Impedance Evaluation of the PF In-Vacuum Undulator: Theory, Simulations, and Measurements

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Self introduction

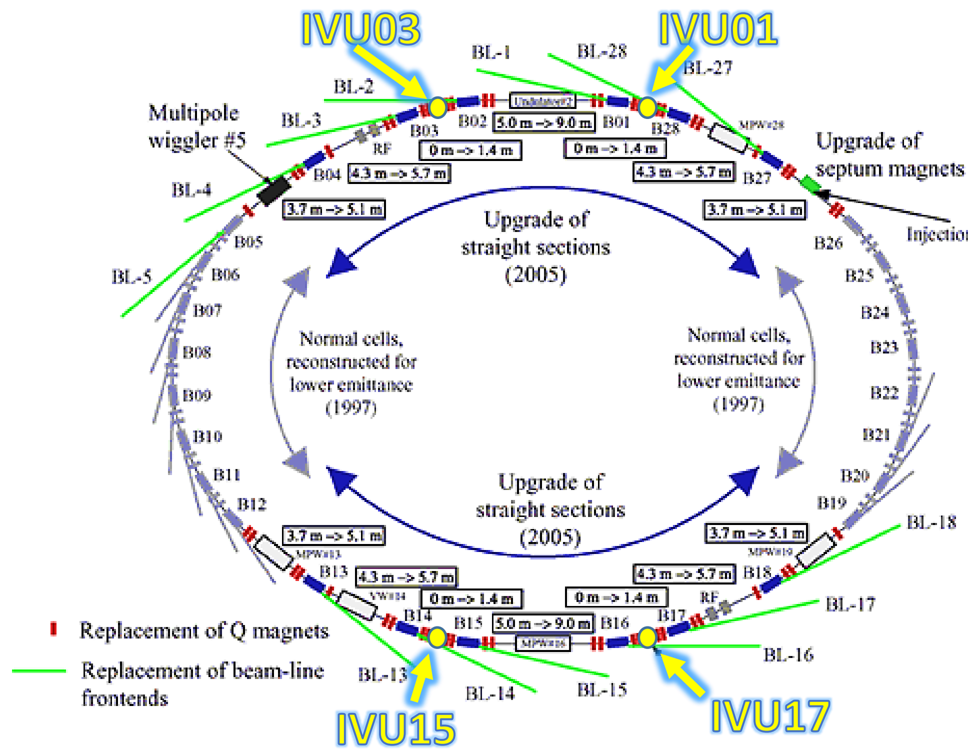
- Currently working at KEK Accelerator Laboratory as **Special Assistant Professor**
- Experience in the field of Accelerator Physics is **6 years**
- Interests:
  1. Impedance model of PF In-vacuum undulators;
  2. Beam halo & beam loss studies at the Compact ERL

Introduction

PF ring and IVU

- Four **In-Vacuum Undulators (IVU)** have been installed to PF recently
- They have RF shields using the standard design to reduce the impedance significantly
- These IVUs were installed to PF long after the construction of the ring itself was completed, and there was a need of the proper IVU's impedance evaluations

- **Four IVUs (Short straight section, beam duct is copper)**
- **There are nine out-vacuum undulators (Straight section, duct is changed SUS ➡ AL)**
- **Beam duct is Al**



Introduction

Motivation

- No **impedance budget** calculation at PF ring so far…
- Need something to begin with -> **narrow duct IVUs**
- Need somebody’s experience to follow:
  - Analytical estimation
  - CST Studio simulations
  - Measurements

V. Smaluk, Phys. Rev. ST Accel. Beams 17, 074402 (2014)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **17,** 074402 (2014)

Coupling impedance of an in-vacuum undulator: Measurement, simulation, and analytical estimation

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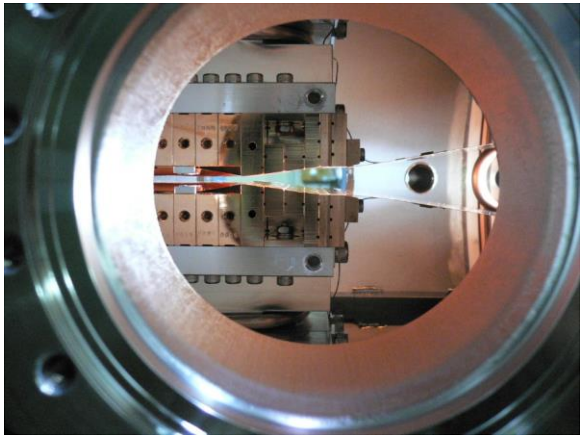
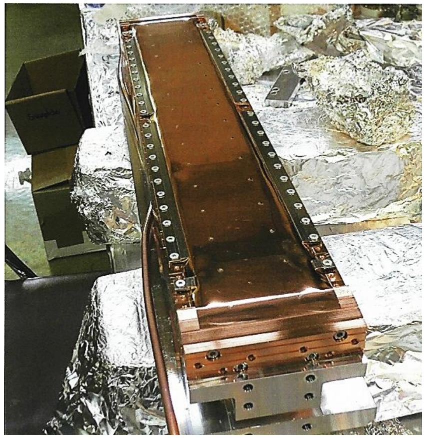
Introduction

What is PF IVU?

- Three major **impedance contributors** of PF IVU:





1. **Taper** between the flange and the undulator (200 mm thick) for the **geometrical impedance**
2. **Copper plate** (60 mm copper and 25 mm nickel coating) on top of the undulator for the **resistive-wall impedance**
3. **Step transition** from the octagon to the rectangular chambers for the **geometrical impedance**

2. Impedance Evaluation for PF IVU by Simulations and Theory

2. Impedance Evaluation for PF IVU

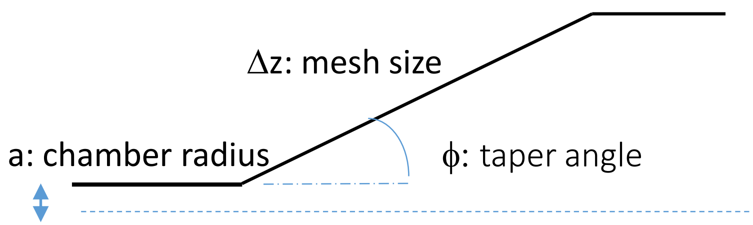
CST Studio Model of the Taper

- To calculate the pure geometrical impedance of the taper, we first assume the perfectly conductive material instead of using copper resistivity

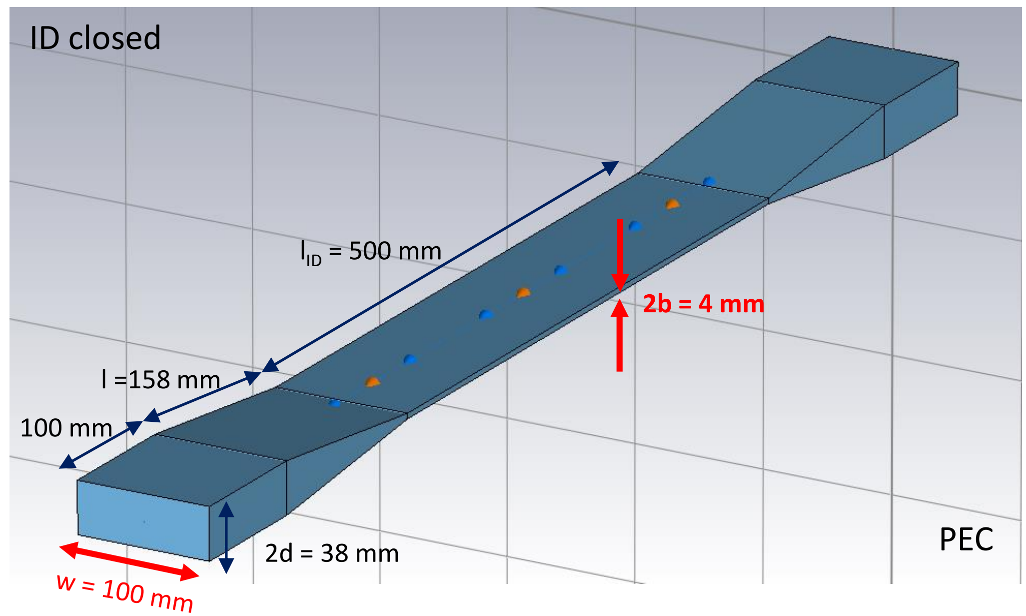
Mesh size matters!

$\Delta z < 150\ \mu m$

$$100 \leq \frac{a\phi}{\Delta z} \cdot \frac{\sigma_z}{\Delta z}.$$

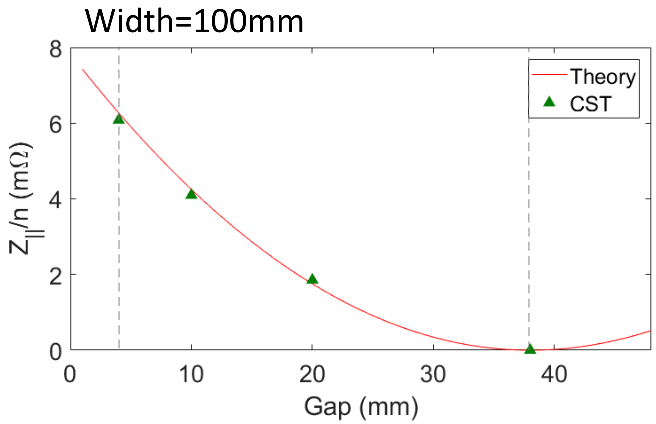


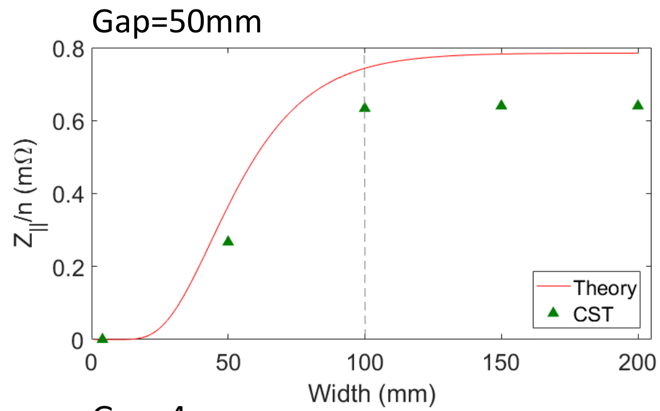
Frasciello's slide at SIF2014
on wakes of LHC collimators

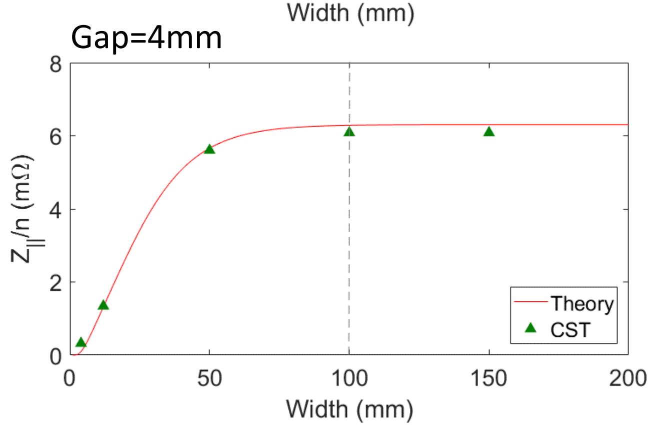


2. Impedance Evaluation for PF IVU

Longitudinal Geometrical Impedance of Taper







$$\frac{Z_l}{n} = -i\frac{Z_0\omega_0}{4\pi c}\int_{-\infty}^{\infty}(g')^2 F\left(\frac{g}{w}\right)dz, \quad b \ll w \ll l$$

$$F(x) = \sum_{m=0}^{\infty}\frac{1}{2m+1}\operatorname{sech}^2\left((2m+1)\frac{\pi x}{2}\right)\tanh\left((2m+1)\frac{\pi x}{2}\right).$$

G. Stupakov, Phys. Rev. ST Accel. Beams 10, 094401 (2007)

2. Impedance Evaluation for PF IVU

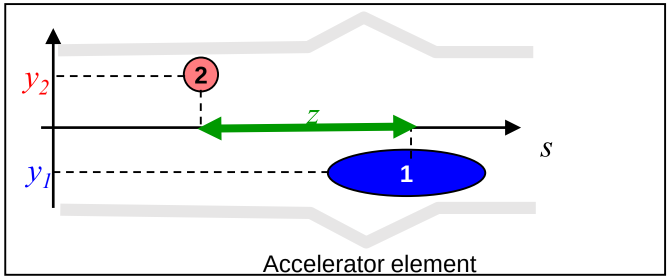
Transverse Geometrical Impedance of Taper (I)

- We need a careful treatment of the transverse impedance, since it includes both the dipolar and the quadrupolar components:

$$W_{y,tot}(y_1, y_2, z) = W_{y,dip}(z) y_1 + W_{y,quad}(z) y_2$$

Total wake   Dipolar wake   Quadrupolar wake

B. Salvant, Beam physics for FAIR



- They produce vertical kick factors

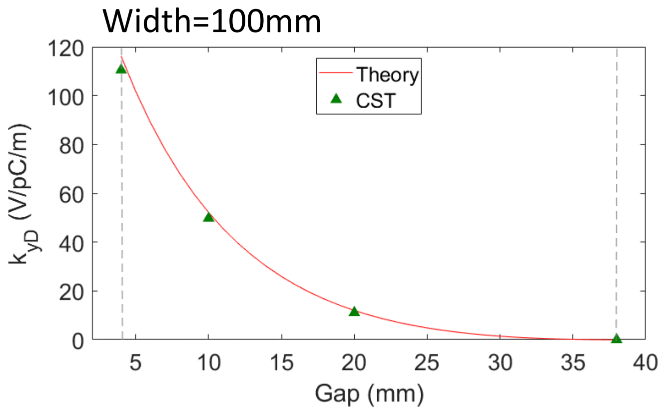
$$k_\perp = \frac{\mathrm{Im} Z_\perp c}{2\sqrt{\pi}\sigma_s},$$

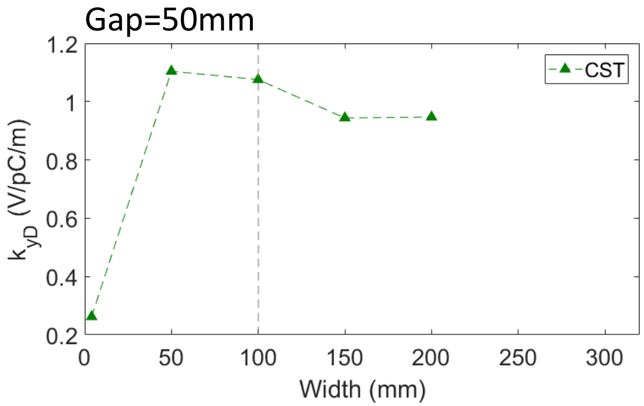
- Transversely, the calculation of kick factors is most important since it provides additional coherent vertical tune shift

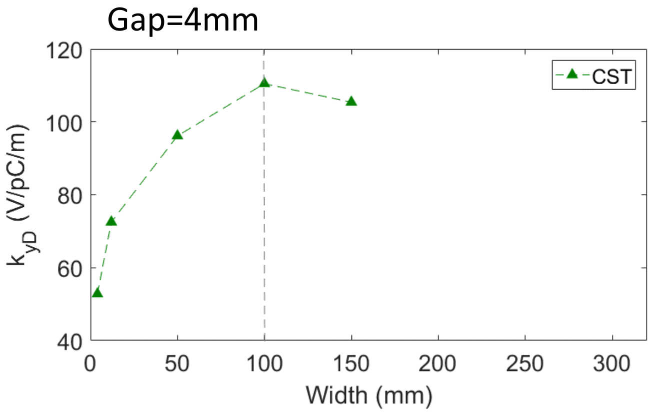
2. Impedance Evaluation for PF IVU

Transverse Geometrical Impedance of Taper (II)

Dipolar







$$Z_{yD}(k) = -i\frac{Z_0}{2\pi b}\int_{-\infty}^{\infty}\frac{\xi^2}{\sinh^2\xi}\sum_{n=0}^{\infty}\delta_n\frac{H(k_n,k)+H(k_n,-k)}{2ik_n b}d\xi$$

$$H(p,k) = \int_{-\infty}^{\infty}\int_{-\infty}^{z_1} S'(z_1)S'(z_2)e^{i(p+k)(z_1-z_2)}dz_1 dz_2, \quad k_n b = \sqrt{(kb)^2-\xi^2-(\pi n)^2}$$

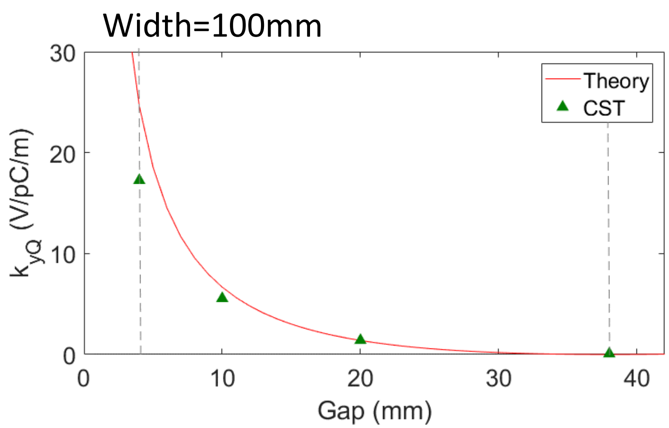
$$w \to \infty$$

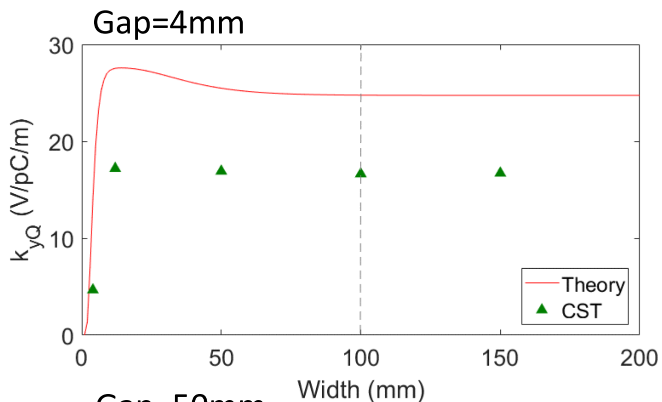
S. Krinsky, Phys. Rev. ST Accel. Beams 8, 124403 (2005)

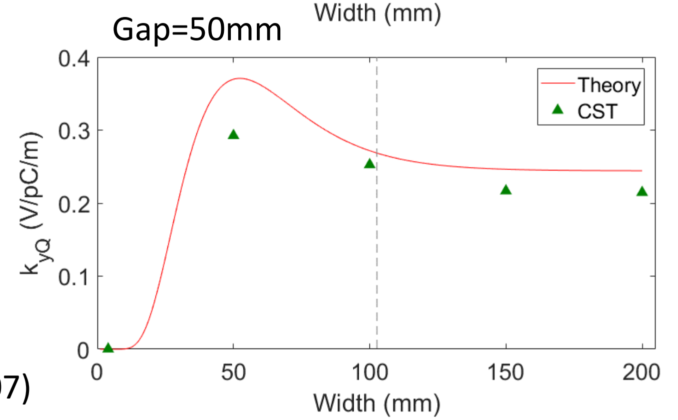
2. Impedance Evaluation for PF IVU

Transverse Geometrical Impedance of Taper (III)

Quadrupolar







$$Z_{yQ} = -i\frac{\pi Z_0}{4}\int_{-\infty}^{\infty}\frac{(g')^2}{g^2}G\left(\frac{g}{w}\right)dz,$$

$$G(x) = x^2\sum_{m=0}^{\infty}(2m+1)\times\mathrm{sech}^2\left((2m+1)\frac{\pi x}{2}\right)\tanh\left((2m+1)\frac{\pi x}{2}\right).$$

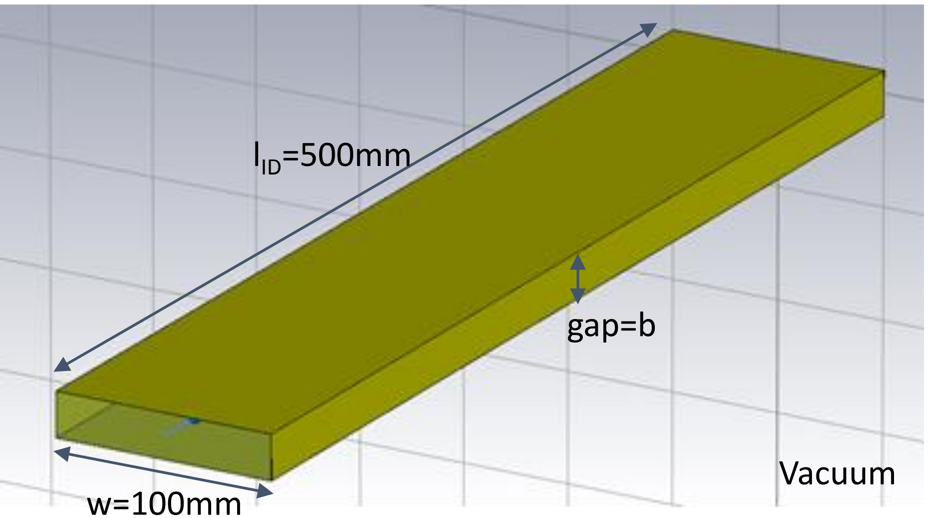
$$b \ll w \ll l$$

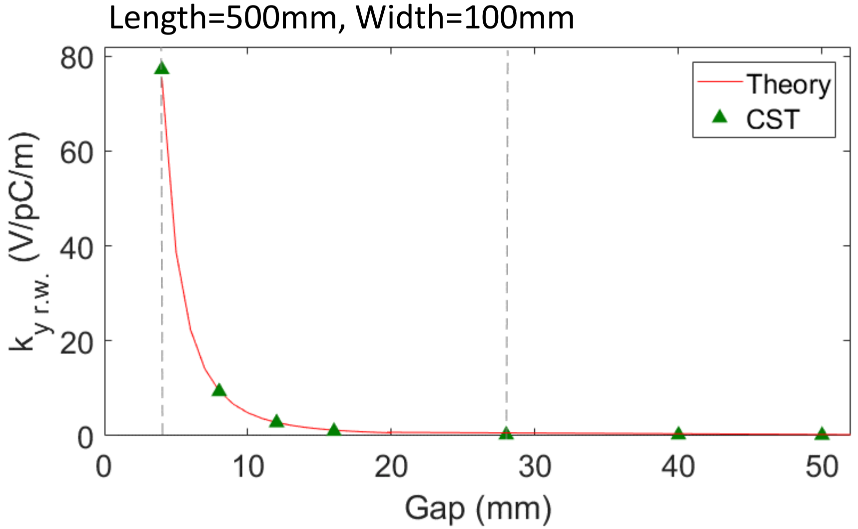
G. Stupakov, Phys. Rev. ST Accel. Beams 10, 094401 (2007)

2. Impedance Evaluation for PF IVU

Resistive-Wall Impedance of Undulator

- By using the copper resistivity in CST, we can calculate the resistive impedance of the undulator with copper sheet





Electric conductivity of copper ：

$$\sigma_c = 5.9 \times 10^7 S/m$$

$$k_{yR.W.} = \frac{cL}{8b^3}\sqrt{\frac{2Z_0}{\sigma_z \sigma_c}}\,\Gamma\left(\frac{5}{4}\right)$$

L=Length of undulator

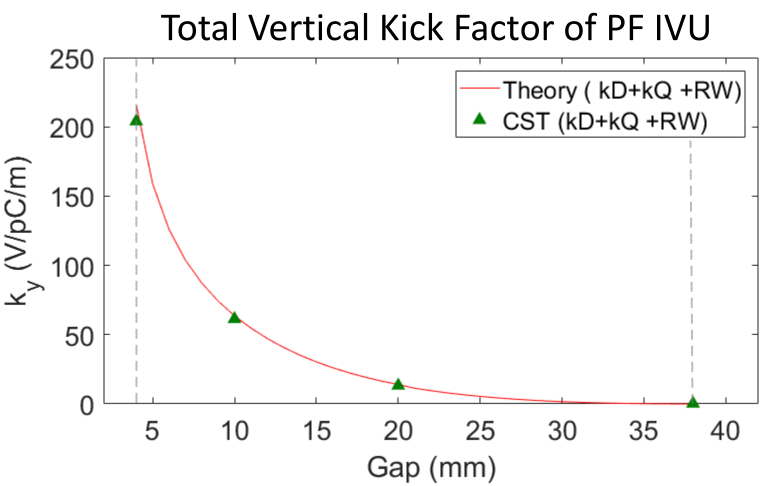
O. Frasciello + V. Smaluk

$\Gamma\left(\frac{5}{4}\right)$=0.9064

2. Impedance Evaluation for PF IVU

Total Transverse Impedance of the IVU

- The total **vertical kick factor** due to 1 IVU is



Vertical kick factor per 1 IVU		CST PS	Theory
Taper vertical kick factor, V/pC/m	Dipolar	110.47	116.13
	Quadrupolar	16.64	24.61
Undulator vertical kick factor, V/pC/m	Dipolar	50.80 +	75.57
	Quadrupolar	26.40	
Total vertical kick factor, V/pC/m		**204.31**	**216.31**

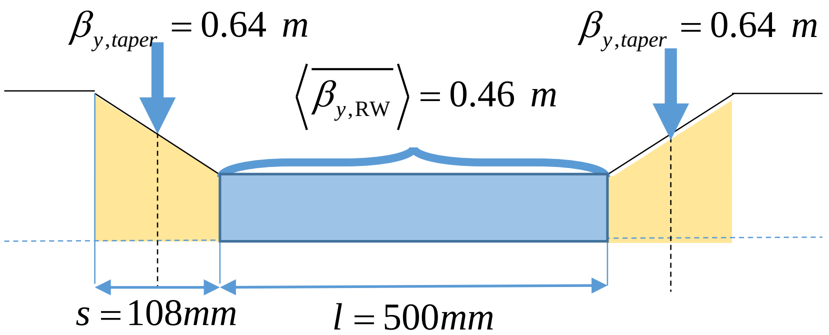
- Impact of the step transition is three orders less, therefore is negligible

3. Measurements of Kick Factors

3. Measurements of Kick Factors

Tune Shift Measurement Method

- This **additional tune shift corresponds** to a difference of the vertical tune shifts for ID open (gap=42mm) and ID closed (gap=3.83mm) cases



$$\frac{\Delta \nu_y}{I_b} = -\frac{1}{4\pi(E/e) f_0} \sum_j \beta_{y,j} \left[k_{y,j}^{(1)} + k_{y,j}^{(2)} \right]$$

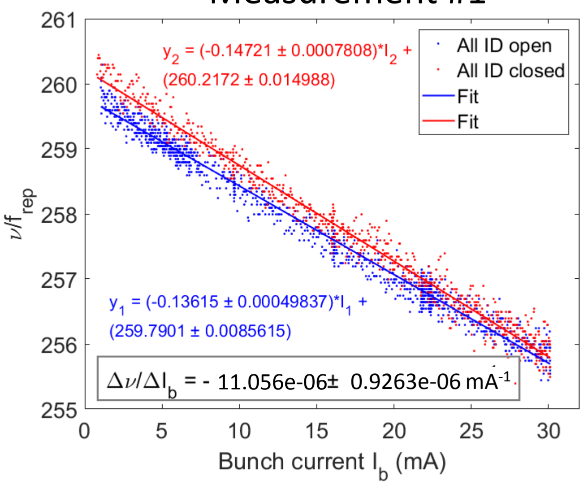
S. Sakanaka, et. al. Phys. Rev. ST Accel. Beams **8,** 042801 (2005)

	CST PS	Theory
Total vertical kick factor, V/pC/m	204.31	216.31
Average betatron function at the undulator, m	0.46	
Betatron function in the center of the taper, m	0.64	
Tune shift per bunch current, mA^{-1}	-10.06×10^{-6}	-10.60×10^{-6}

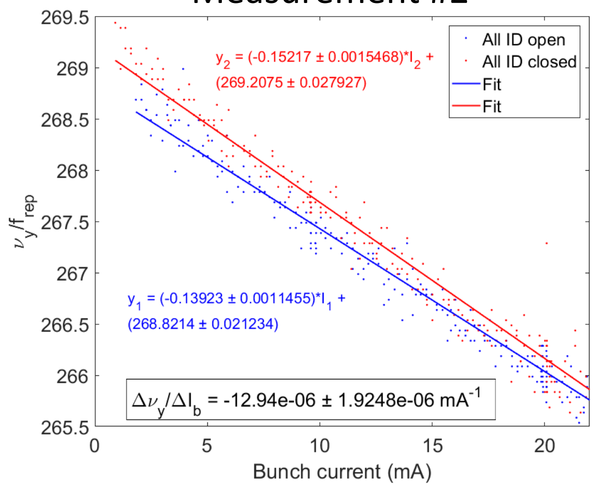
3. Measurements of Kick Factors

Tune Shift Measurement Result

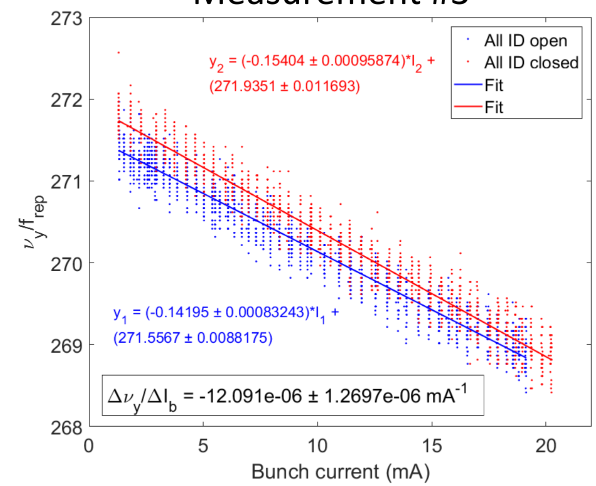
Measurement #1



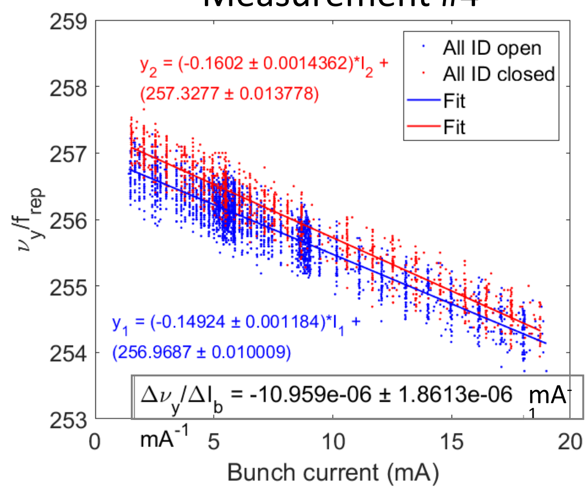
Measurement #2



Measurement #3



Measurement #4



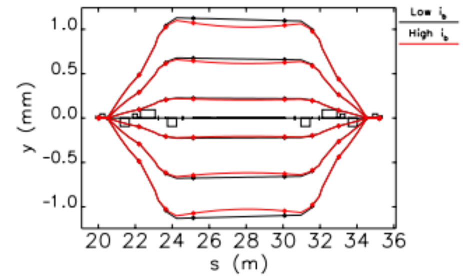
	Theory	CST PS	Measurement
Tune shift per bunch current (mA^{-1})	-10.60×10^{-6}	-10.06×10^{-6}	-10.96×10^{-6} $\pm 1.86\times10^{-6}$

Good agreement with our evaluations!

3. Measurements of Kick Factors

Orbit bump measurement (I)

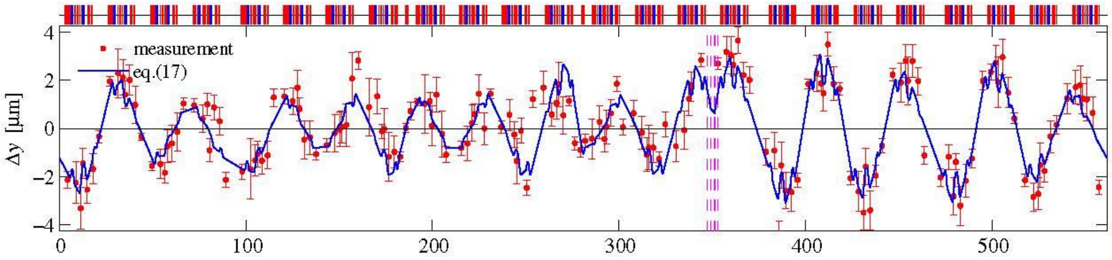
- Create an **orbit bump** at a location including IVU
- This orbit bump (y_0) creates **orbit deviations** ($\Delta y(s)$) proportional to the kick factor (k_y) of IVU along the ring:



L. Emery, APS

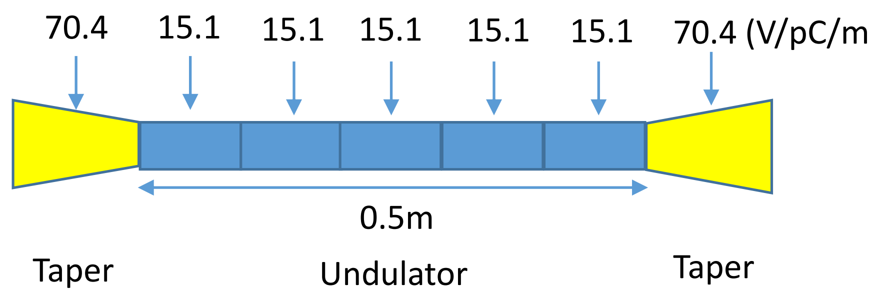
$$\Delta y(s) = \frac{\Delta q}{E/e} k_y y_0 \frac{\sqrt{\beta(s)\beta(s_0)}}{2\sin(\pi\nu)} \cos\left[\left|\mu(s)-\mu(s_0)\right| - \pi\nu\right],$$

V. Smaluk, Phys. Rev. ST Accel. Beams 17, 074402 (2014)

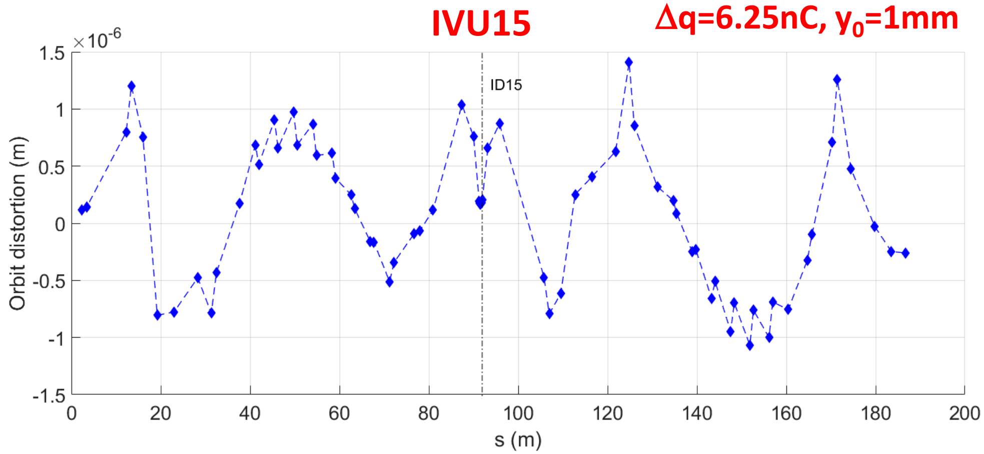


3. Measurements of Kick Factors
Orbit bump measurement (II)

- The **betatron phase advance** changes a lot within the IVU (1.21 m length), because the betatron function is small (around 0.4 m) in the center
- It is necessary **to distribute the kick impact** to various appropriate positions and simulate the accurate beta and betatron phase with calculation.



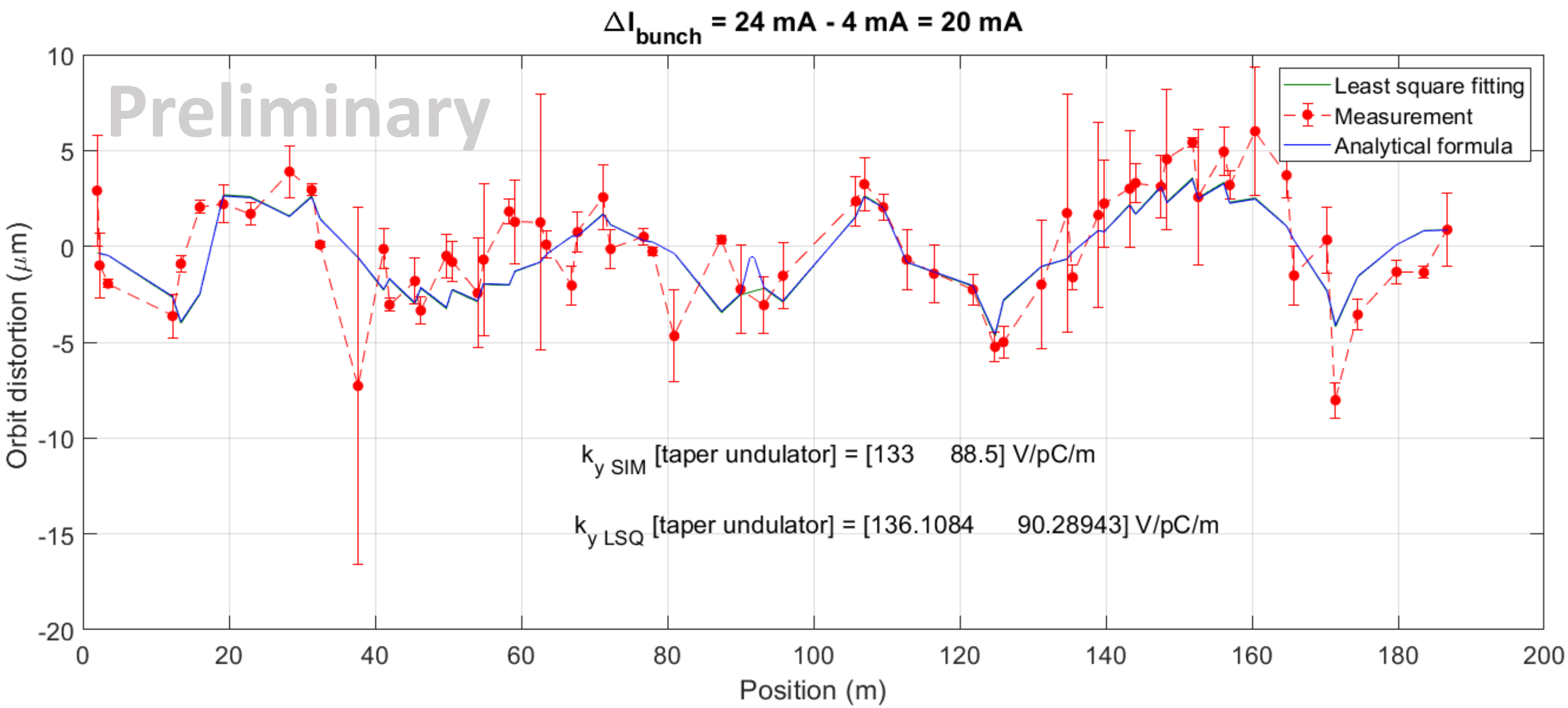
IVU15 **Δq=6.25nC, y_0=1mm**



- I made a bump of **1 mm** at IVU15 and calculated the orbit deviation caused by all BPM (total number is 65 at PF ring)
- I found that the orbit deviation becomes **1.5 µm** at maximum

3. Measurements of Kick Factors

Orbit bump measurement (III)



Conclusion

- I am on my track to evaluate the **transverse kick factors** of the PF in-vacuum undulator
- The study suggests that one should **distribute kick factors** along the ID instead of lumping them to the center of ID for more accurate estimate of orbit deviations. Especially in the case of a long undulator this may be essential
- I have also pointed out, that one should **subtract contributions of other components inside the same bump** orbit but outside of the undulator from analysis for more accurate estimate of kick factors. An evaluation of the impact of these "outside" components will be a natural extension of the present study
- In conclusion we have compared the ID's kick factors obtained by the **measurements** with those obtain by the **simulations** and the **analytical evaluations**
- The upcoming study will include a research on the **individual properties** of each of four IDs affecting the transverse kick, together with its possible reasons

Thank you for your attention!

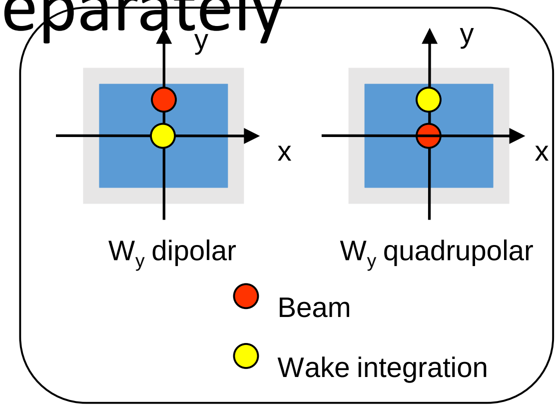
ご清聴ありがとうございました!

Backup

1.インピーダンス理論

ダイポーラー、クァドルポーラー?

- In asymmetric structures, they are different concepts from dipole and quadrupole modes
- They can be calculated by displacing the beam and the wake integration path separately
- Machine measurements
  - Tune shift
    → dipolar + quadrupolar
  - Instability growth rate
    → dipolar



B. Salvant, Beam physics for FAIR

1.インピーダンス理論

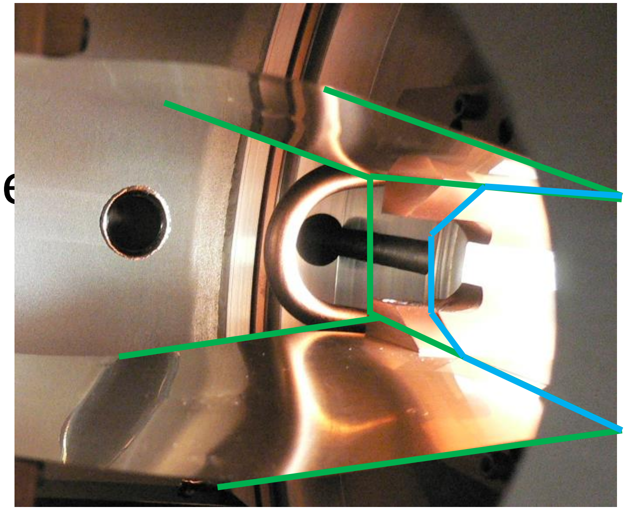
ステップトランジションの幾何学的インピーダンス

- Low-frequency impedance of the step transition at the beginning of the taper can be roughly estimated using formula:

$$Z_y = i\frac{Z_0(d-b)}{\pi b^2}\frac{d^2-b^2}{d^2+b^2}$$

- Its power loss will be taken care by the cooling channel in the present design

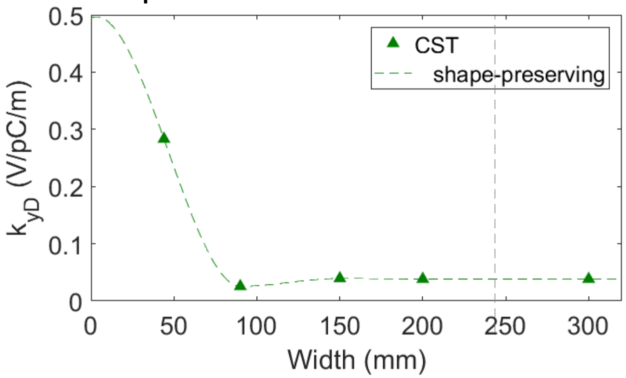
PF IVU



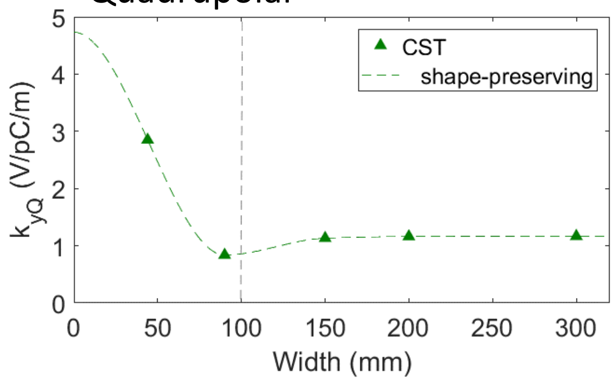
2. PF IVUインピーダンスの評価

ステップトランジションの幾何学的インピーダンス

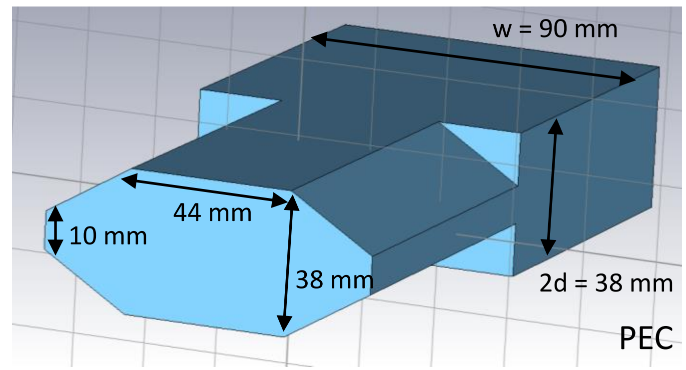
Dipolar



Quadrupolar



CST model of the step transition

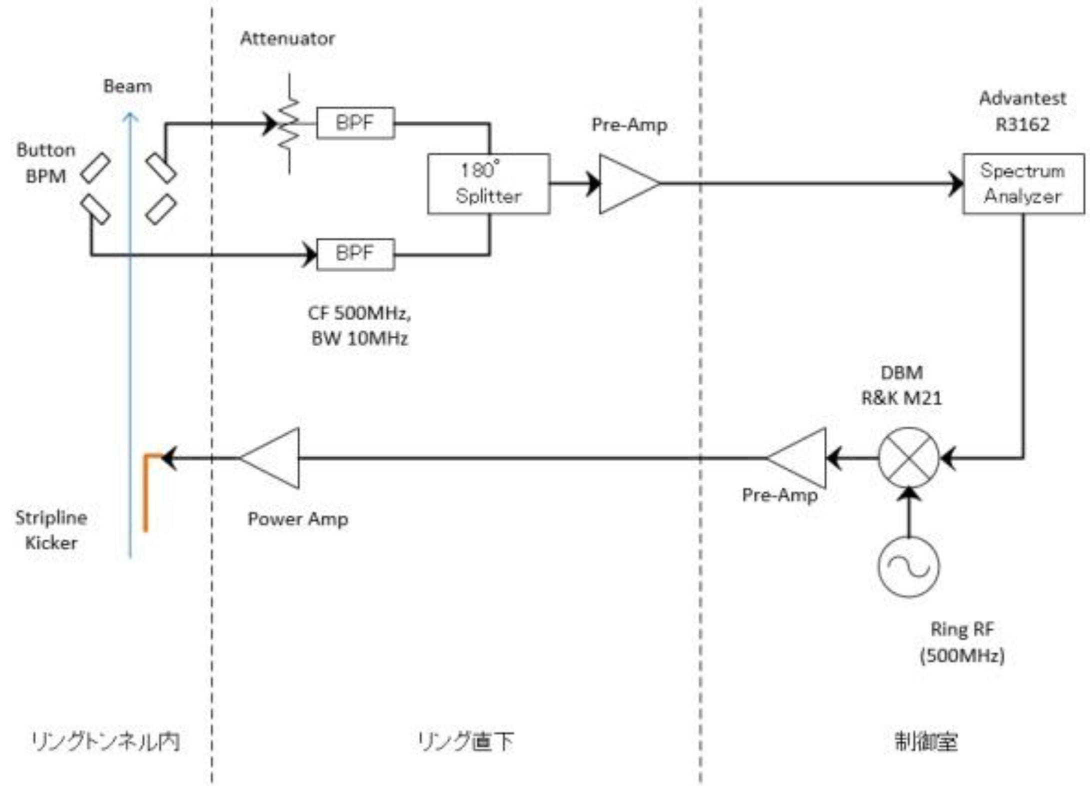


They have very small contributions to the total vertical kick factor and saturate at width = 150 mm

3.チューンシフト測定

RF Knock-Out

- Single bunch
- Feedback OFF
- The responses of the stripline kicker oscillations were measured by sweeping the bunch current (equal to changing the betatron frequency) using a spectrum analyzer equipped with a tracking generator.



Possible reasons of the difference in estimated and measured tune shift values

1. **Size of the gap between two copper shields (3.83 mm vs 4 mm)**
2. **Thickness of the copper shield is not enough**
3. Difference in present and model values of betatron function
4. Difference in values of betatron function when ID gap is opened/closed
5. Reliability of CST code
6. Accuracy of the tune shift measurement

Courtesy of N. Nakamura

1. Size of the gap between two copper shields

- The smallest ID gap $g = 2b = 4$ mm ($b = 2$ mm)
- The smallest ID gap $g = 2b = 4$ mm ($b = 2$ mm)
- Thickness of the shield $t = 60$ mm (Cu) + 25 mm (Ni) = 85 mm
- Real size of the gap $g_s = 2b_s = 4 - 0.085 \times 2 = 3.83$ mm ($b_s = 1.915$ mm)
- Resistive-wall impedance(imaginary part) & kick factor

$$\mathrm{Im}\, Z_y(f) \approx -\frac{\pi Z_0 L}{16 b_s^3}\sqrt{\frac{1}{\pi |f| \mu_0 \sigma_{Cu}}}$$

$$k_y = f_0 \sum_{p=-\infty}^{\infty} \mathrm{Im}\, Z_{Dy}(pf_0 + f_\beta) h(pf_0 + f_\beta)$$

$$h(\omega) = \exp\left\{-\left(\omega\sigma_z / c\right)^2\right\}$$

⬇

$$k_y = 85.97 \text{ V/pC/m} \quad (f = -10 \sim +10 \text{ GHz})$$

$$cf.\ k_y(b = 4\text{mm}) = 75.46 \text{ V/pC/m}$$

Influence of about 14%

Courtesy of N. Nakamura

2. Thickness of the copper shield is not enough

- Frequency at which copper skin depth and copper sheet thickness are the same
- Resistive-wall impedance formula (switched by frequency)

$$\delta_{Cu} = d_{Cu}$$

$$\delta_{Cu} = \sqrt{\frac{1}{\pi\sigma_{Cu}\mu_0|f|}} \rightarrow f_\delta = \frac{1}{\pi\sigma_{Cu}\mu_0 d_{Cu}{}^2}$$

$$|f| \geq f_\delta = \frac{1}{\pi\sigma_{Cu}\mu_0 d_{Cu}{}^2} = 1.19\ \text{MHz}\left(d_{Cu} = 60\ \mu\text{m}\right) \rightarrow \operatorname{Im} Z_y(f) \approx -\frac{\pi Z_0 L}{16b^3}\sqrt{\frac{1}{\pi|f|\mu_0\sigma_{Cu}}}$$

$$|f| < f_\delta\ (f = \Delta\nu_\beta f_0,\ \ f = -(1-\Delta\nu_\beta)f_0) \rightarrow \operatorname{Im} Z_y(f) \approx -\frac{\pi Z_0 L}{16b^3}\sqrt{\frac{1}{\pi|f|\mu_0\sigma_{NdFeB}}}$$

$$\sigma_{NdFeB} = 0.6\times10^6\ \Omega^{-1}\text{m}^{-1}, \sigma_{Ni} = 14\times10^6\ \Omega^{-1}\text{m}^{-1}$$

$$k_y = f_0\sum_{p=-\infty}^{\infty}\operatorname{Im} Z_y(pf_0 + f_\beta)h(pf_0 + f_\beta)$$

$$k_y = 86.04\ \text{V/pC/m}\ \ (f = -10 \sim +10\ \text{GHz}) \quad cf.\ k_y(Cu) = 75.46\ \text{V/pC/m}$$

Courtesy of N. Nakamura

Influence of about 14%