Stabilization of Beam Instabilities by Intra-Bunch Feedback System at J-PARC MR*

Y.H. Chin, T. Obina, M. Okada, M. Tobiyama,
T. Toyama (KEK), K. Nakamura (Kyoto University),
Y. Shobuda (JAEA)

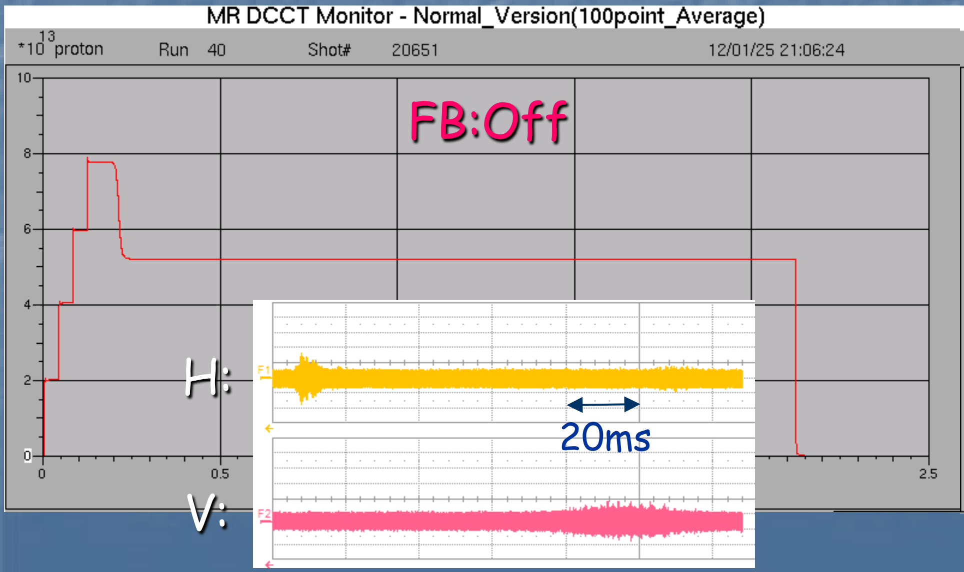
The 11th Annual Meeting of PASJ
Aomori, Japan, on 9-11 August, 2014

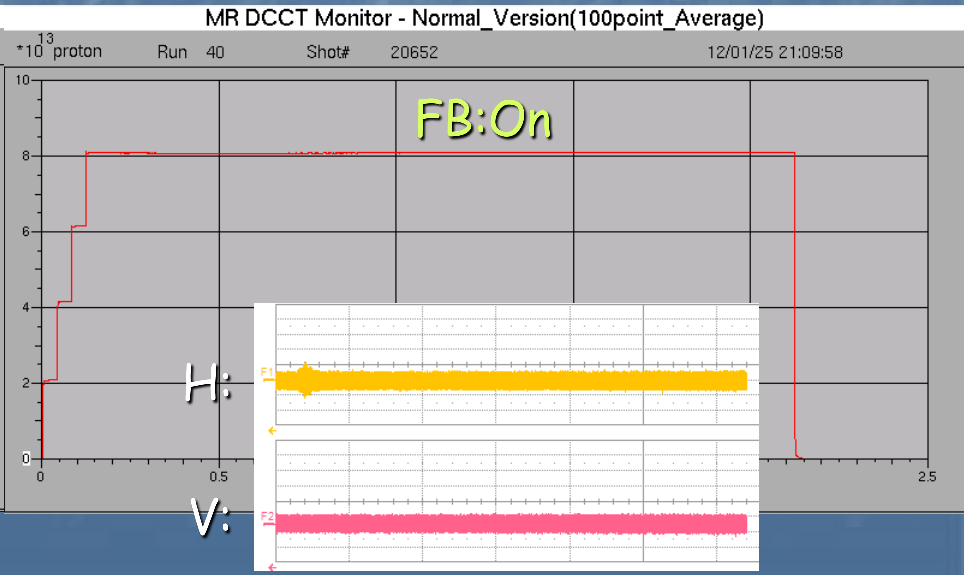
*This work was supported by MEXT KAKENHI Grant Number 25105002, Grant-in-Aid for Scientific Research of Innovative Areas titled "Unification and Development of the Neutrino Science Frontier"

Transverse Instabilities and Intra-Bunch Feedback System

Instabilities and Feedback System at J-PARC MR

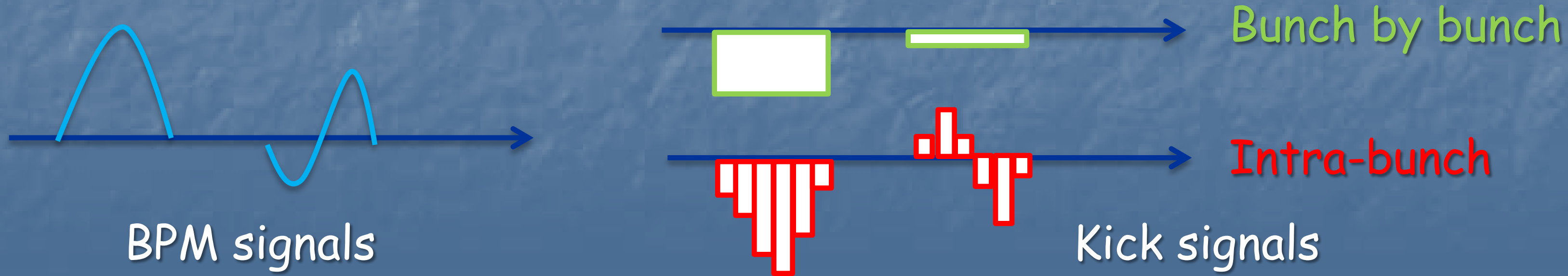
- The present bunch-by-bunch feedback system (BxB FB) at MR effectively suppresses observed transverse dipole oscillations, together with help from the chromaticities, allowing to attain the 230 kW beam power.



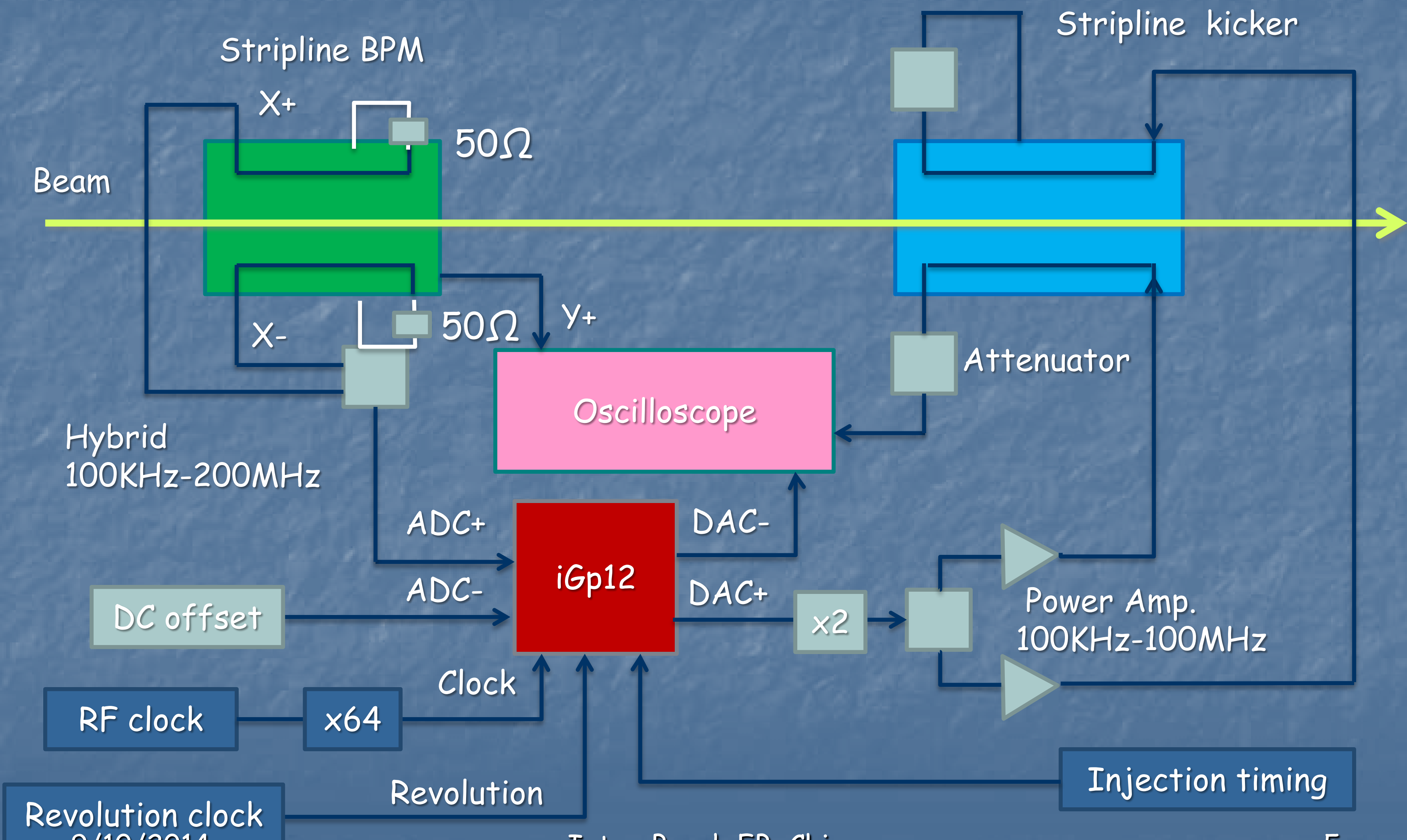


Bunch by Bunch vs. Intra-Bunch FB

- The BxB FB can damp only the dipole oscillations of the center of mass motions of the whole bunches.
  - Even when it is on, internal bunch oscillations have been still observed, which are causing additional particle losses.
- To suppress intra-bunch oscillations, a more wideband and elaborate feedback system has been developed.
  - The new intra-bunch feedback system divides an RF bucket into 64 segments (~10ns long).
  - It acts on each segment (bin) as if it is a small bunch (bunch-let) in a narrowband mode, even if it is empty.

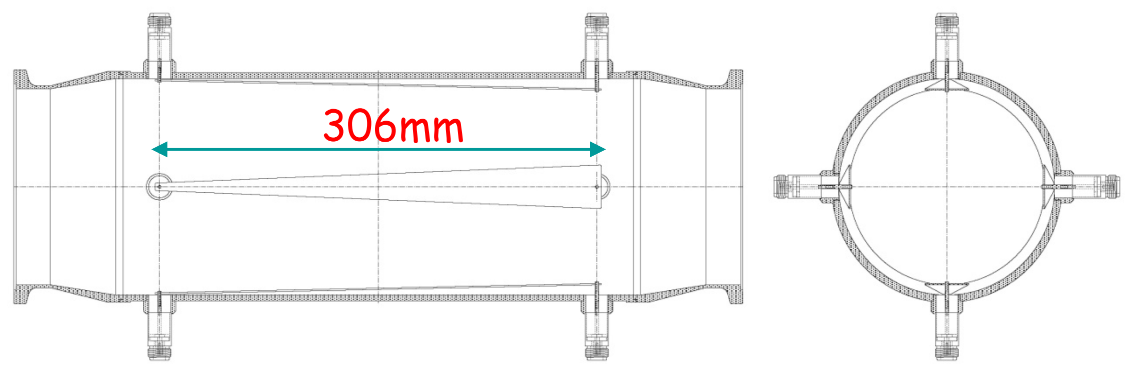


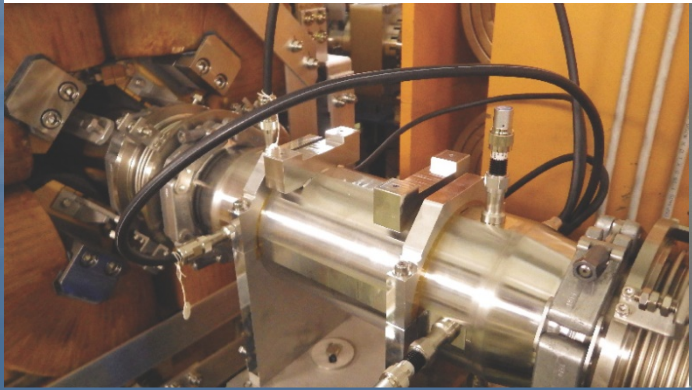
Schematic of Intra-Bunch FB System

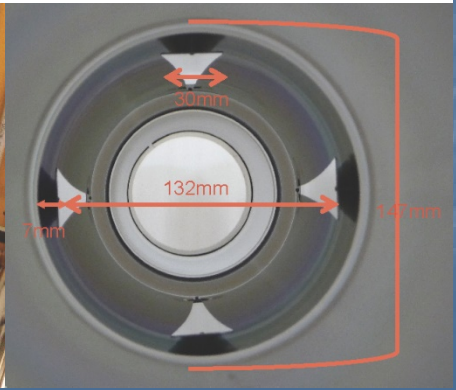


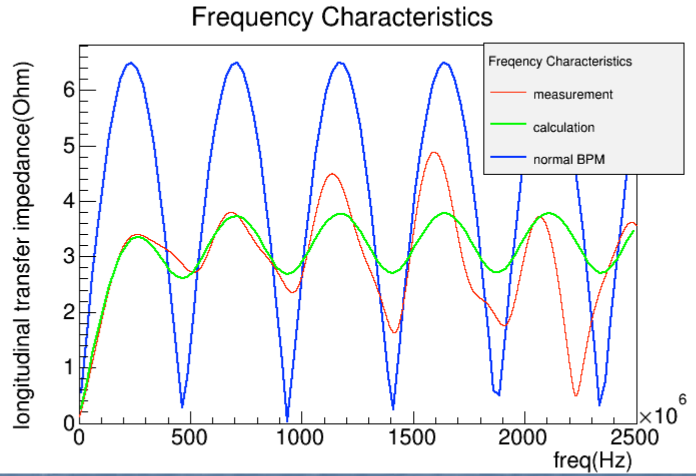
Exponentially Tapered Electrodes

- A new stripline BPM for the intra-bunch feedback system for J-PARC MR has exponentially tapered electrodes for an improved frequency response, compared to rectangular ones (Linnecar, CERN-SPS).









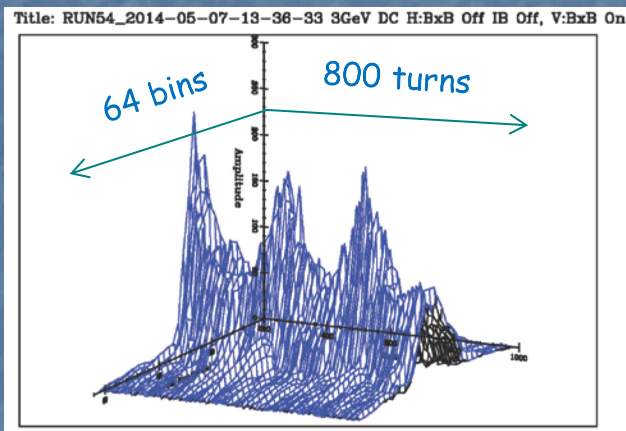
More details will be discussed later in this talk!

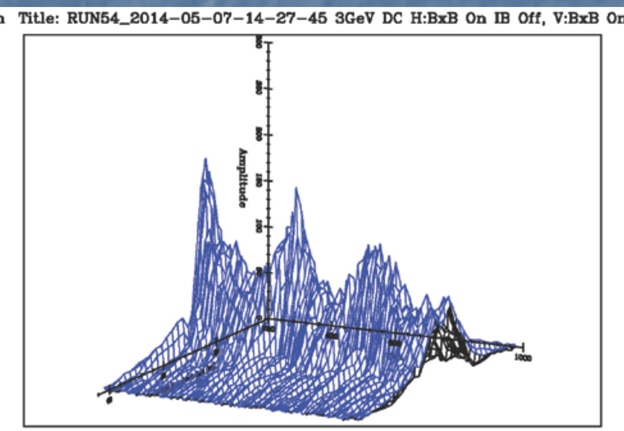
Main Parameters

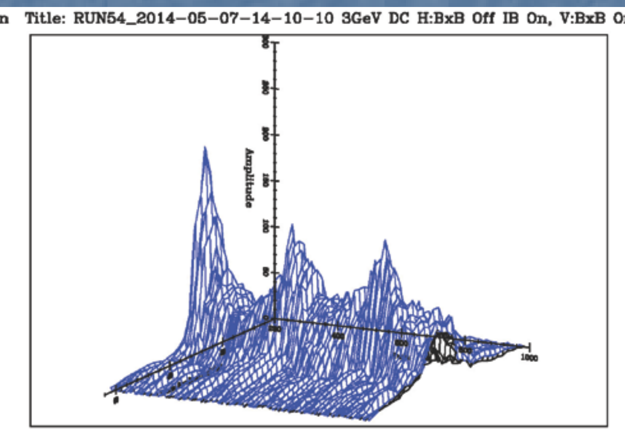
	@Routine Operation	@Beam Test in May
Circumference	1568m	
Energy	3-30GeV	3GeV
Repetition Period		2.48s
Beam Power	230kW (30GeV)	0.5 kW (3GeV)
RF Frequency	1.67-1.72MHz	1.67 MHz
Number of Bunches	8	1
Synchrotron Tune	0.002-0.0001	0.0017
Betatron Tune (hor./ver.)		22.41/20.75
Intensity (/pulse)	1.3×10^{14}	2.7×10^{12}
Bunch Length	50-200 ns	150-200 ns
Chromaticity (hor./ver.)	-4 / -1	+0.5/+1.2
Horizontal Feedback		BxB FB/Intra-bunch FB on/off
Vertical Feedback		BxB FB Always on

Horizontal Beam Tests on May 7

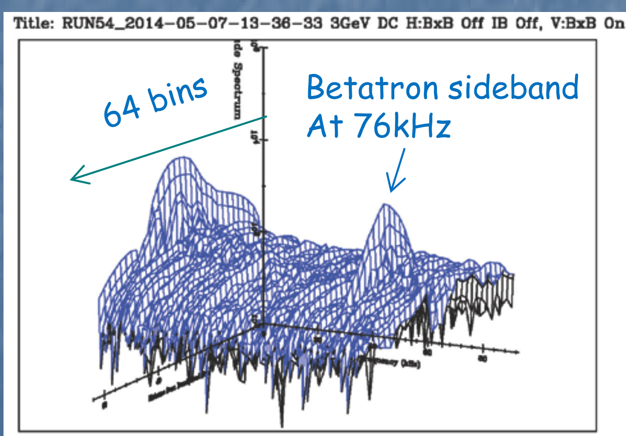
- Single bunch, $N_b = 2.7 \times 10^{12}$

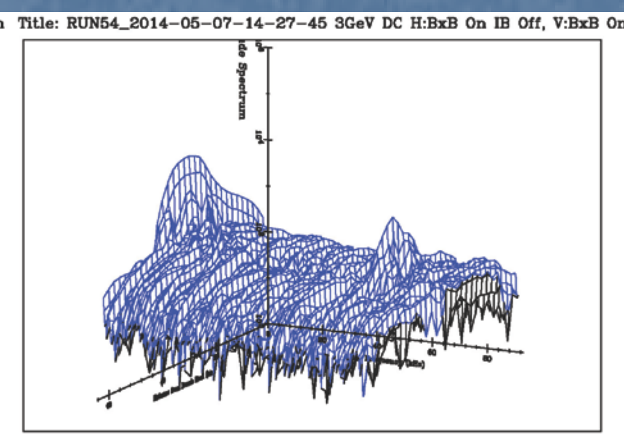


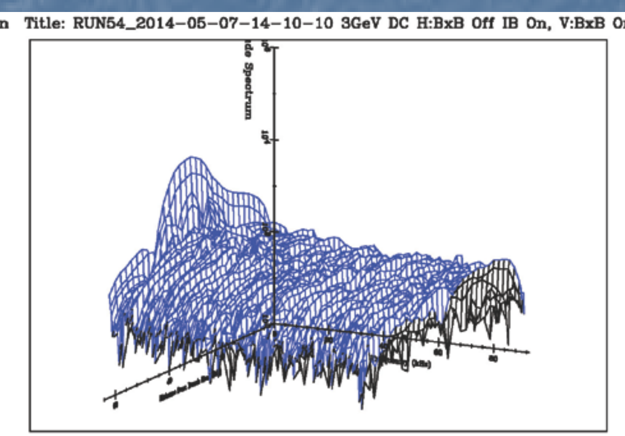




BxB off; Intra-Bunch off　　BxB on; Intra-Bunch off　　BxB off; Intra-Bunch on

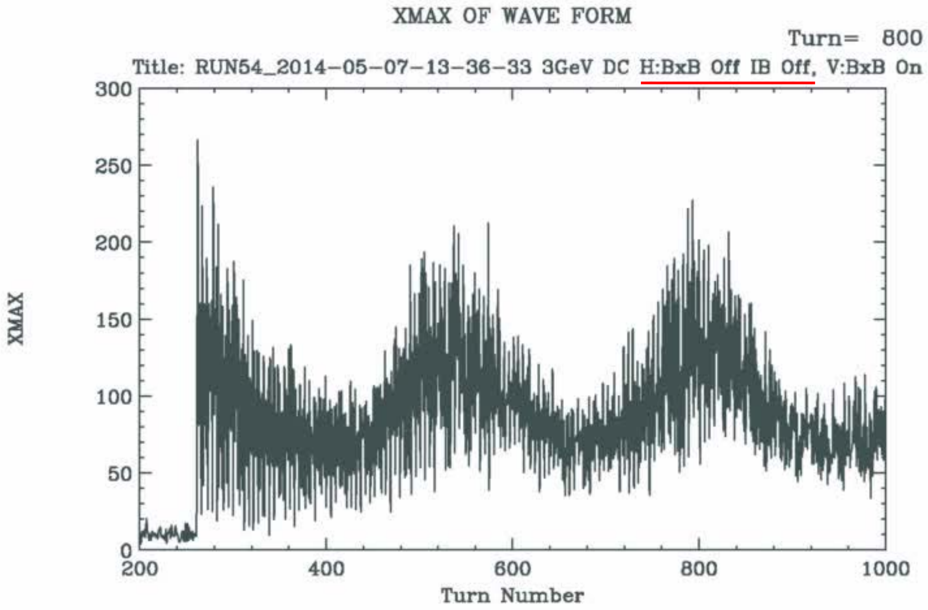


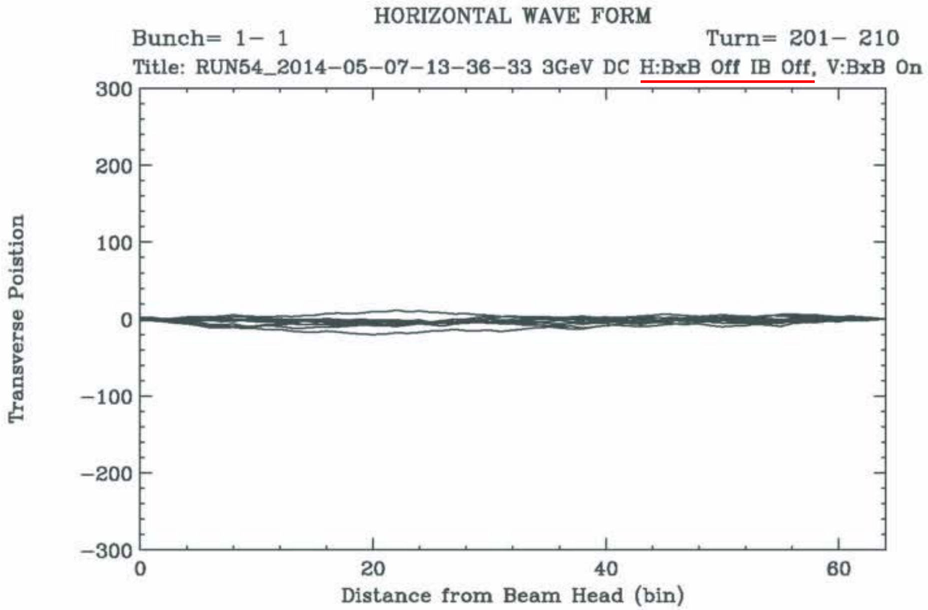




Horizontal Oscillations inside a Bunch

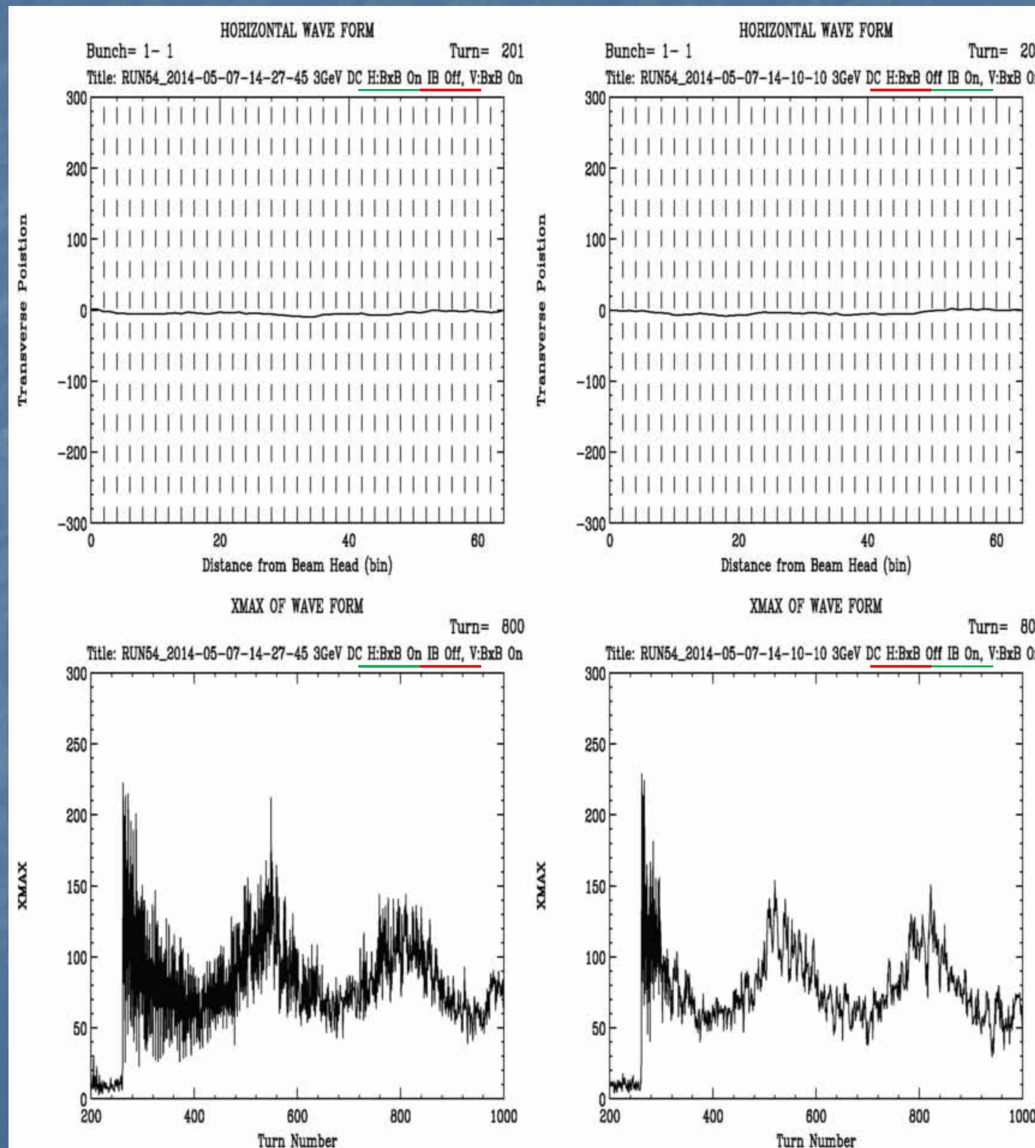
- BxB FB off and Intra-Bunch FB off
  - The large horizontal oscillations are excited around the 262th turn due to the mismatching field of the injection kicker magnets.





On/Off of BxB and Intra-Bunch FBs

- BxB on
- Intra-Bunch off



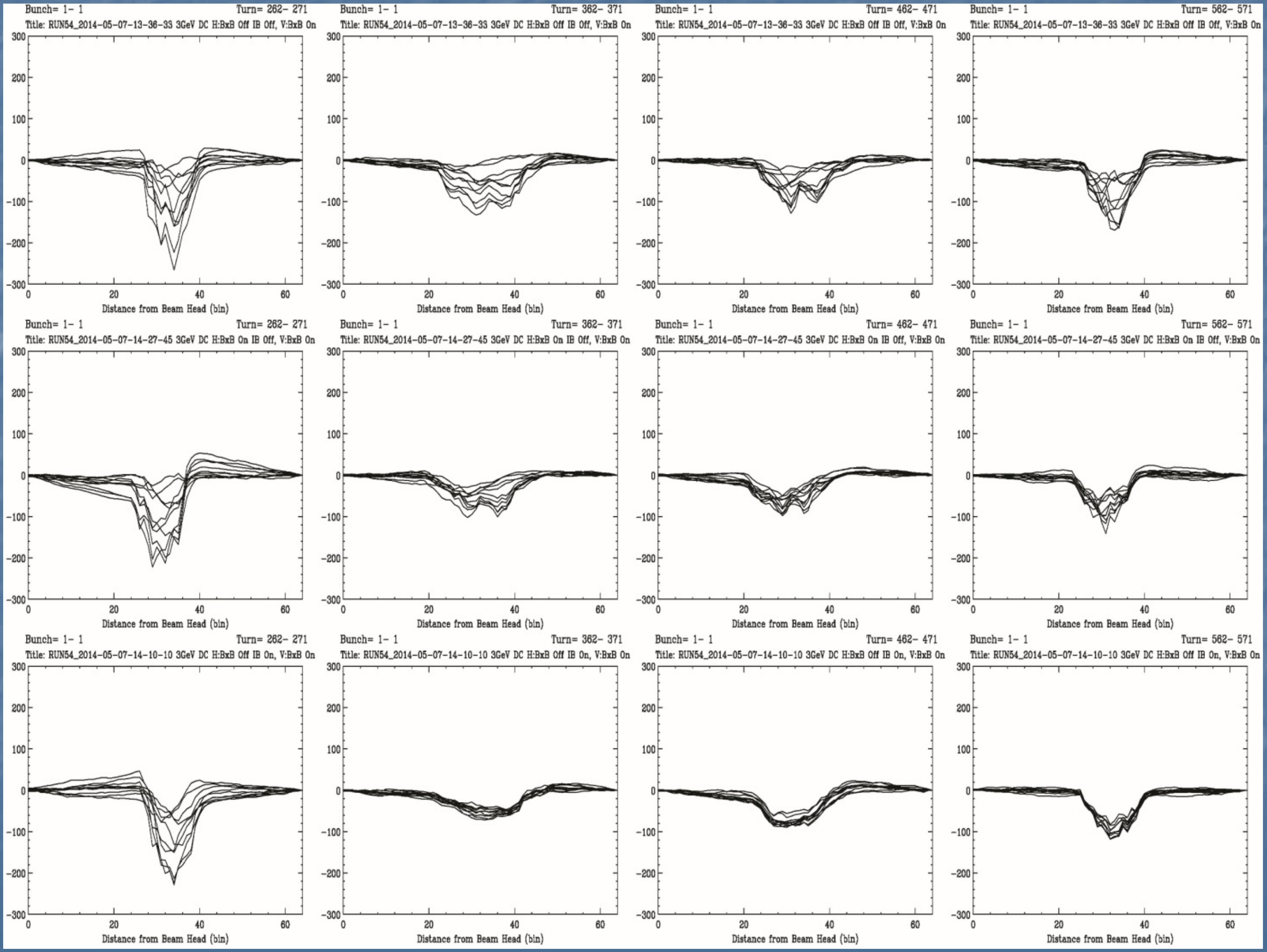
- BxB off
- Intra-Bunch on

Time Evolution of Oscillation Envelops at Every 100 Turns

- BxB off
- IB off

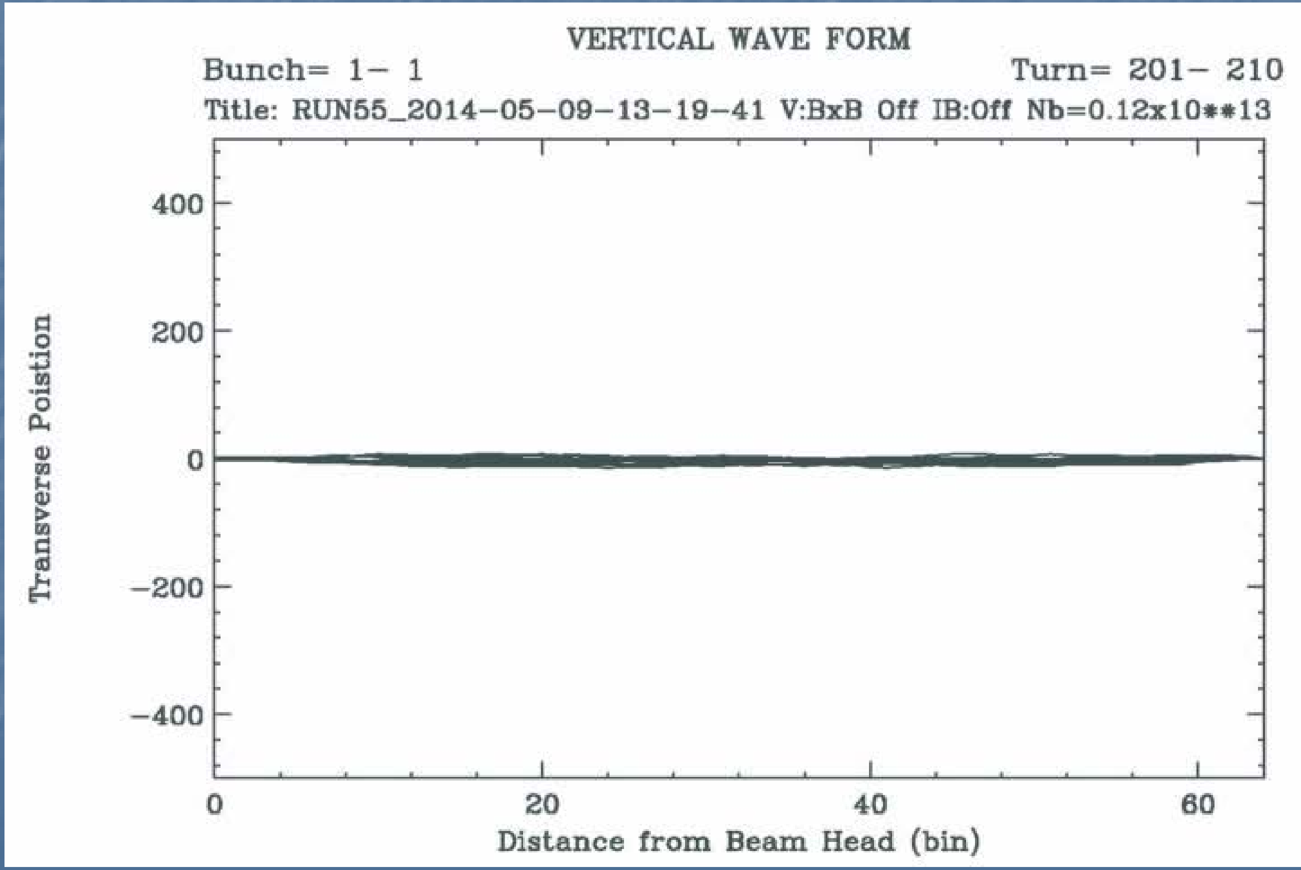
- BxB on
- IB off

- BxB off
- IB on



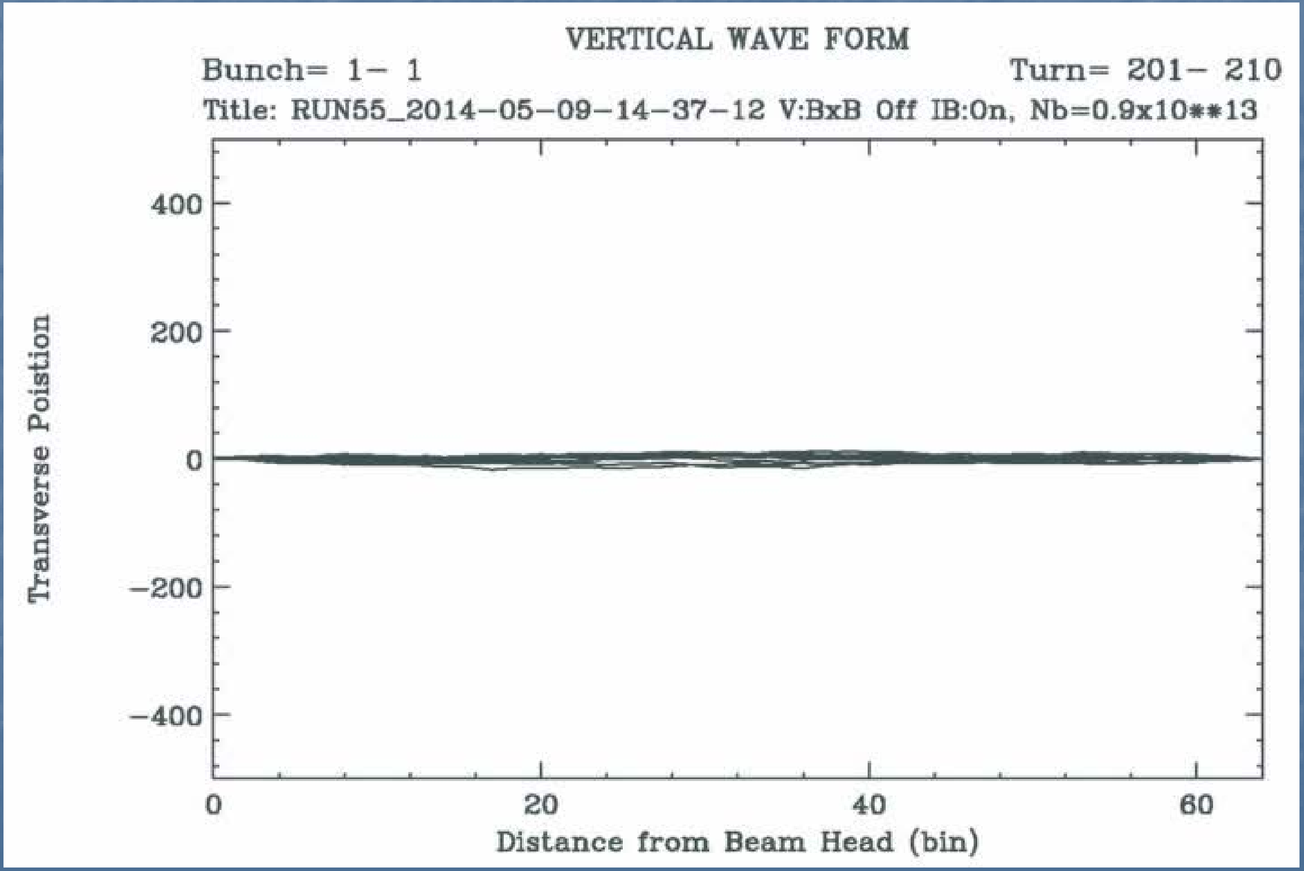
Preliminary Results for Vertical Instabilities at Onset of Acceleration

- N_b=0.12x10^{13}
- Vertical BxB off; IB off



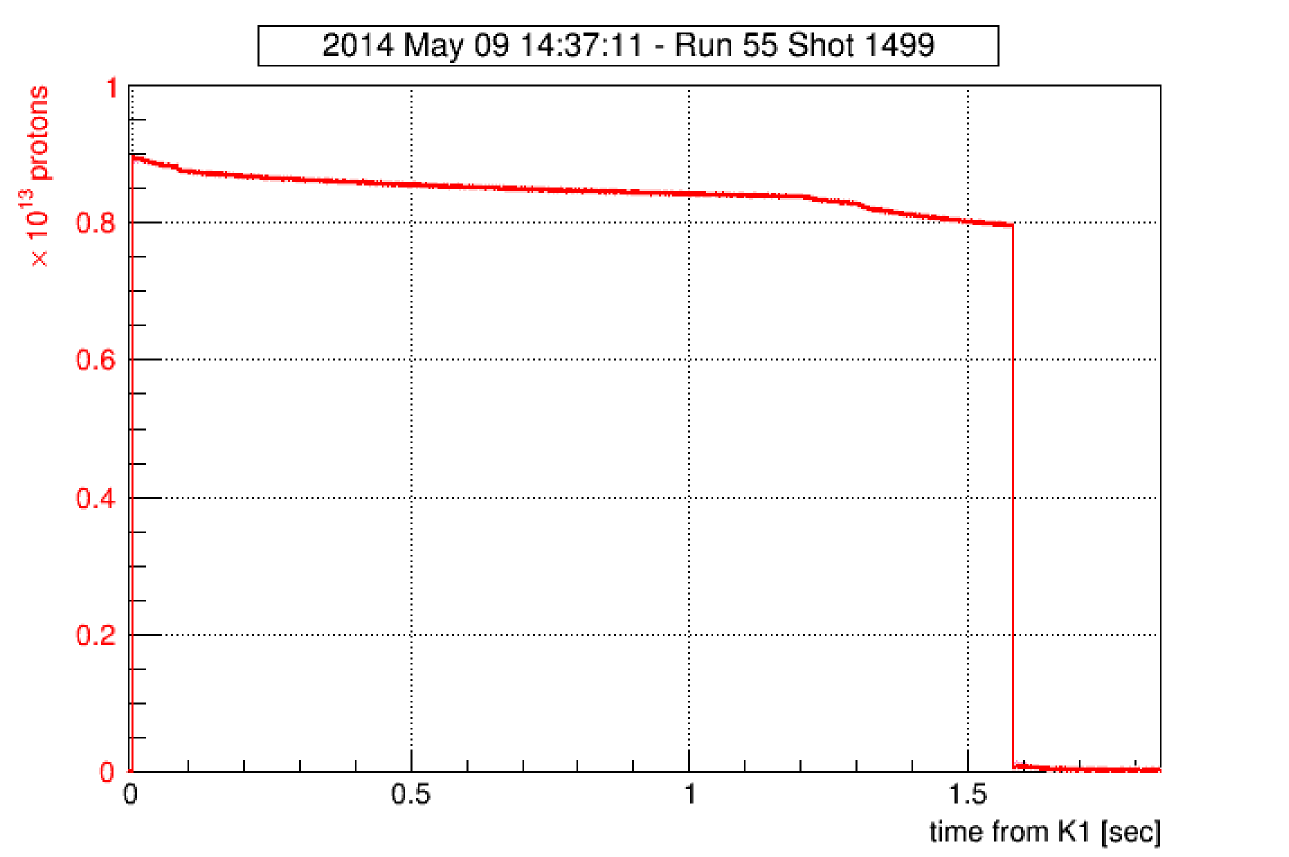
Vertical Intra-Bunch FB Turned On

- $N_b=0.9\times10^{13}$
- Vertical BxB off; IB on



More Tuning of IB FB and Help from Chromaticity Needed

- Still large particle losses observed during the acceleration in the case of (N_b=0.9x10^{13}/IB on):



Optimization of Stripline Electrode Shape for a Flatter Frequency Response

Exponential Electrode: Prototype and Measurement at SPS

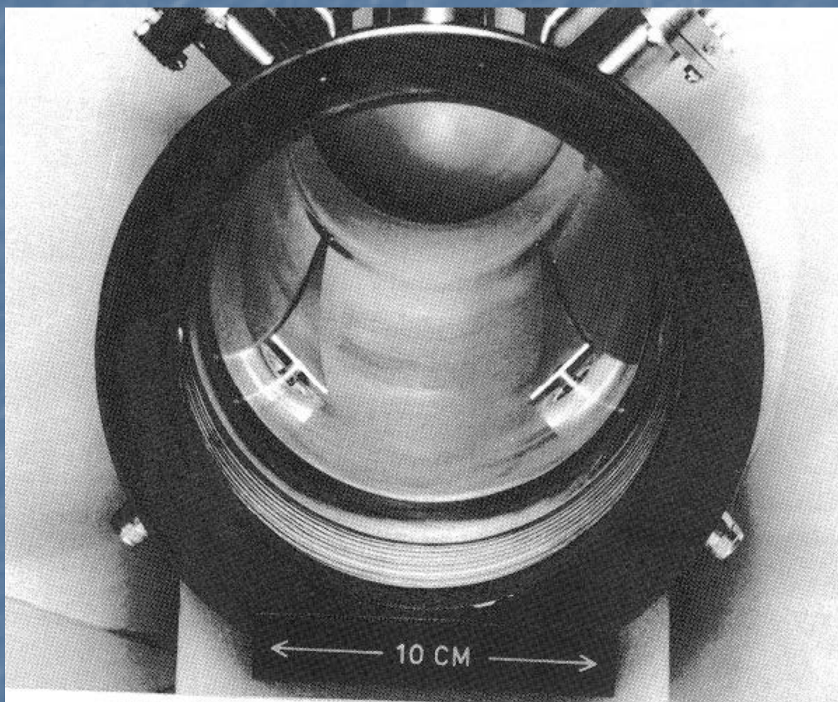


Fig. 31b - Interior of directional coupler pick-up

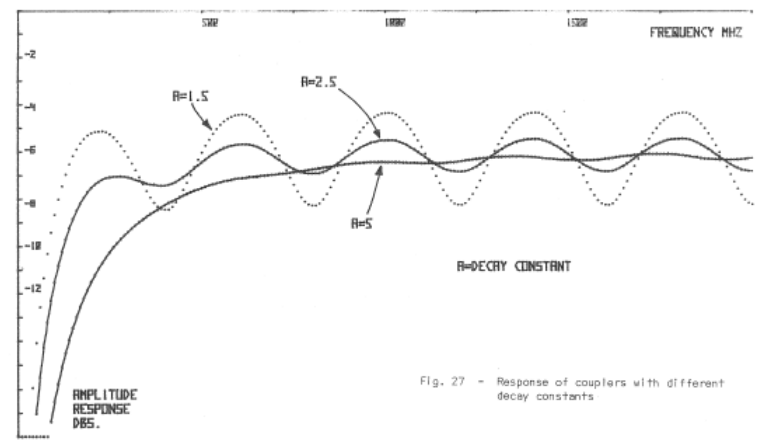


Fig. 27 - Response of couplers with different decay constants

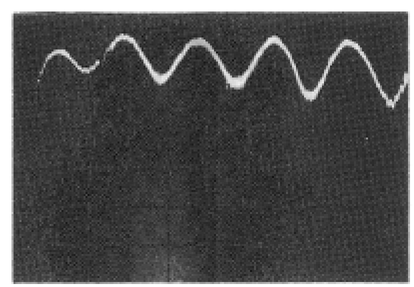
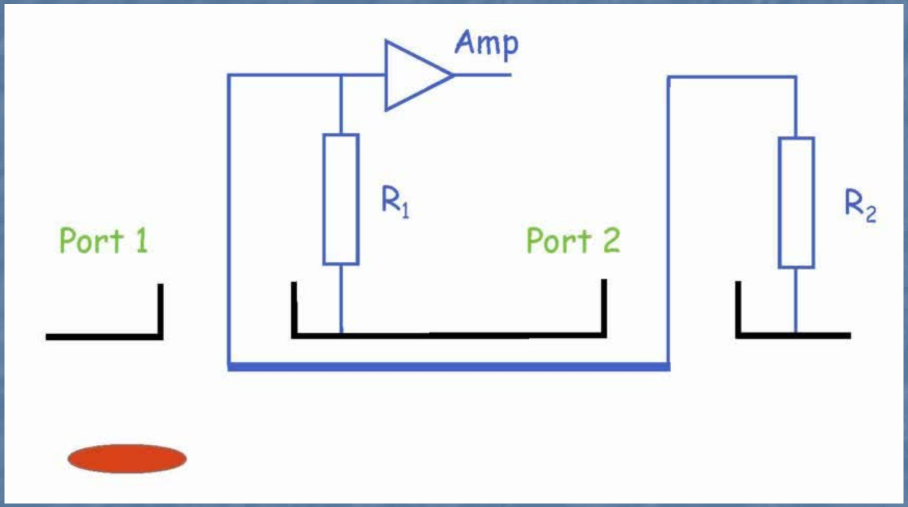
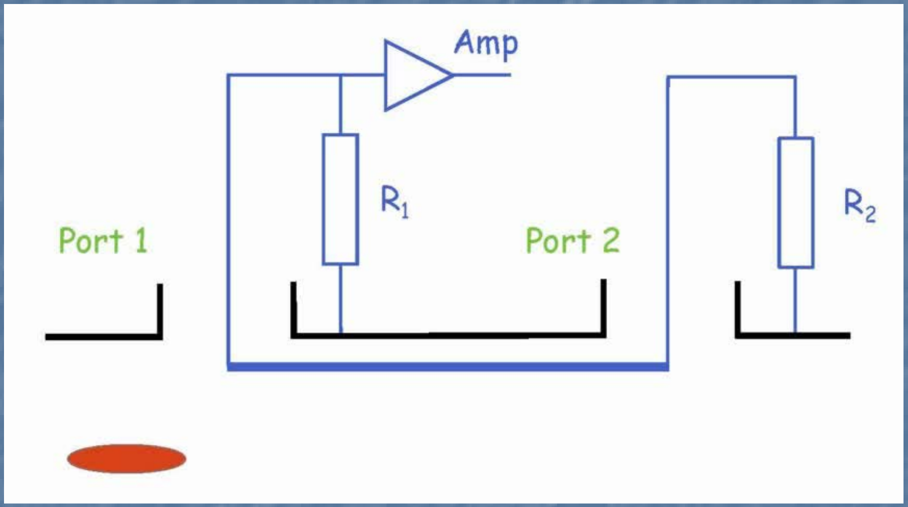


Fig. 37 - Frequency response of sum signal from directional coupler pick-up
200 MHz/div 2.5 dB/div

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

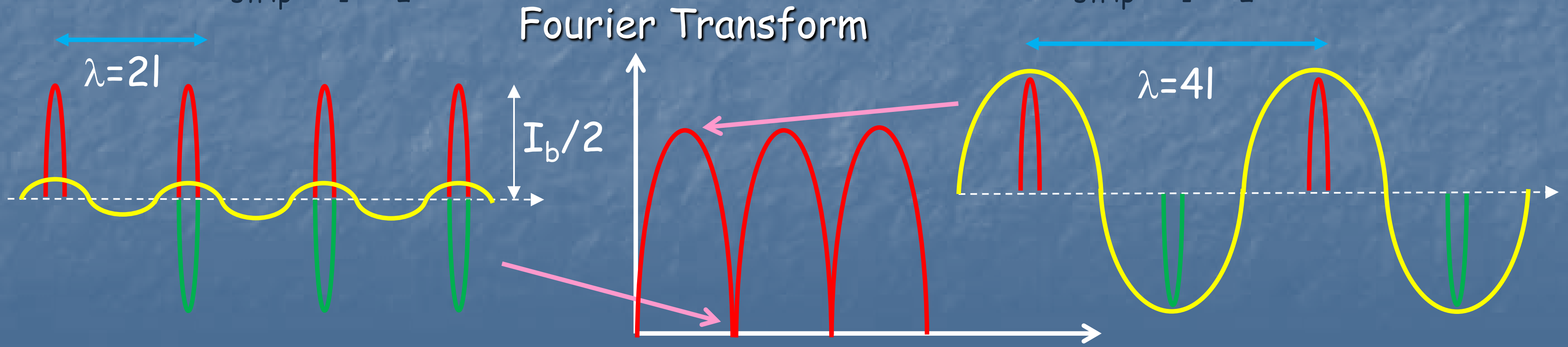
Frequency Response of a Rectangular Electrode (Length=l)





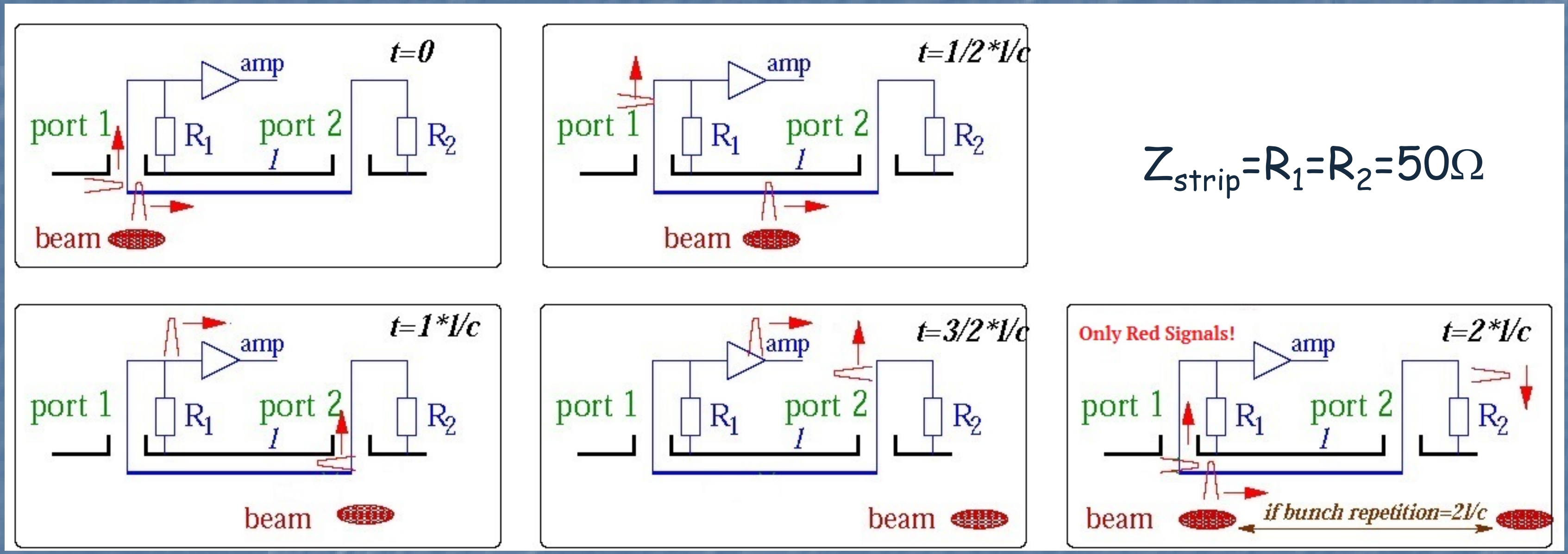
$Z_{strip}=R_1=R_2=50\Omega$

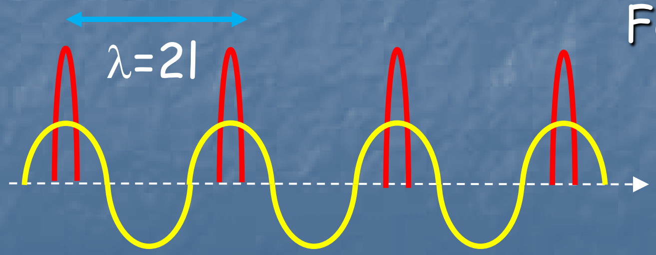
$Z_{strip}=R_1=R_2=50\Omega$



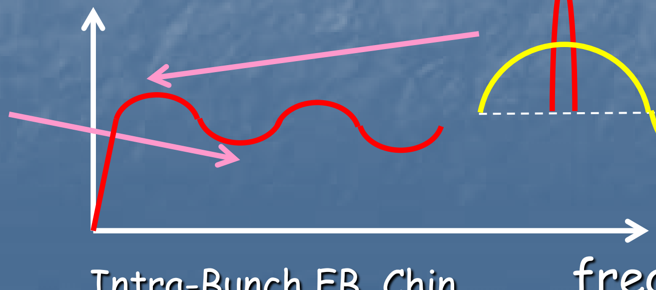
If the Electrode Becomes Very Narrow toward Downstream, the Leaving Bunch Will Not See it.

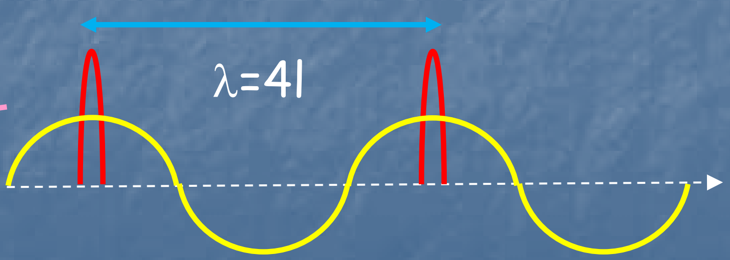
- No pair of green image currents will be generated.





Fourier Transform





Theory

- Transfer function:

$$F(\omega) = i\omega \int_0^{\frac{2l}{v}} \frac{1}{2} k(\frac{vt}{2}) e^{-i\omega t} dt = \frac{i\omega}{v} \int_0^l k(z) e^{-i\frac{2\omega}{v}z} dz,$$

- Example
  - Linnecar's exponential electrode

$$k_{linnecar}(z) = k_0 e^{-\frac{az}{l}},$$

  - Transfer function

$$\lambda = \frac{2\omega l}{v}$$

$$F_{linnecar}(\lambda) = \frac{k_0}{2}[\frac{i\lambda(1-e^{-a-i\lambda})}{(a+i\lambda)}].$$

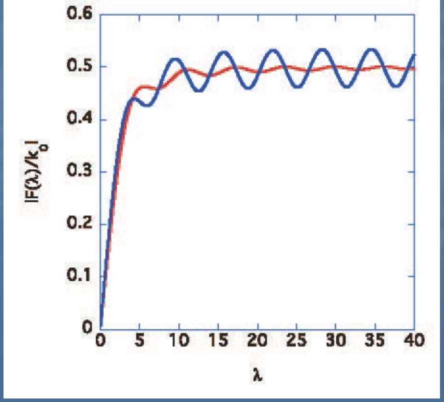
Improved Exponential Electrode

- To make the end value of k(z) zero, let us subtract the end value k(l) from k(z):

$$k^{new}_{linnecar}(z) = k_0\left(\frac{e^{-\frac{az}{l}} - e^{-a}}{1 - e^{-a}}\right).$$

- Transfer function

$$F^{new}_{linnecar}(\lambda) = \frac{k_0}{2}\left[\frac{a(1 - e^{-i\lambda}) + i(1 - e^{a})\lambda}{(1 - e^{a})(a + i\lambda)}\right]. \qquad \lambda = \frac{2\omega l}{v}$$

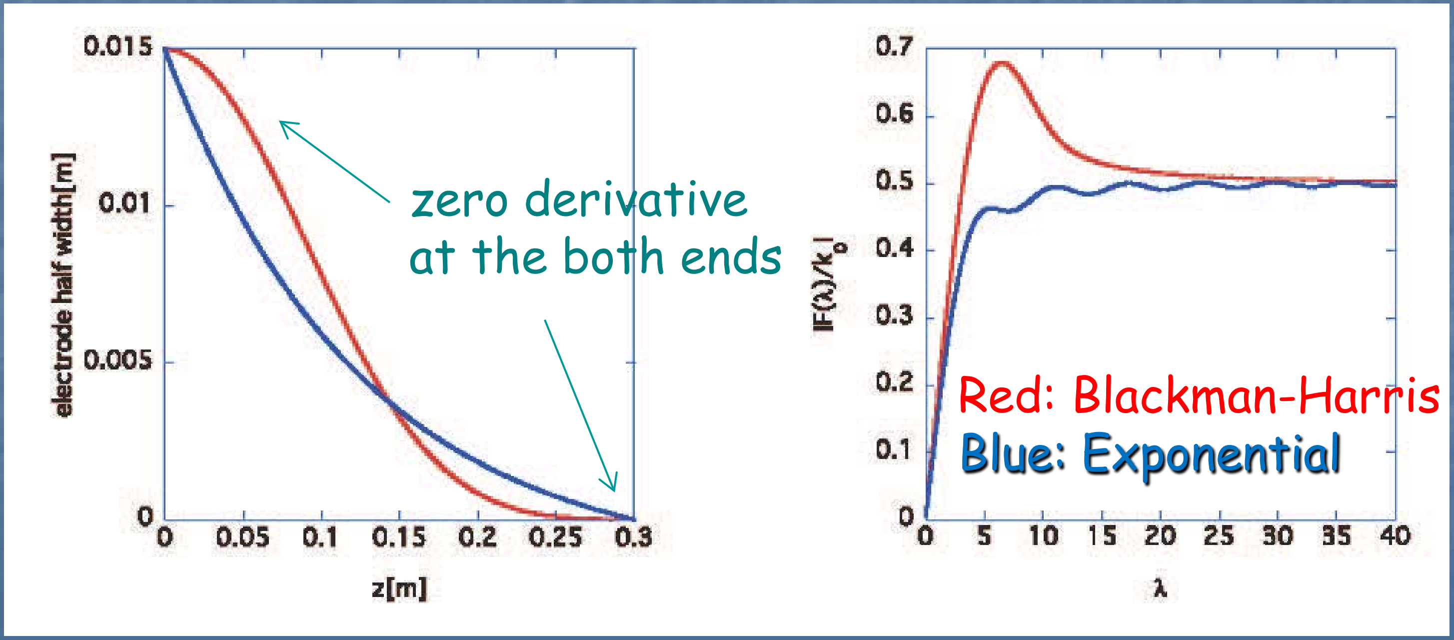


Red: Improved exponential
Blue: Original exponential

Blackman-Harris Window Function

- Blackman-Harris window function for k(z)

$$k_{blackman-harris}(z) = k_0(0.35875 - 0.48829\cos[\pi(\frac{z}{l} - 1)] + 0.14128\cos[2\pi(\frac{z}{l} - 1)] - 0.01168\cos[3\pi(\frac{z}{l} - 1)]).$$

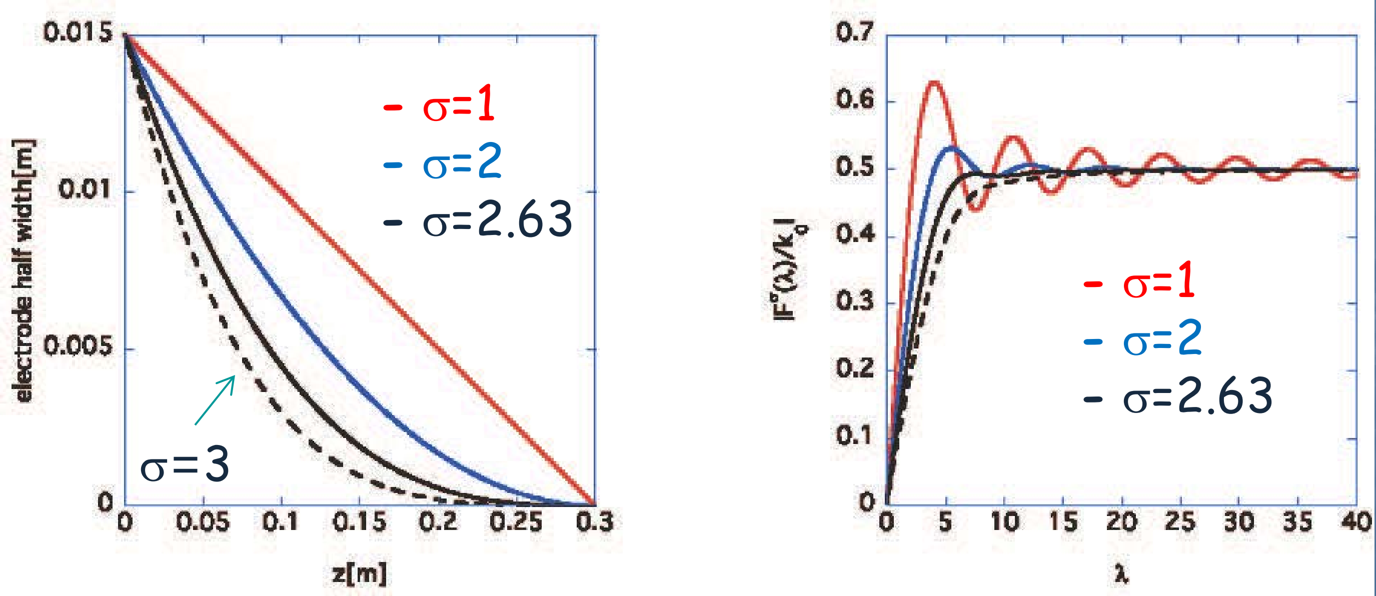


Three Conditions for a Flat Response

- Zero value at the end
- Smooth tapering toward zero derivative at the end
- Negative derivative at the beginning

- Polynomial Electrode

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

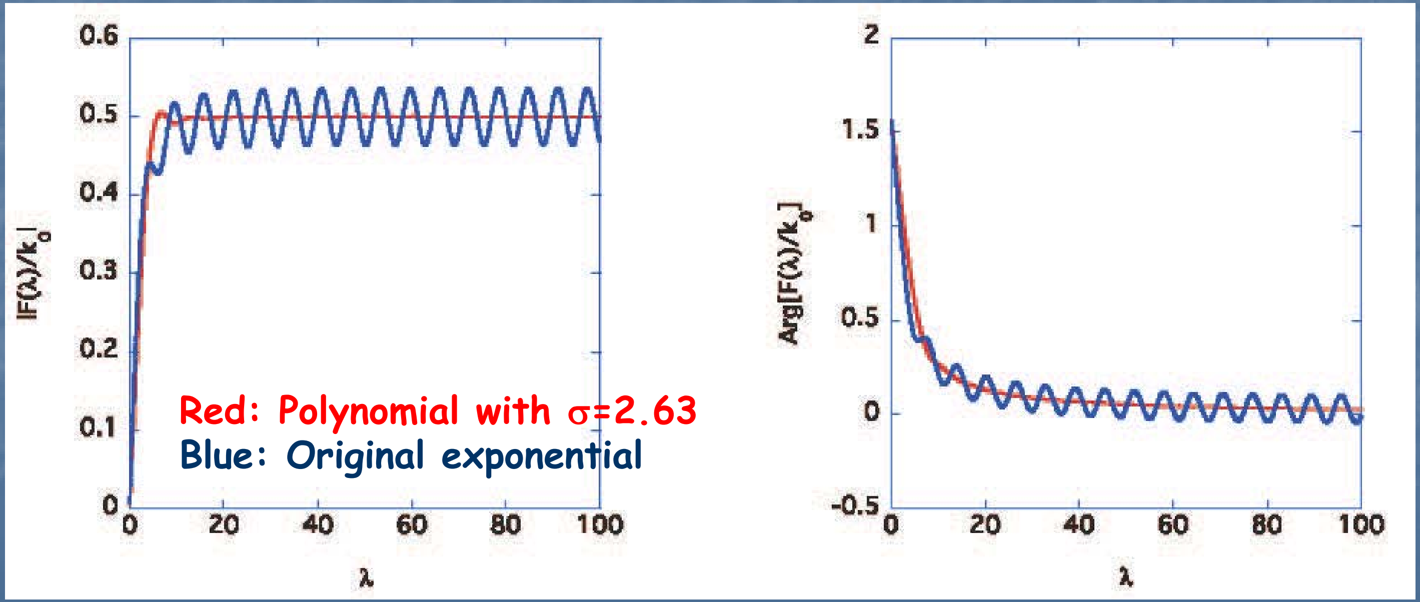


Optimum σ

- Let us optimize σ which minimize the following function:

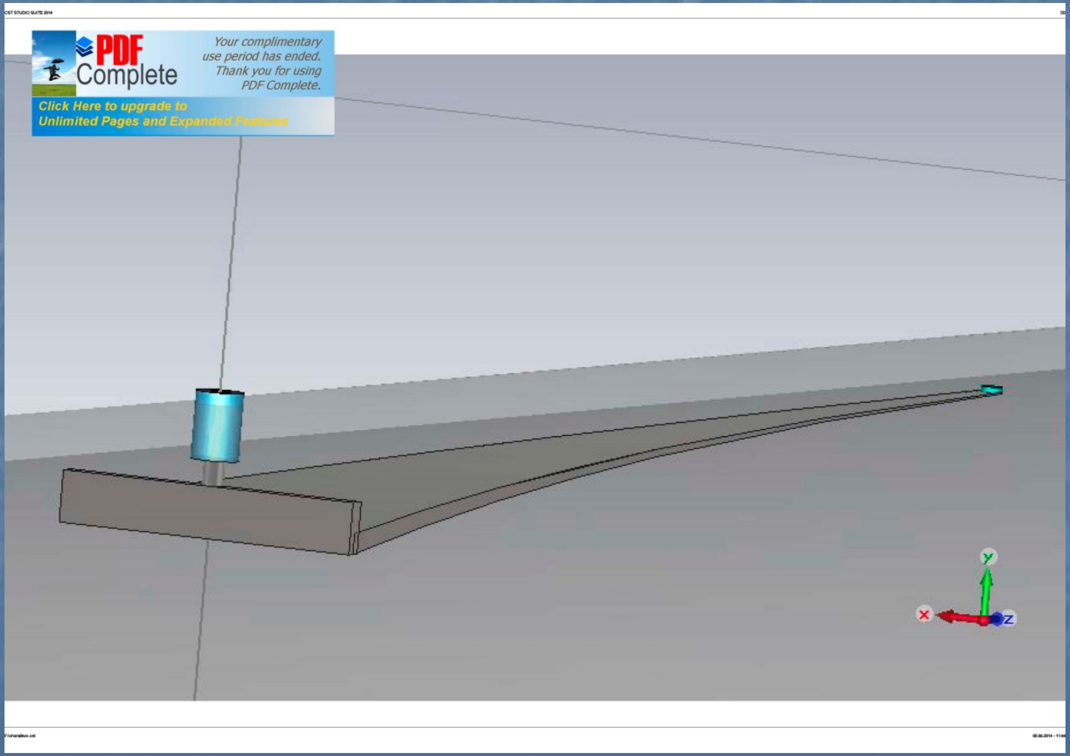
$$I(\sigma) = \int_{\lambda_{low}}^{\lambda_{up}} d\lambda \left(\left| \frac{F^{\sigma}(\lambda)}{k_0} \right| - 0.5 \right)^2 .$$

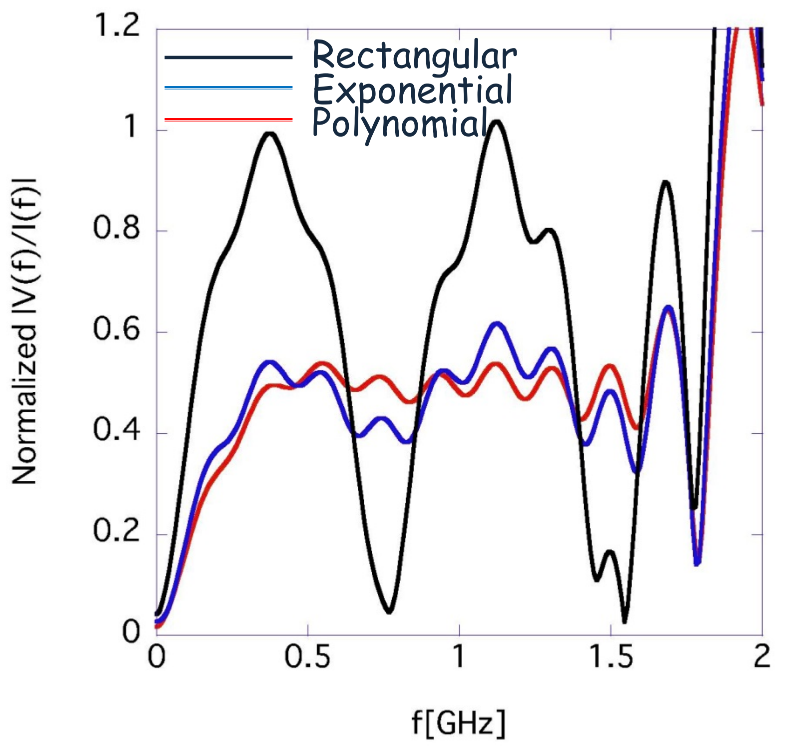
$$\sigma = 2.63$$



Simulations with CST Studio

- Simulations with nearly full satisfaction of the impedance matching conditions.
  - Correct width, height, thickness, resistors, etc.





Summary

- The first beam test successfully demonstrates that the new intra-bunch FB system is quite effective to suppress intra-bunch oscillations.
- The intra-bunch FB system is now used in routine operation at J-PARC MR.
  - The beam loss at the injection is reduced from 350W to 170W.
- The polynomial electrode was proposed for a very flat transfer function of a stripline BPM.
- Measurements for proof of its validity are under preparation.