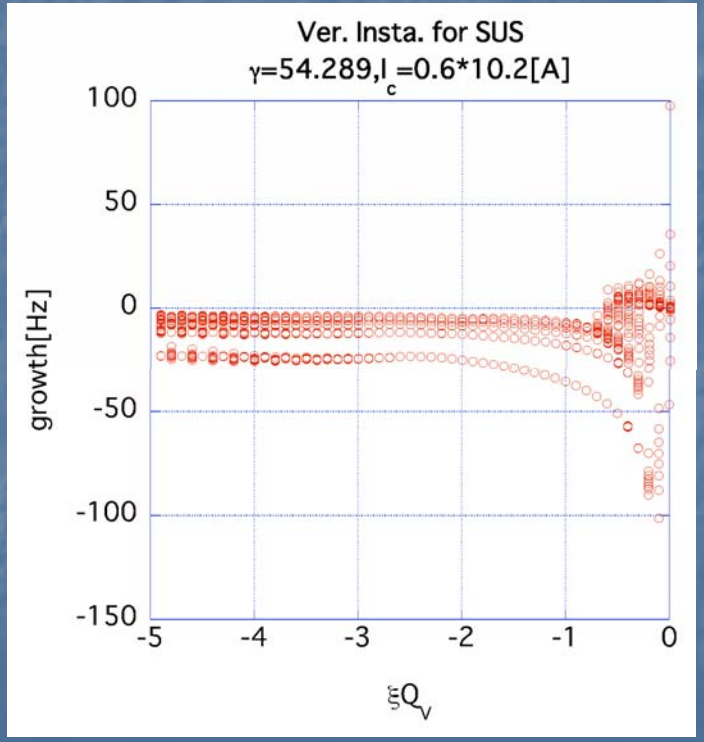




Resistive-Wall Impedance of MR Stainless-Steel Chamber

- Stainless-steel chamber is another dominant source of the transverse impedance and corresponding transverse beam instabilities at MR.





Questions

- Typically, MR stainless-steel chamber has
  - the diameter =120mm,
  - the thickness =2mm.
- The first unstable betatron frequency line is around 50-60 kHz ($f_0 \times \Delta_\beta$).
- At this frequency, the skin depth becomes comparable with the thickness of the chamber.
- Questions:
  - Will wakefields leak out of the chamber?
  - If so, the previous calculation of impedance based on the classical formula was overestimate?

$$Z_T = Z_0(1-i)\frac{L\delta_s}{2\pi b^3}$$

LHC Graphite Collimator

- Renewed interest in the resistive-wall impedance at LHC where the skin depth (δ_s=18mm) at the betatron oscillation frequency (8kHz) in the LHC graphite collimators (25mm thick) is much larger that the aperture of the graphite (b=1mm) , and thus the classical formula is out of applicable range.

$$Z_T = Z_0(1-i)\frac{L\delta_s}{2\pi b^3}$$

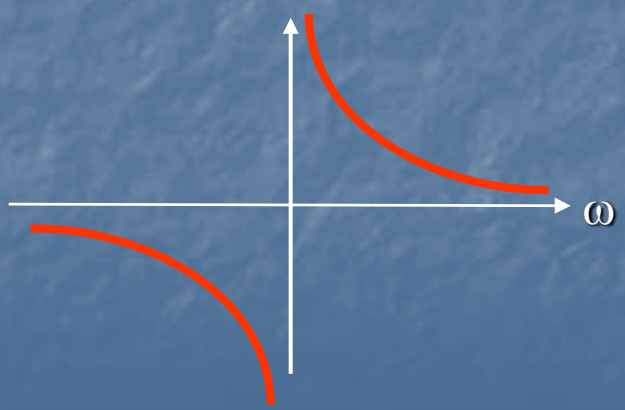




Figure 1: Secondary LHC collimator jaw. The 1 m long flat carbon surface and tapering at both ends, the support and Cu cooling is visible.

Zotter and Metral Theory

- The transverse impedance becomes linear to frequency ω at low frequency, instead of $1/\omega^{1/2}$ dependence.

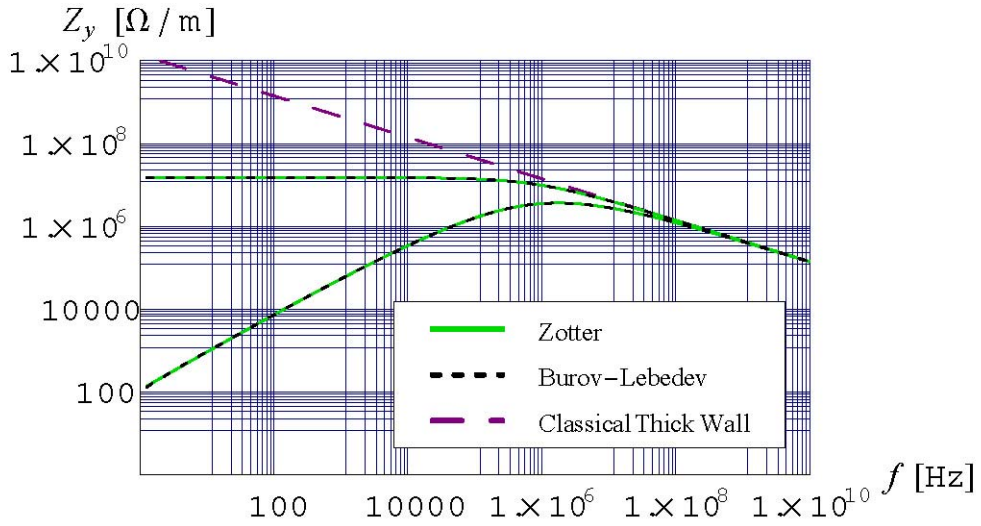
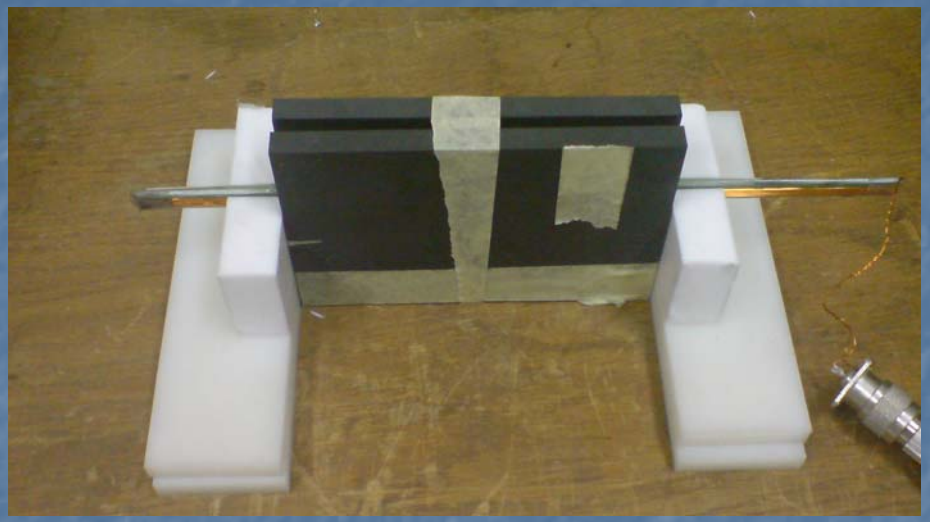
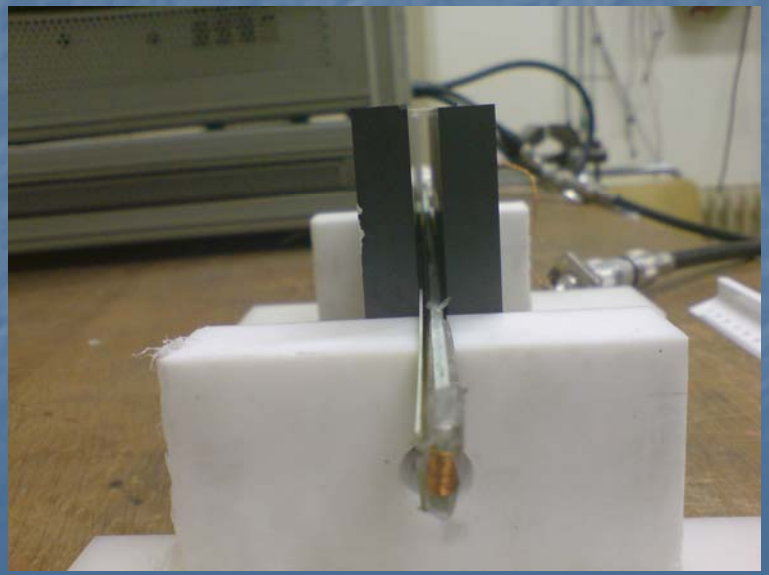


Figure 1: Transverse impedance of Graphite LHC Collimators

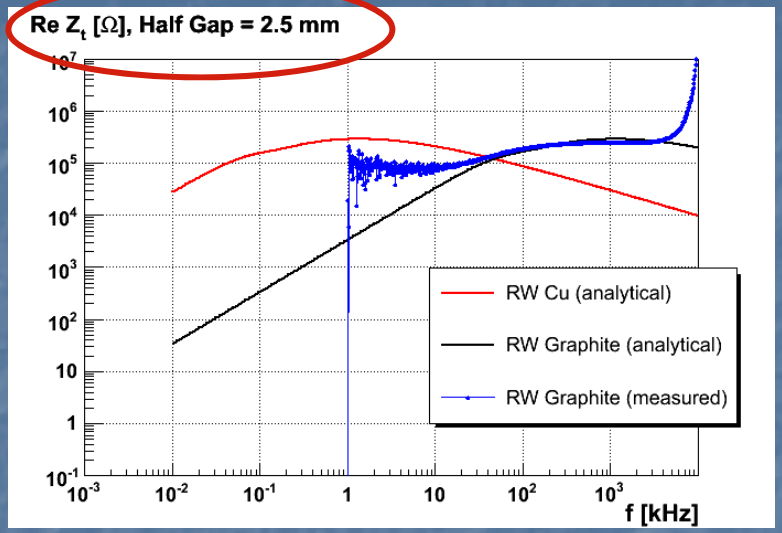
Measurement Setup at CERN

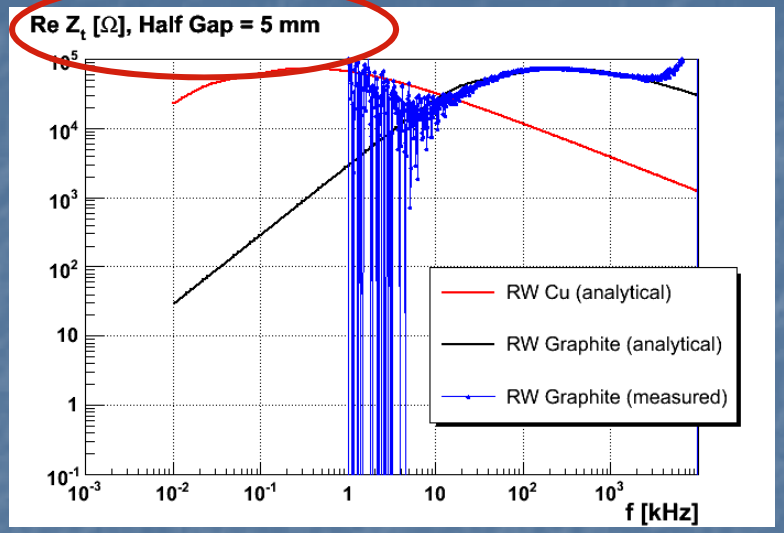


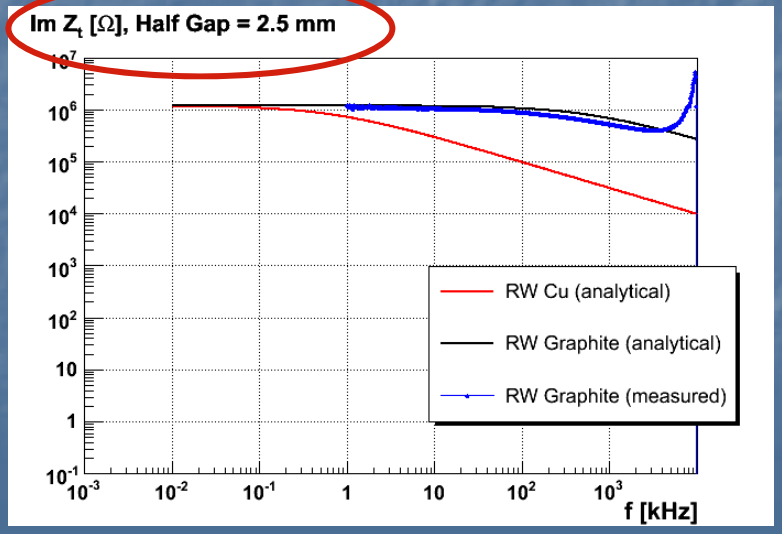


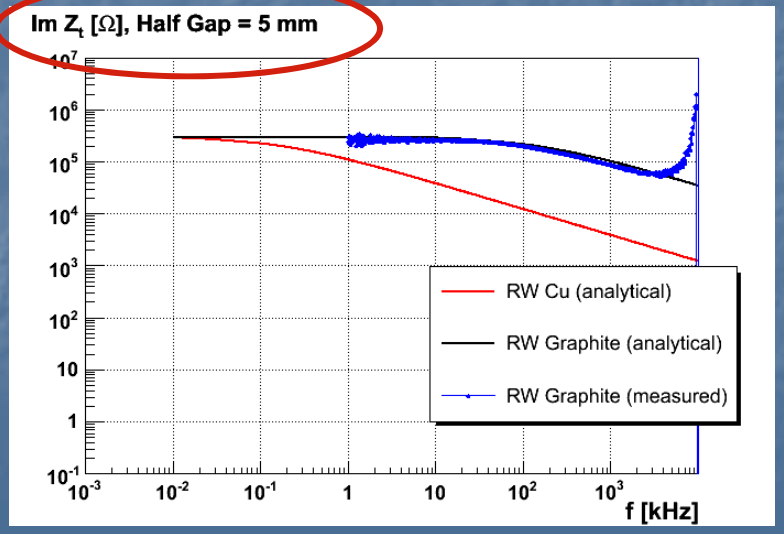


Preliminary results - processed data







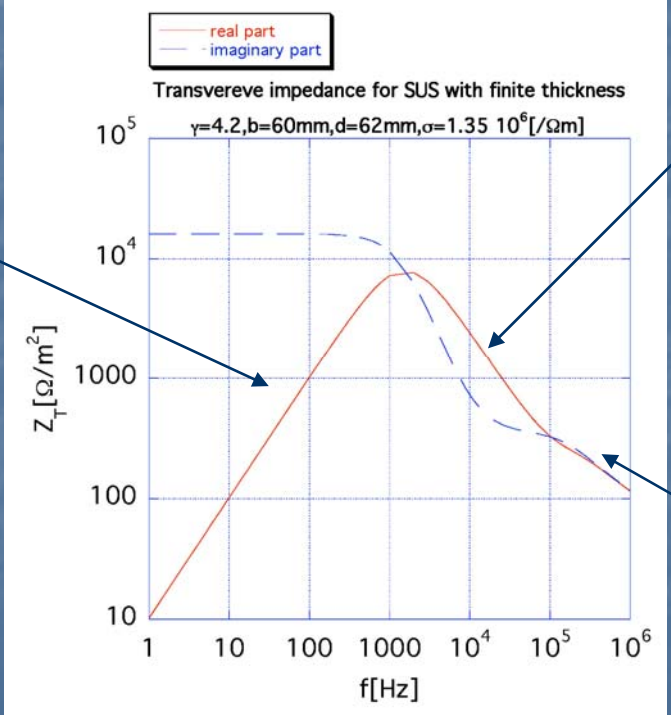


New Impedance Estimate for MR

- Using Zotter-Metral formula assuming open air outside of the chamber, we found that the transverse impedance of MR chamber becomes even larger!

$Z_T \propto \omega$

Extremely thin wall region where wake fields leak out of the chamber.



$Z_T \propto 1/\omega$

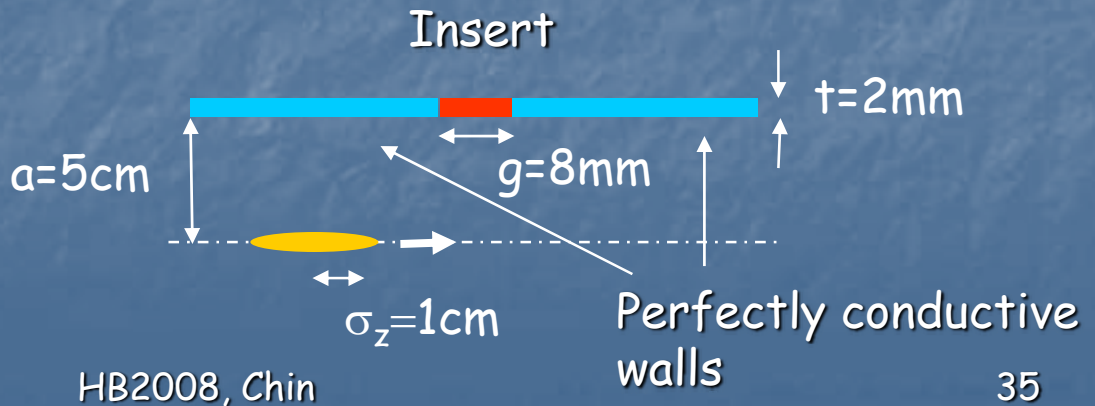
Unconventional region where the skin depth is larger than the wall thickness, but the whole image current still runs on the thin wall, and thus wake fields do not leak out.

$Z_T \propto 1/\omega^{1/2}$

Conventional region where the skin depth is much smaller than the wall thickness.

Check with ABCI: Impedance of a Short, Thin Insert

- ABCI was modified to insert a resistive material in a structure.
- We consider the impedance of a short and thin resistive insert, sandwiched by two perfectly conductive walls at both ends.
- The resistive insert has no outer layer=open to air.
- The case of interest is that the skin depth exceeds the thickness of the resistive-wall in the frequency range of interest.

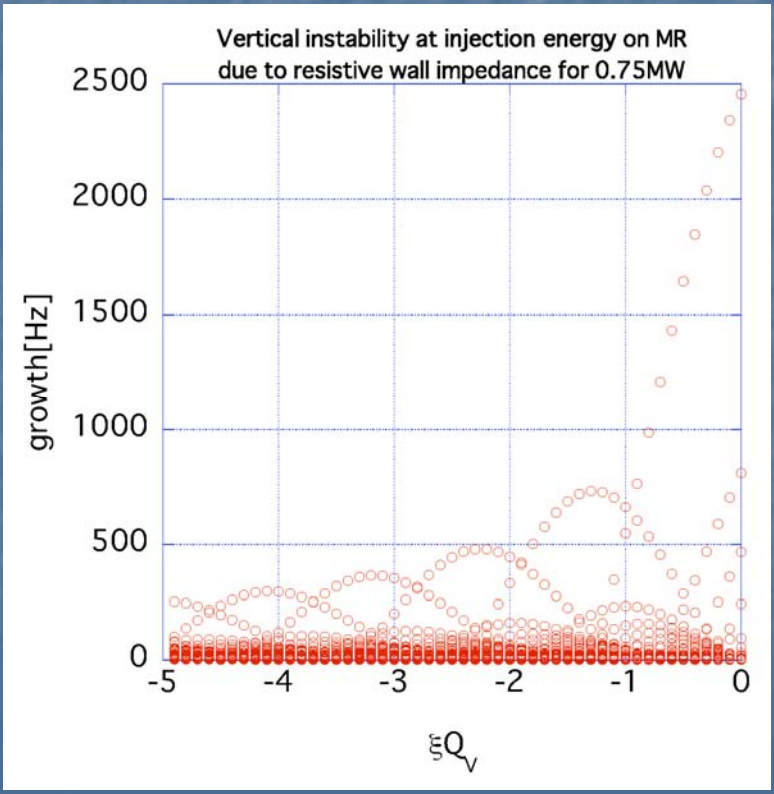


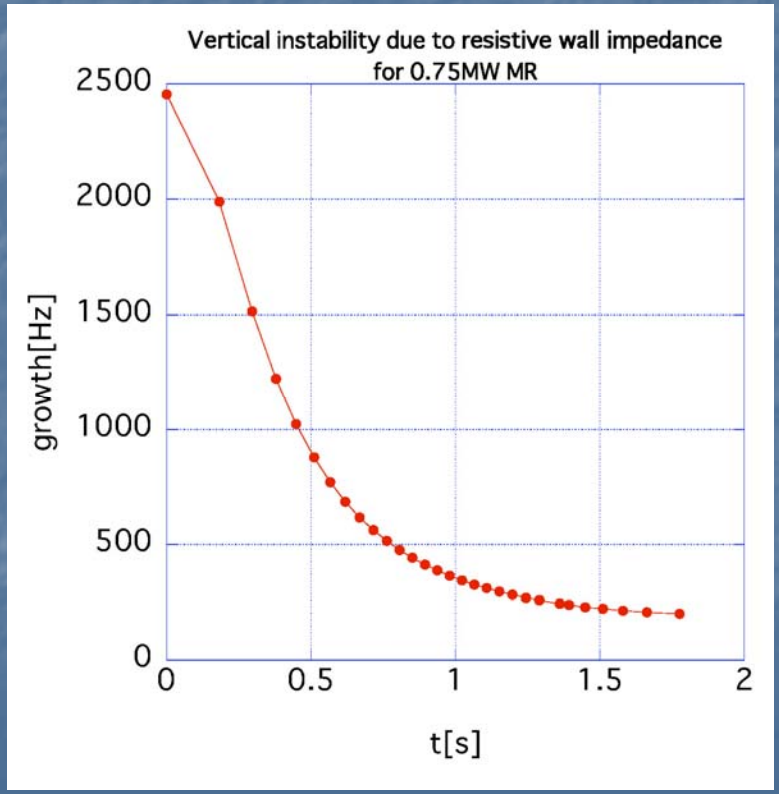
Parameter Choices

- The bunch with σ_z=1cm can excite the impedance up to 10GHz.
- The skin depth=the thickness of the insert=2mm at 10GHz requires the conductivity σ of the insert to be 10 (unrealistic, but it is just for test).
  - The skin depth=20mm at 100MHz (=10GHz/100), 10 times larger than the thickness of the insert.
- We will see that in this ratio of the skin depth to the thickness of the insert, the EM fields virtually stay inside of the pipe, and the entire image current runs on the thin insert.
- When we reduce the conductivity σ of the insert to less than 10, we start to see that the EM fields can propagate out from the gap.

New Beam Instability Estimate

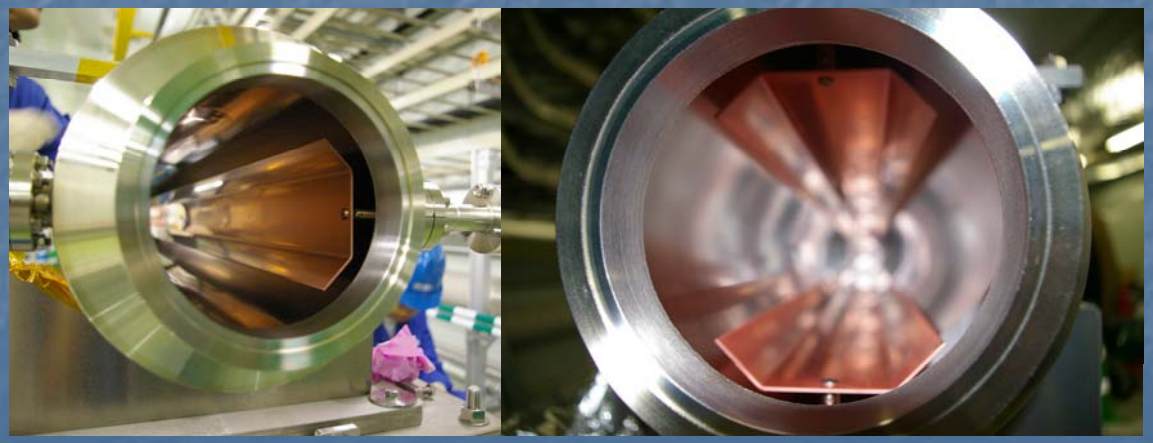
- Accordingly, and due to change in $\nu_{\beta v}$ to $\nu_{\beta v}$=20.793, the growth rates of vertical beam instabilities due to MR stainless-steel chamber increase by a factor of 2.





Exciters as Dampers

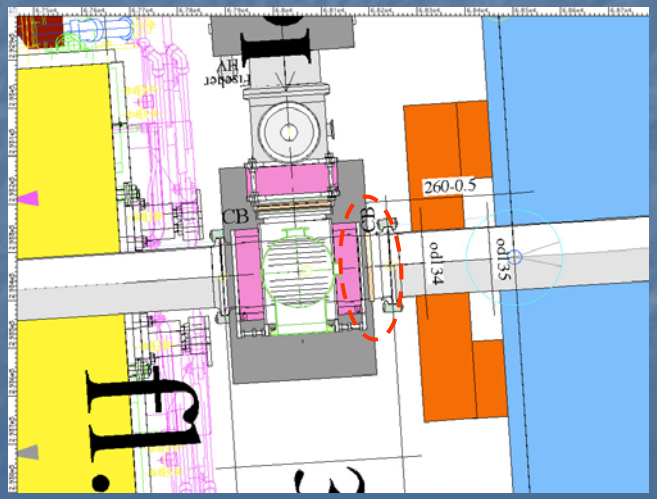
- There are two exciters (horizontal and vertical) installed at MR for transverse tune measurements.
- Study is going on to use this exciter as a damper to damp transverse beam instabilities at MR.
  - The input power of P=1kW can create a 7.6kV/turn kick to a beam.

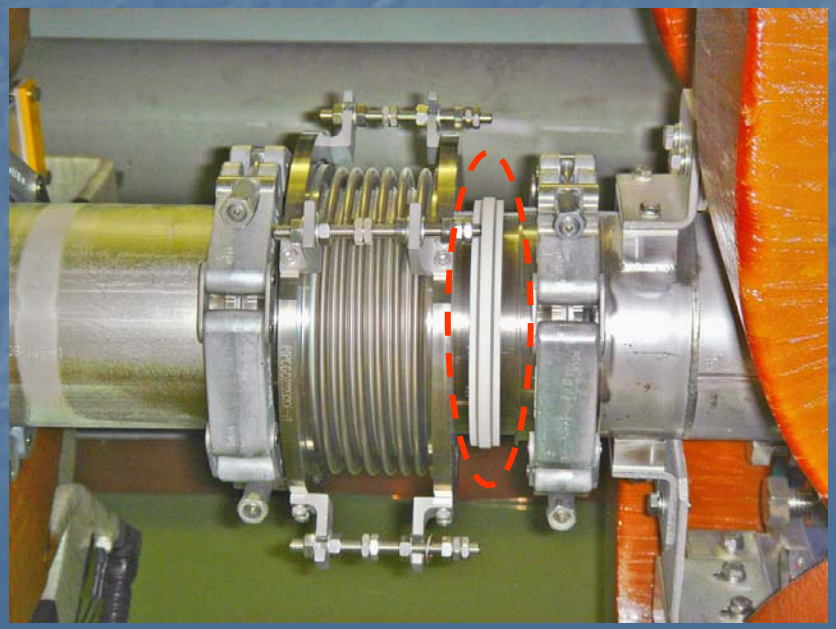




Ceramic Break at MR

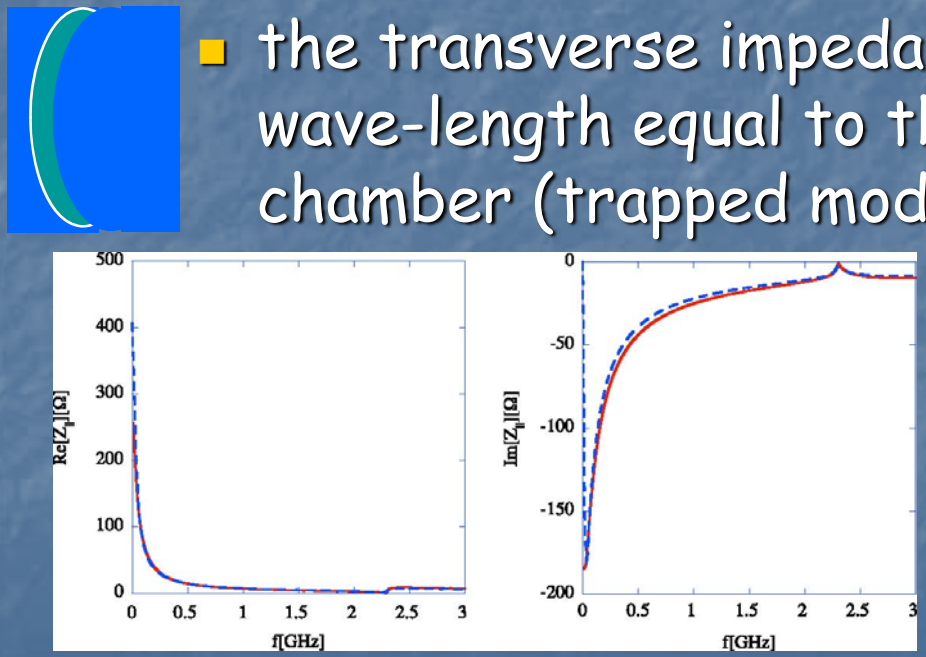
- At MR, ceramic breaks are installed to the beam chambers next to every bending magnets (96 in total) to reduce the eddy current effects.
  - The ceramic break is sandwiched by the circular chambers with the diameter of 130 mm (the circumference=400mm).



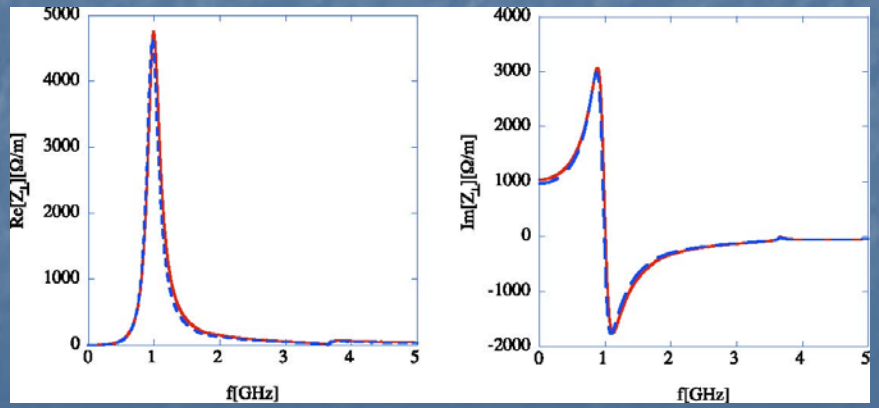


Radiation from a Gap and Trapped Mode

- Our new theory on the gap impedance (Phys. Rev. ST Accel Beams 10, 044403 (2007)) predicts
  - the longitudinal impedance has a sharp peak at low frequency.
  - the transverse impedance has a sharp peak at the wave-length equal to the circumference of the chamber (trapped mode along the circumference).



Longitudinal for ϕ100mm



Transverse for ϕ100mm

Interesting Finding Related with the Gap Impedance

- If a short (shorter than the pipe radius), probably electron, bunch passes through a cavity, it will not have enough time to see the details of the structure (i.e., it sees only the gap)
  - The amount of interaction between the bunch and the cavity, in other words, the short range wake potential of the cavity, is almost determined by the gap size (+ pipe radius and bunch length).
  - If this conjecture is true, the loss factor of a small cavity can be estimated once the gap size is given, without knowing the detail of the cavity structure.

Check with ABCI

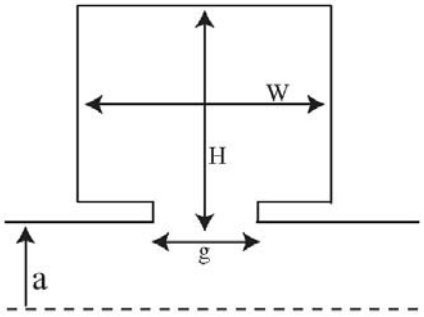


FIG. 5. The cavitylike structure parametrized by its width W, its height H, and its opening size g (the gap size).

Roughly speaking, the loss factor of the cavity saturates to that of the gap when the size of the cavity W=H exceeds twice the gap size.

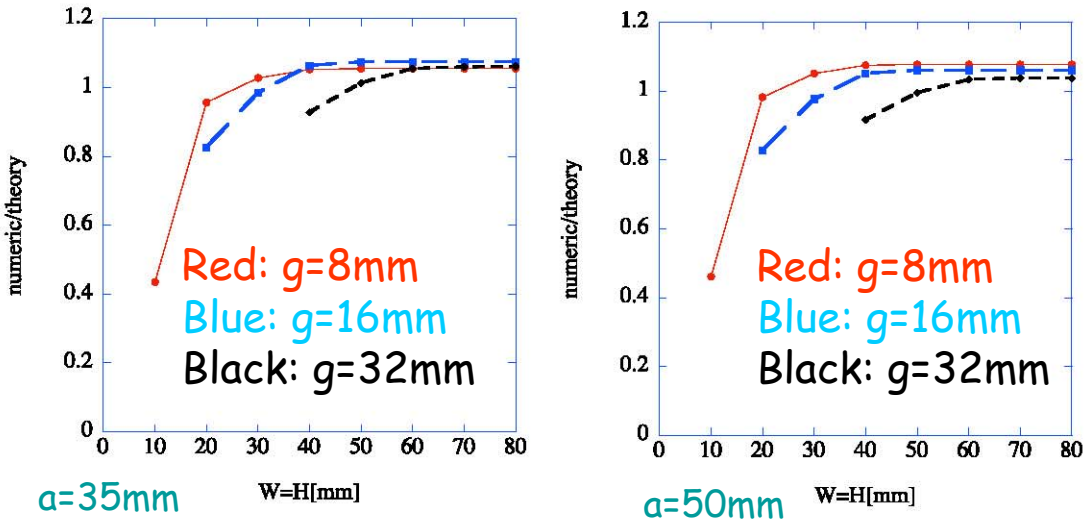


FIG. 6. (Color) The dependence of loss factor on the size of cavity. The vertical axis represents the ratio of the loss factor calculated by numerical calculation to that by the present theory [obtained from Eq. (17)]. The horizontal axis shows the value of $W = H$. The size of the beam σ_s is chosen to be 1 cm. The left and the right figures represent the $a = 3.5$ and $a = 5$ cm cases, respectively. The red, blue, and black lines show $g = 8$, $g = 16$, and $g = 32$ mm cases, respectively. Roughly speaking, the loss factor of the cavity saturates to that of the gap when the size of the cavity $W = H$ exceeds twice the size of the gap.

RF Shield

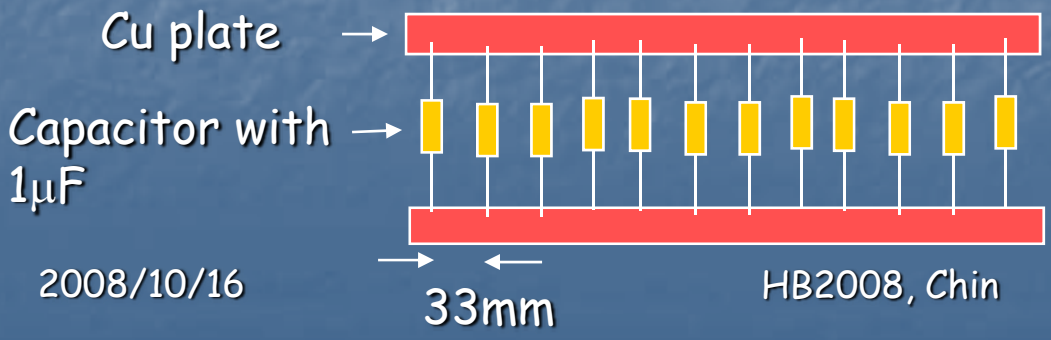
- To stop this low frequency radiation from the ceramic break and the transversely trapped mode, RF shields with capacitors (similar to ones at RCS) need to be installed to every ceramic breaks.
- However, we do not want to repeat RCS-type extremely fine intervals of strip lines (1cm) from the cost and fabrication points of view.

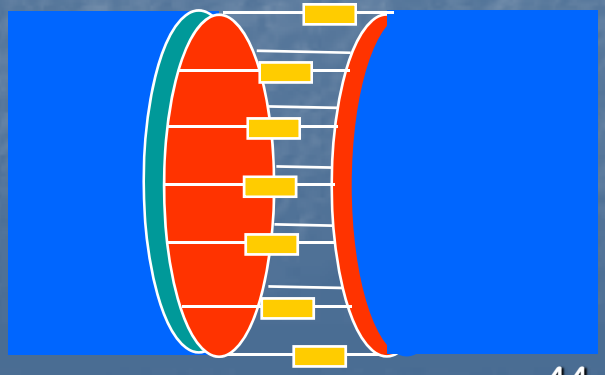


RF shield of ceramic chamber at RCS

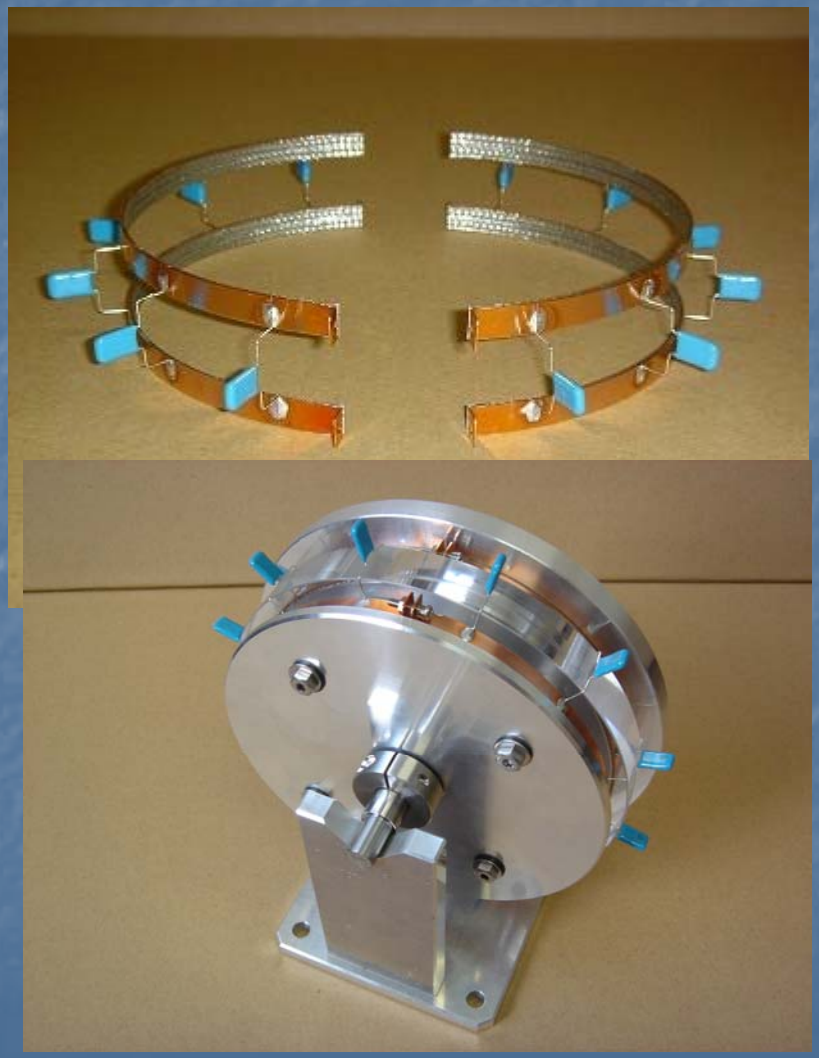
RF Shield Design

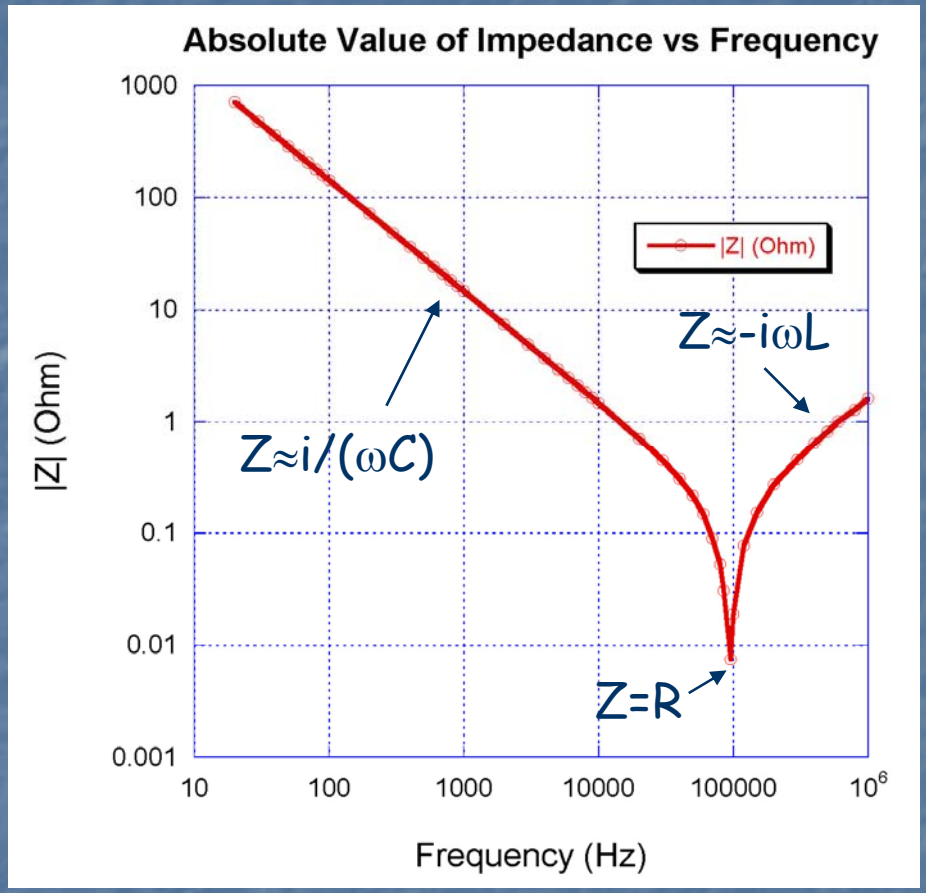
- The sharp peak in the transverse impedance almost diminishes at the frequency twice larger (namely, at the half wave-length~200mm).
- According to some references, a metallic mesh with finesse of 1/8 of the target wave-length is effective enough as an RF shield.
  - the mesh size of 25mm(-> 33mm)
  - 12 capacitors with 1μF each (withstand voltage=600V)





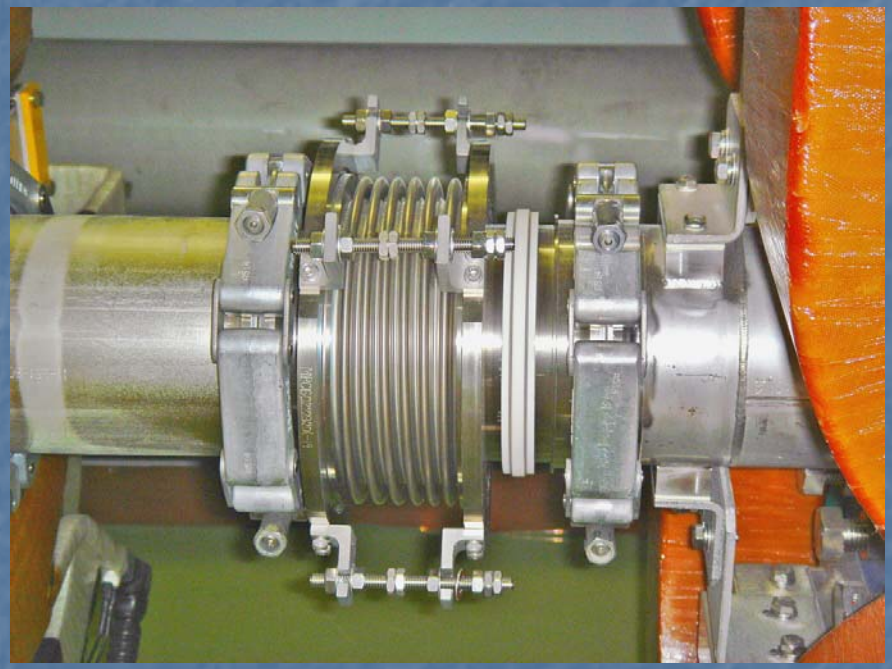
Prototype

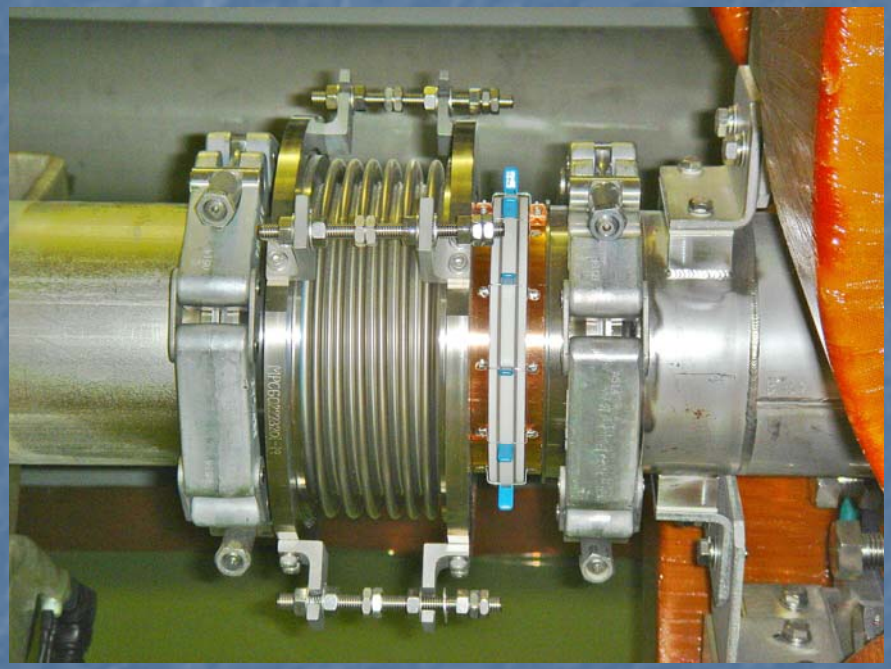




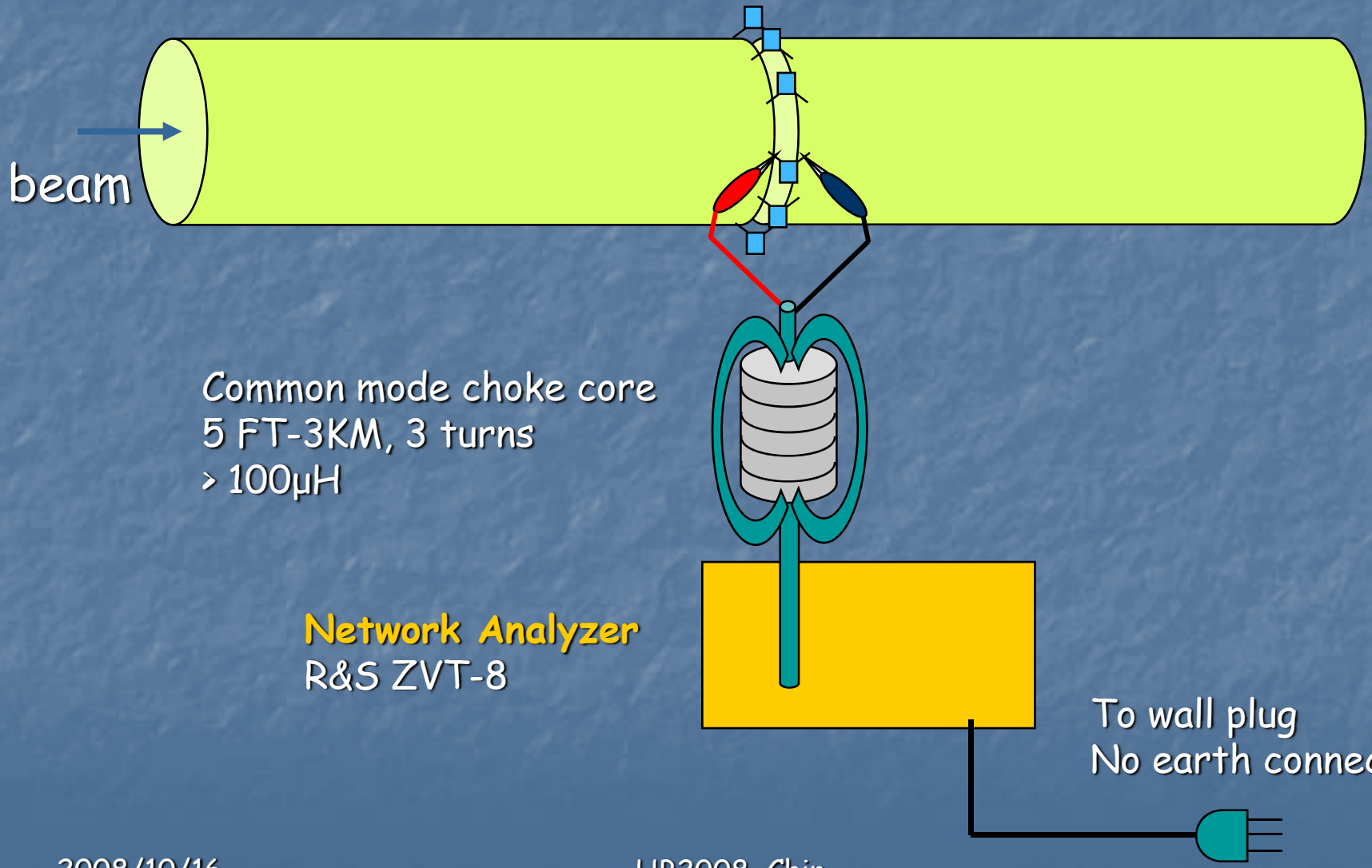
Absolute value of impedance vs. frequency measured with LCR meter

Actual Installation to MR Ring



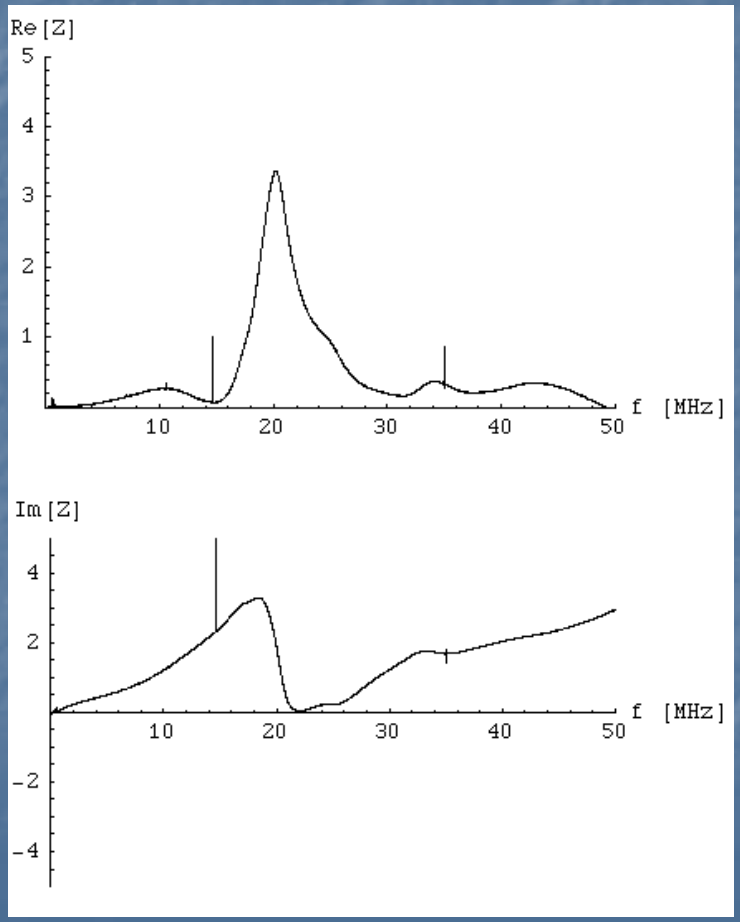


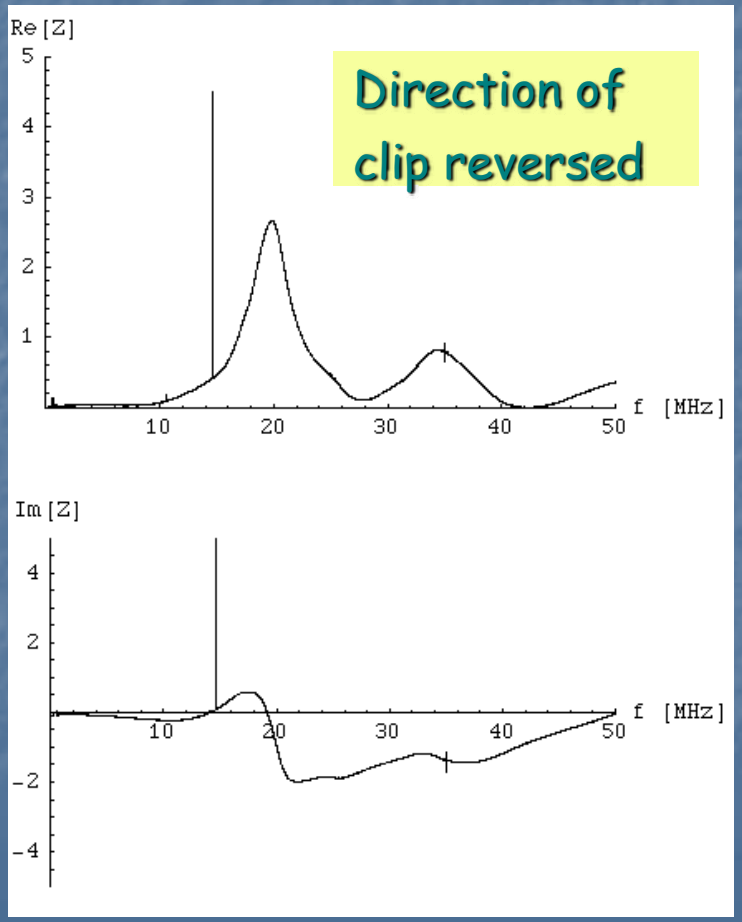
Measurement of Impedance after Installed to the Ring



Measurement Results

- A resonance with 3Ω/gap seen around 20MHz.





Summary

- Both at RCS and MR, the transverse kicker impedances may impose serious limitations on the beam power (around a few 100 kW?).
  - Should be confirmed with the realistic simulation code ORBIT.
  - Several damping methods of cable resonances are under investigation, and will be applied if necessary.
- MR stainless-steel chamber may impose even more serious limitation on the beam power at MR.
  - Even by adjusting the chromaticity, the growth rates of the horizontal and vertical head-tail instabilities will remain around 200Hz at low energy .
  - Study is under way to use exciters as dampers.
- RF shields of ceramic breaks were designed, fabricated and installed at MR.