Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring

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Contents of the report

- Research meaning
- Design of the stripline transverse quadrupole kicker
- Design of the stripline Beam Position Monitor(BPM)
- Calibration of the stripline BPM
- Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring
- Measurement of injected beam transverse quadrupole oscillation

Research meaning

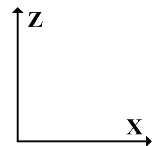
Research meaning follows：

- Studying the influence of transverse quadrupole oscillation on beam parameters and **enhancing understanding of higher-order transverse oscillation generated by the beam**;
- Analysising the influence of space charge force on transverse quadrupole oscillation and **enhancing understanding of the role of space charge force**;
- Analysising the effect of short-range transverse quadrupole wakefield on transverse quadrupole oscillation and **enhancing understanding of the short-range transverse quadrupole wakefield**

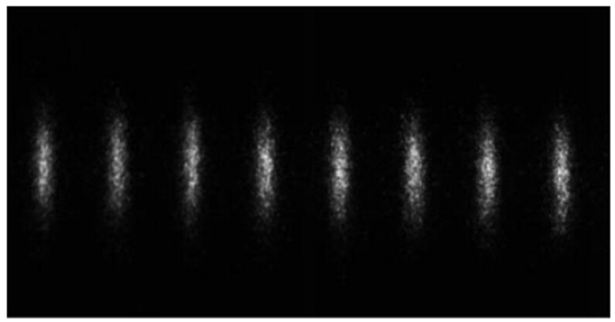
横向四极振荡的定义

According to the theories of collective beam instabilities, transverse oscillations of a bunched beam can be described by a superposition of many normal modes of oscillation: **dipole mode**, **quadrupole-mode**, and so on.

The contents of **reference [1]** **'Excitation and Detection of a Transverse Quadrupole -Mode Bunch Oscillation in the KEK Photon Factory Storage Ring'**(S. Sakanaka, Y. Kobayashi, et al. Jpn. J. Appl. Phys. **42** (2003) 1757) show that:

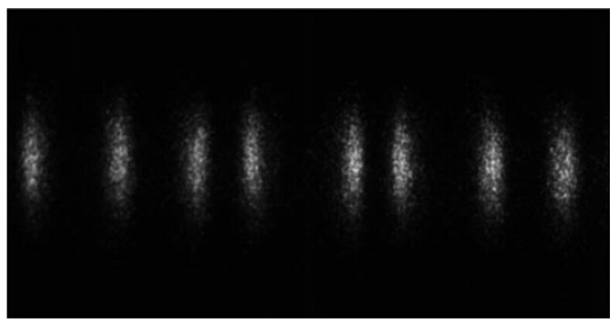


no transverse oscillation



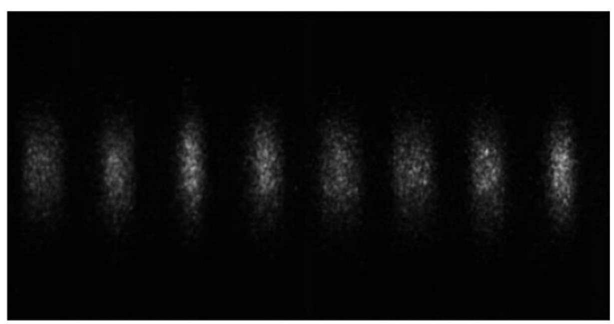
Bunch centroid and bunch transverse dimension are not oscillating

transverse dipole oscillation



Bunch centroid is oscillating

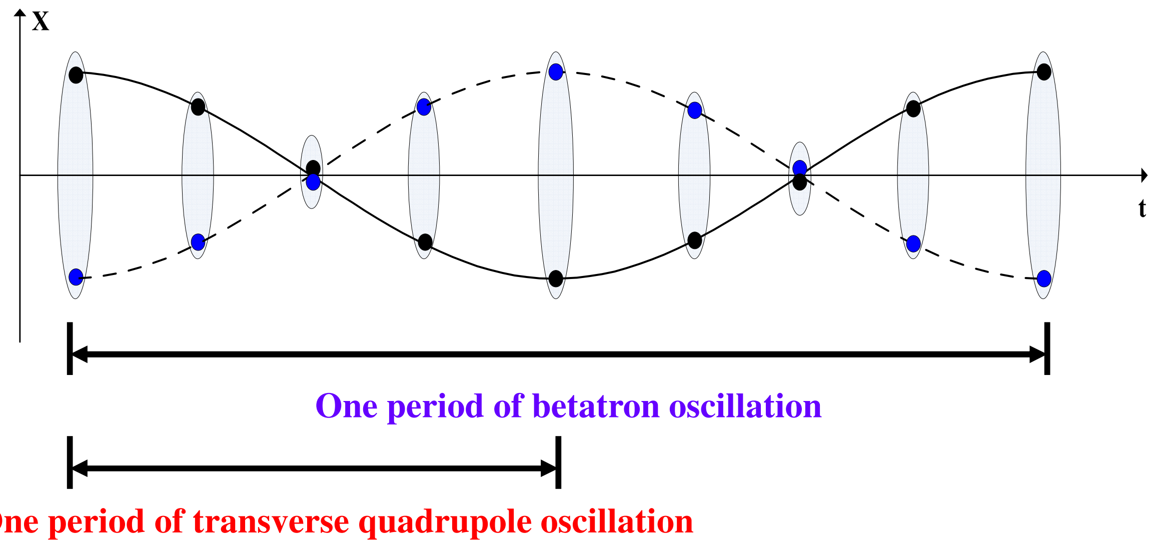
transverse quadrupole oscillation



Bunch transverse dimension is oscillating

Relationship between transverse quadrupole oscillation and transverse dipole oscillation

Beam transverse dipole oscillation is the performance of particles collective Beta oscillation. Oscillation frequency is the frequency corresponding to the operating point $\left(n \pm \Delta\nu_{x,y}\right) f_0$



transverse quadrupole oscillation frequency $\left(n \pm 2\Delta\nu_{x,y}\right) f_0$

space charge force

short-range transverse quadrupole wakefield

Transverse quadrupole oscillation frequency has a small offset relative to the theoretical value

Sweep Excitation in order to identify the accurate frequency

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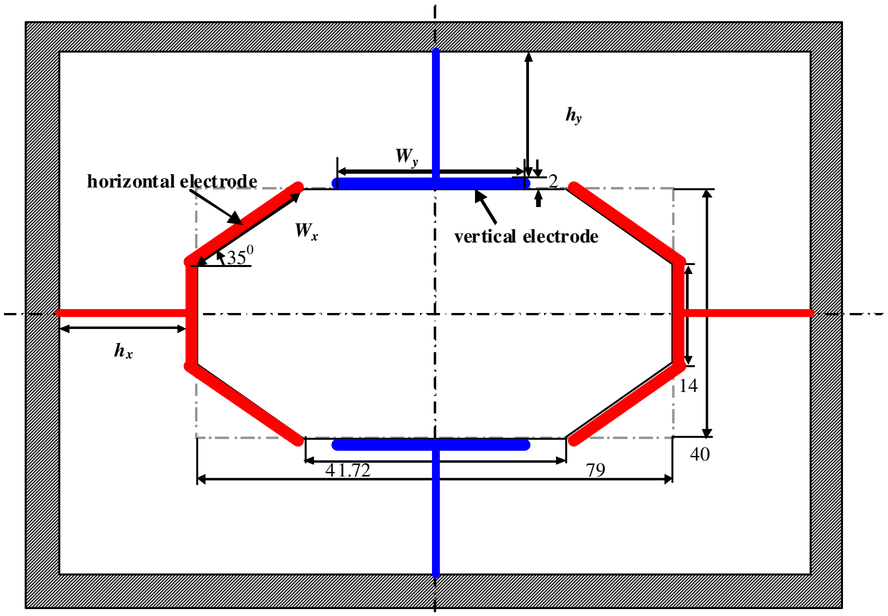
Design of the stripline transverse quadrupole kicker



The **cross section** of the HLS II stripline transverse quadrupole kicker

Refer to structure parameters of the HLS II stripline transverse dipole kicker , electrode length and thickness of the stripline transverse quadrupole kicker are:

- **electrode length *l*=183.8mm**;
- **electrode thickness *t*=2mm**;

Size and shape of the vacuum chamber is fixed. Combined Parameters (*hx*, *hy*,*Wx*,*Wy*) are optimized in order to match characteristic impedances of electrodes with characteristic impedances of Feedthrough..

Capacitor between stripline electrode and vacuum chamber can store electromagnetic energy and characteristic impedance is calculated by the following formula:

$$Z = \frac{(V_1 - V_2)^2}{2Ec} \qquad (1)$$

c is the speed of light, V_1 and V_2 are the potentials with electrodes and the vacuum chamber. When V_1 is equal to ±1V and V_2 is equal to 0V , the formula is as follows:

$$Z = \frac{1}{2Ec} \qquad (2)$$

The transverse quadrupole kicker is modeled by Poisson code, electrostatic energy E is automaticly calculated and finally characteristic impedances of electrodes are calculated

Design of the stripline transverse quadrupole kicker

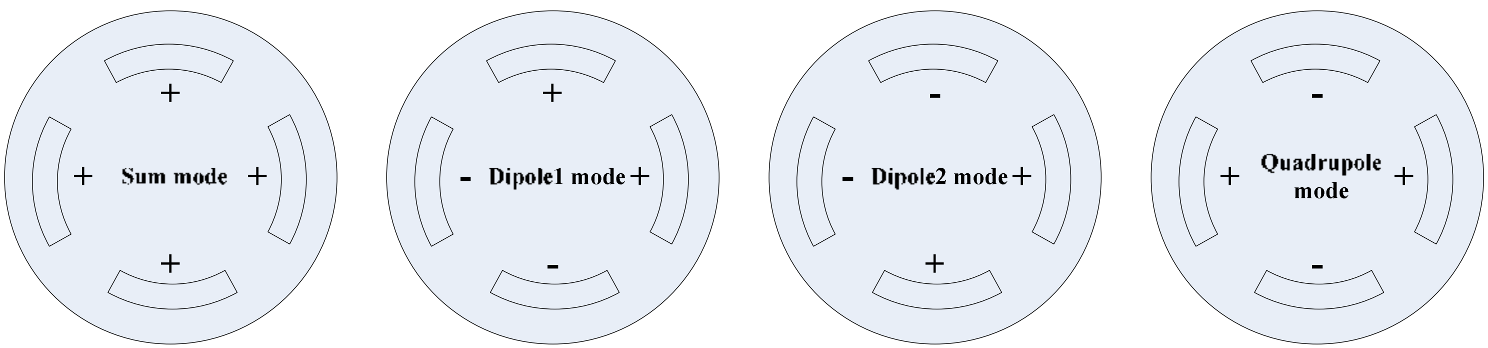
Refer to reference [2], if the characteristic impedances of electrodes are matched with characteristic impedance of Feedthrough, the following equation must be satisfied:

$$Z_0^2 = Z_{dipole1} Z_{dipole2} = Z_{sum} Z_{quad}$$

Where Z_0 is characteristic impedance of Feedthrough and equal to 50Ω.

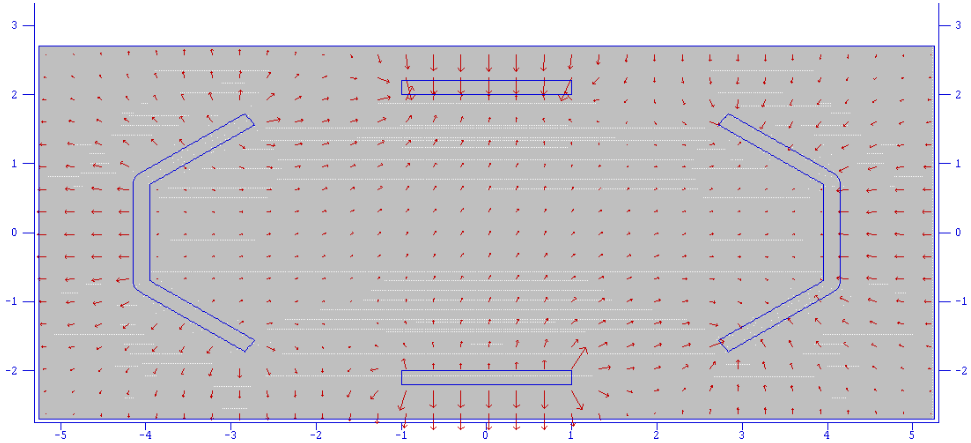
Caracteristic impedance of some modes

	R	*T*	*L*	*B*
Z_{dipole1}	+1 V	+1 V	-1 V	-1 V
Z_{dipole2}	+1 V	-1 V	-1 V	+1 V
Z_{sum}	+1 V	+1 V	+1 V	+1 V
Z_{quad}	+1 V	-1 V	+1 V	-1 V

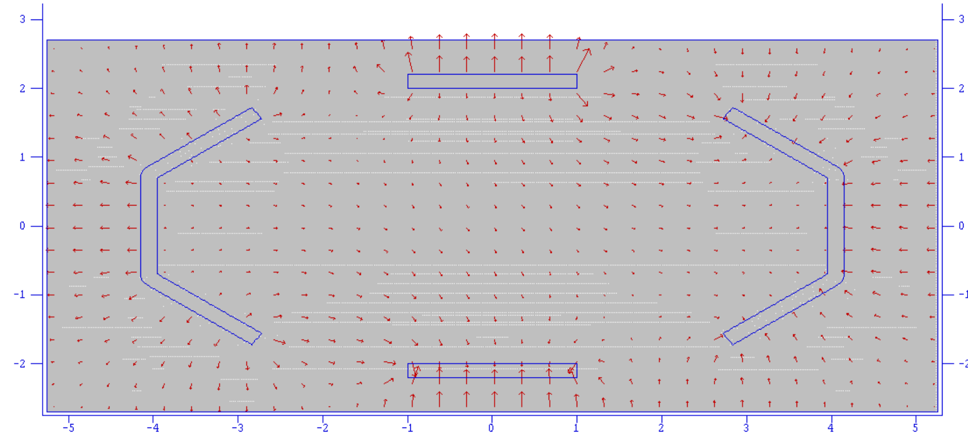


Design of the stripline transverse quadrupole kicker

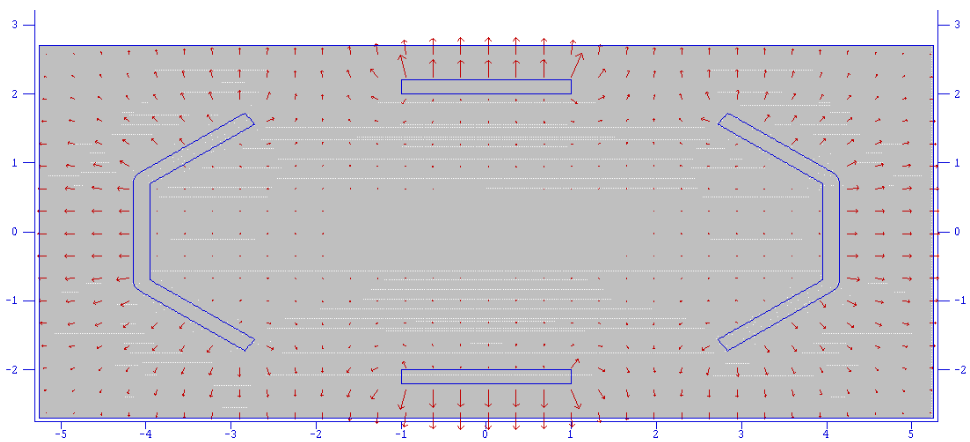
electric field distributions for some modes in the kicker



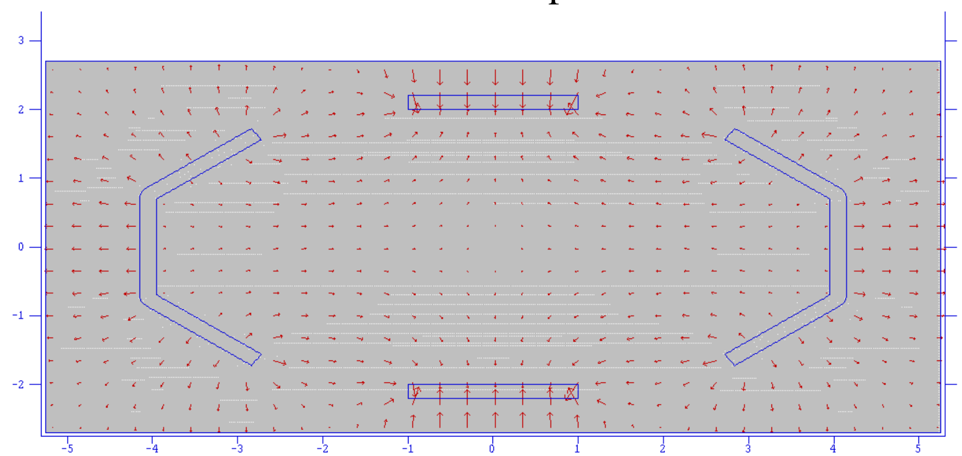
electric field for dipole1mode



electric field for dipole2 mode



electric field for sum mode



electric field for quad mode

条带型横向四极激励器的研制

Optimization step：

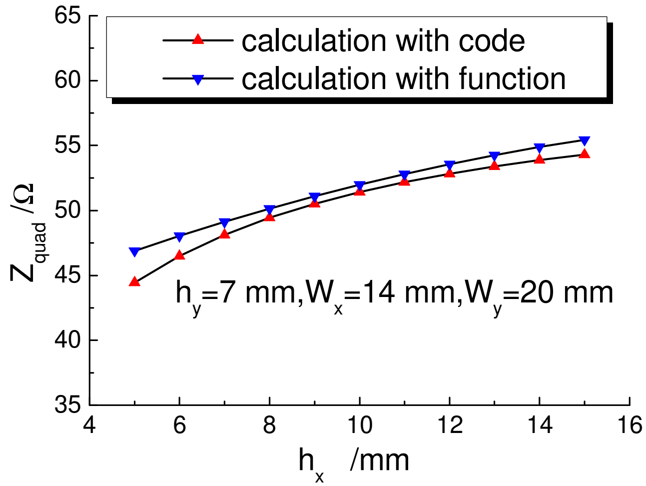
1. Dozens of different groups of combined parameters (*hx*, *hy*,*Wx*,*Wy*) are changed and four modes characteristic impedances for each group of combined parameters are calculated by Poisson code;
2. **Fitted functions about** combined parameters(*hx*, *hy*,*Wx*,*Wy*) **for** four modes characteristic impedances are calculated using the least squares method.

$$
\begin{aligned}
\mathbf{Z}_{\mathbf{dipole1}} = \mathbf{Z}_{\mathbf{dipole2}} = {} & 40.1384 + 2.3935h_x + 5.7856h_y - 0.4392W_x \\
& - 1.1163W_y - 0.0467h_x^2 - 0.2500h_y^2 - 0.0033W_x^2 \\
& + 0.0182W_y^2 + 0.0659h_x h_y - 0.0397h_x W_x - 0.0191h_x W_y \\
& + 0.0357h_y W_x - 0.0386h_y W_y - 0.0090W_x W_y
\end{aligned}
$$

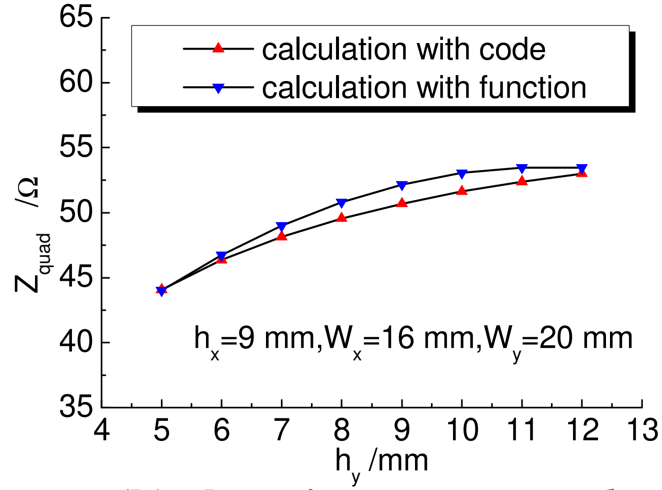
$$
\begin{aligned}
\mathbf{Z}_{\mathbf{sum}} = {} & 44.5111 + 2.4952h_x + 5.6986h_y - 0.7459W_x \\
& - 1.3043W_y - 0.0907h_x^2 - 0.2804h_y^2 - 0.0158W_x^2 \\
& + 0.0184W_y^2 + 0.1867h_x h_y + 0.0093h_x W_x - 0.0261h_x W_y \\
& + 0.0749h_y W_x + 0.0054h_y W_y - 0.0001W_x W_y
\end{aligned}
$$

$$
\begin{aligned}
\mathbf{Z}_{\mathbf{quad}} = {} & 39.3137 + 2.2287h_x + 5.5120h_y - 0.3750W_x \\
& - 0.8959\mathrm{W}_y - 0.0324h_x^2 - 0.2291h_y^2 - 0.0021W_x^2 \\
& + 0.0170W_y^2 + 0.0446h_x h_y - 0.0401h_x W_x - 0.0238h_x W_y \\
& + 0.0146h_y W_x - 0.0452h_y W_y - 0.0172W_x W_y
\end{aligned}
$$

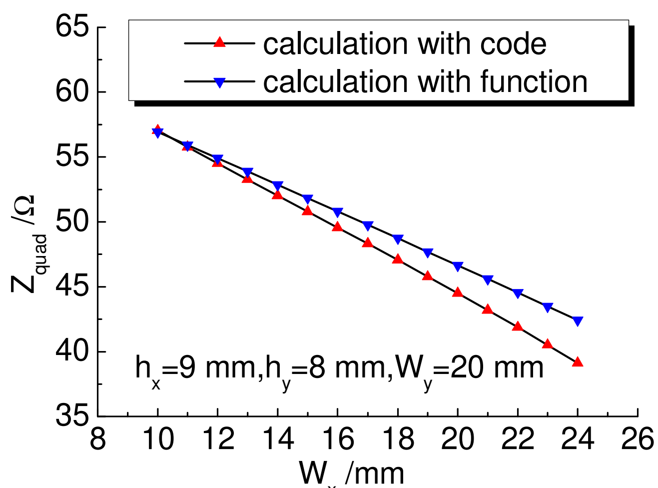
Design of the stripline transverse quadrupole kicker



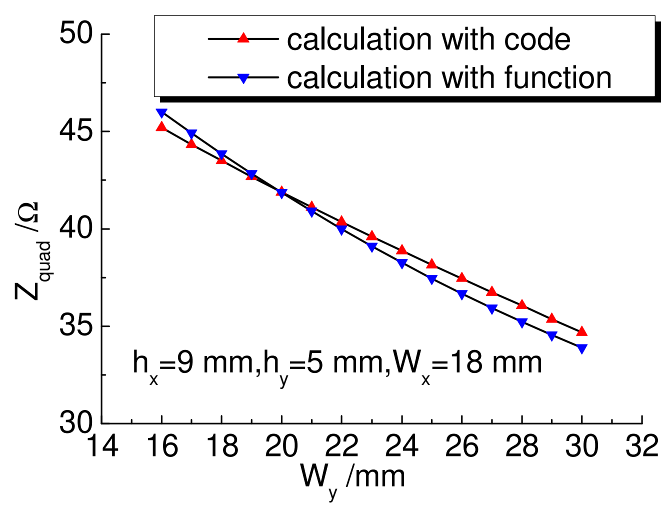
(a) changing parameter h_x



(b) changing parameter h_y



(c) changing parameter W_x



(d) changing parameter W_y

Design of the stripline transverse quadrupole kicker

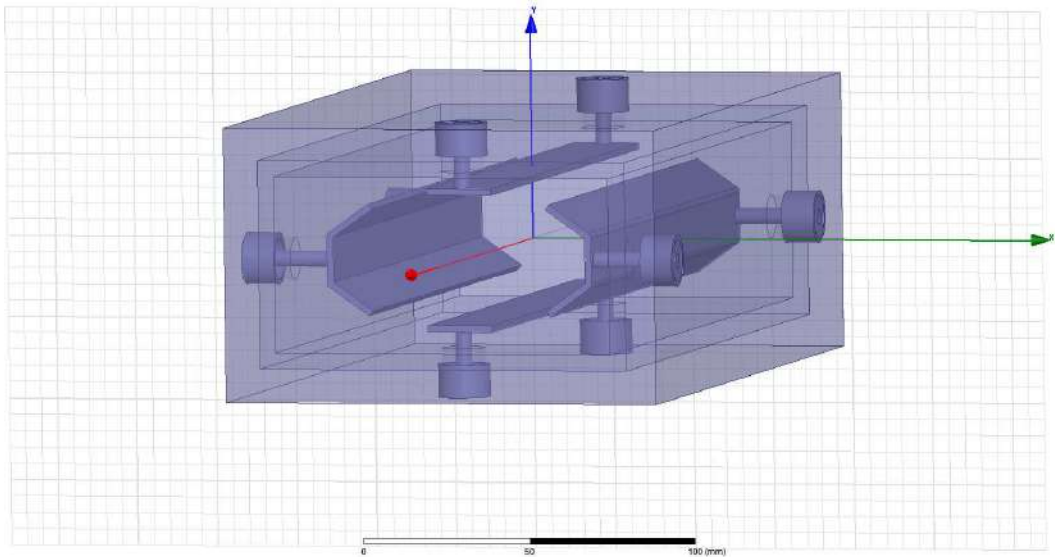
Since optimal sizes calculated by least squares fitted functions have fitting error, so final sizes are obtained by Finly tuning optimum sizes calculated by least squares fitted functions

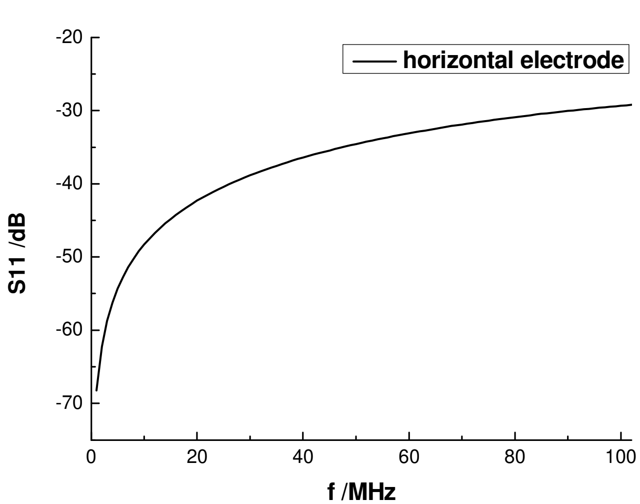
final sizes of the stripline transverse quadrupole kicker

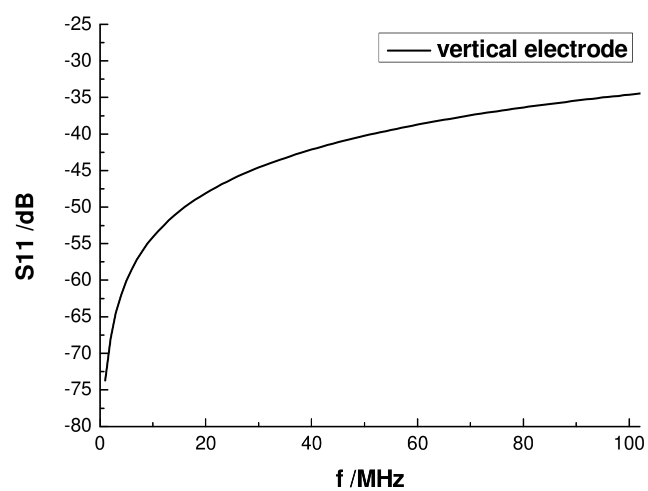
Parameter	Value /mm
$\boldsymbol{l}$	183.8
$\boldsymbol{t}$	2
$\boldsymbol{h_x}$	11
$\boldsymbol{h_y}$	5
$\boldsymbol{W_x}$	15
$\boldsymbol{W_y}$	20

$Z_{\mathrm{dipole1}}=Z_{\mathrm{dipole2}}=49.98\Omega$、 $Z_{\mathrm{sum}}=60.93\Omega$ 、$Z_{\mathrm{quad}}=46.42\ \Omega$

Design of the stripline transverse quadrupole kicker



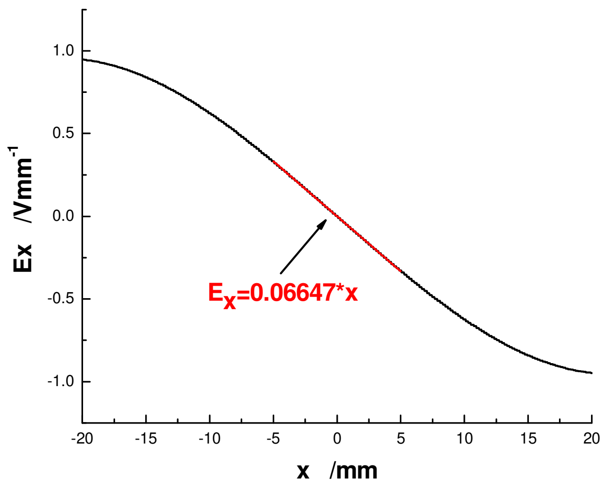


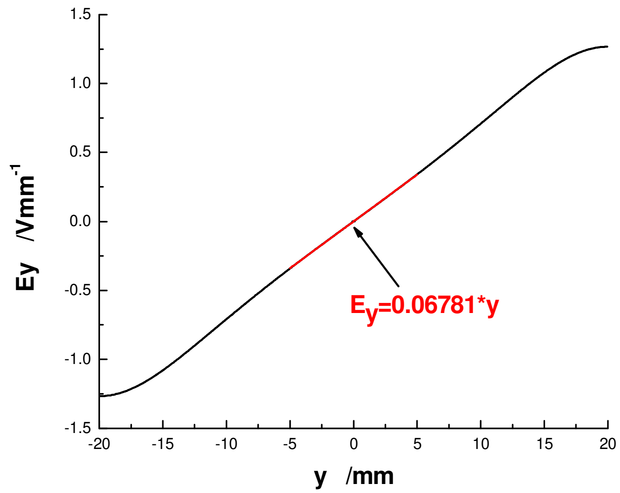


Each of electrode port reflection parameters for horizontal electrode and vertical electrode in the 102MHzbandwidth is **less than -30dB**. Electrodes ports reflect very small show that characteristic impedances of electrodes match with characteristic impedances of Feedthrough.

Design of the stripline transverse quadrupole kicker

Using the Poisson code, the electric potential of four transverse quadrupole kicker stripline electrodes are set as 20 V, around the center beam line, the electric field along the X and Y is shown in the following.





$$K_x = \frac{e}{E_0}\left|\frac{\partial E_x}{\partial x}\right|_{(0,0)} = 8.31\times10^{-11}\left(1/mm^2\right)$$

$$K_y = \frac{e}{E_0}\left|\frac{\partial E_y}{\partial x}\right|_{(0,0)} = 8.48\times10^{-11}\left(1/mm^2\right)$$

$$\delta\nu_x = \frac{K_x l}{4\pi}\beta_x = 4.25\times10^{-6}$$

$$\delta\nu_y = \frac{K_y l}{4\pi}\beta_y = 6.98\times10^{-6}$$

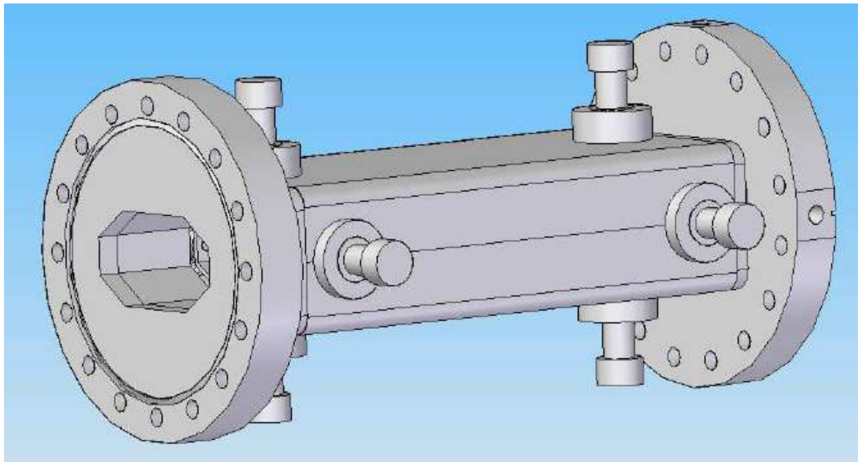
$$\alpha_{g,x} = \pi f_0 \delta\nu_x = 60.54\left(\mathrm{S}^{-1}\right)$$

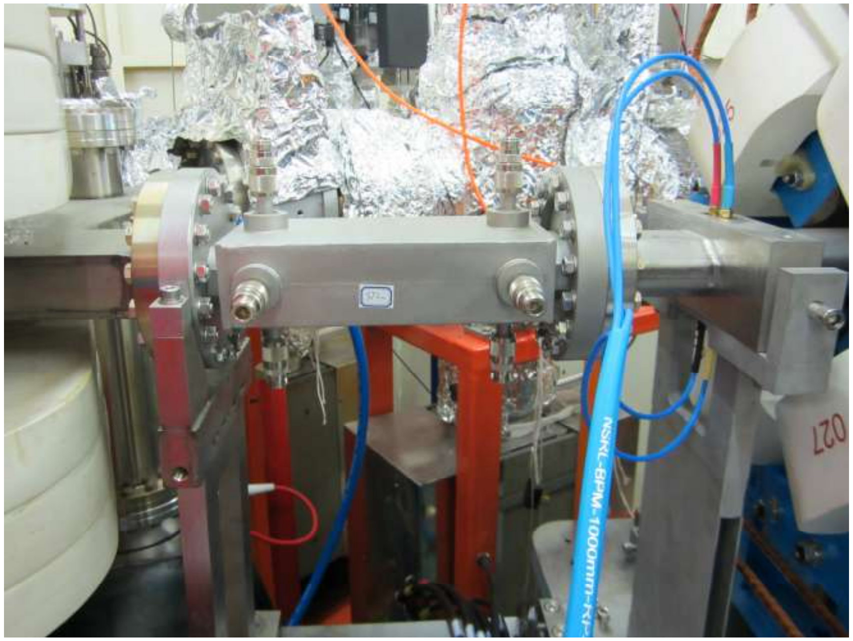
$$\alpha_{g,y} = \pi f_0 \delta\nu_y = 99.42\left(\mathrm{S}^{-1}\right)$$

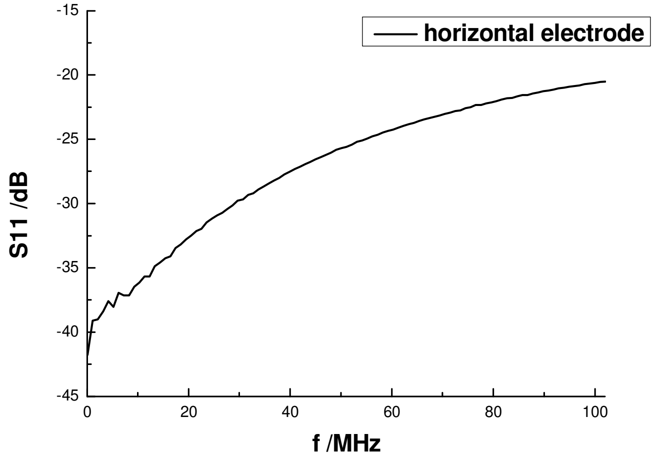
In the upgrade project of the HLS II, the transverse radiation-damping rate is 47~50 s^{-1}, the above growth rate exceeds the transverse damping rate, so this transverse quadrupole kicker can excite transverse quadrupole oscillation.

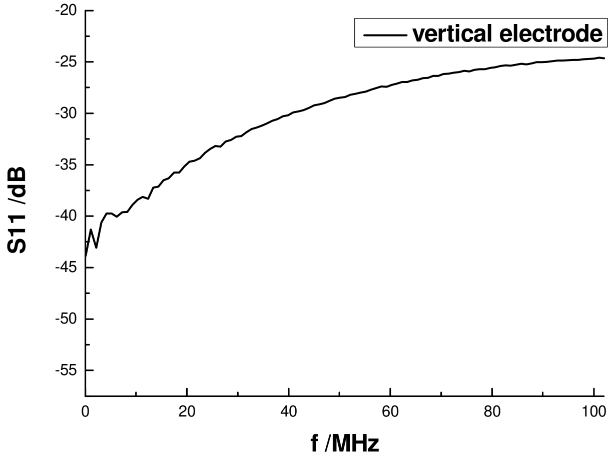
The above verification is based on hypothesis that only 20V amplitude of sinusoidal signal is set on the electrodes and corresponding power is only 4W. Amplifier model AR75A250A used in the experiment can output maximum output power of 75W and fully meet the job requirements.

Design of the stripline transverse quadrupole kicker









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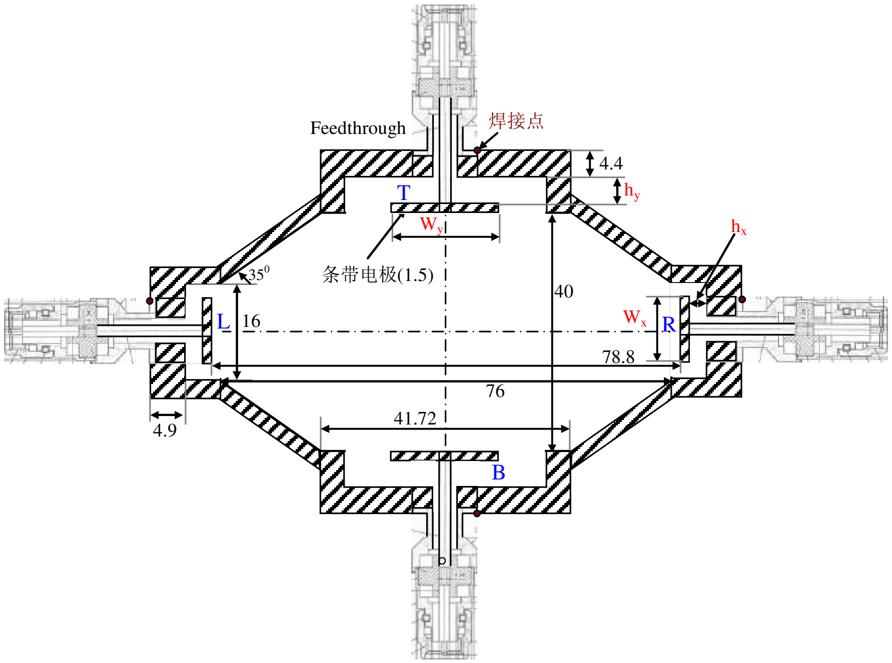
Design of the stripline BPM



The **cross section** of the HLS II stripline BPM

- Since the signal measured from BPM is filtered by Libera Brilliance, which has a bandwidth of 10MHz at **center frequency *f* of 408MHz**, in order to **make the induced signal amplitude largest**, the stripline length was designed to be 183.8 mm.

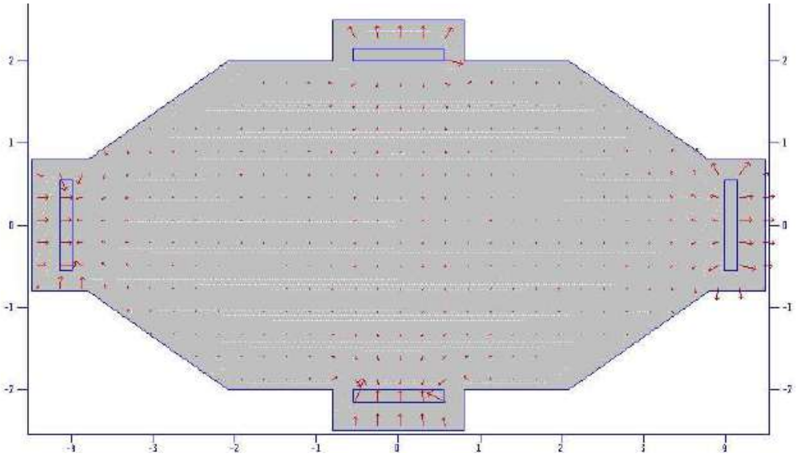
$$l = \frac{c}{4f} = 183.8\text{mm}$$

- Refer to electrode thickness of the HLS II linear accelerator stripline BPM , electrode thickness of the stripline BPM is:

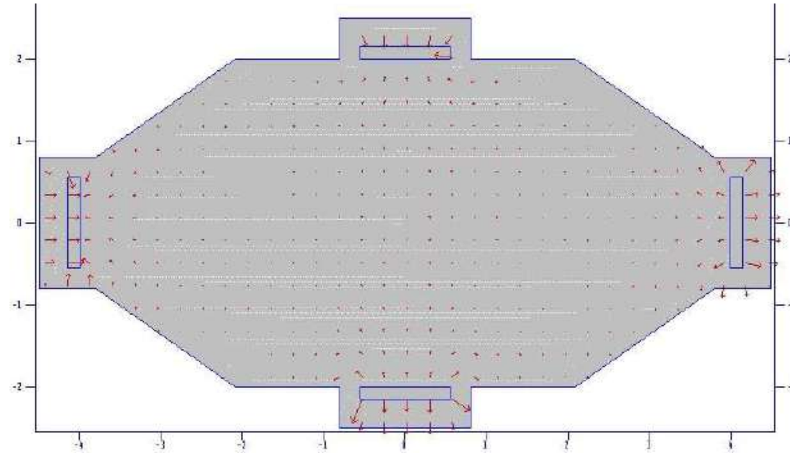
$$t = 1.5\text{mm}$$

Refer to design method for the stripline transverse quadrupole kicker, Combined Parameter (hx, hy,Wx,Wy) are optimized in order to match characteristic impedances of electrodes with characteristic impedances of Feedthrough..

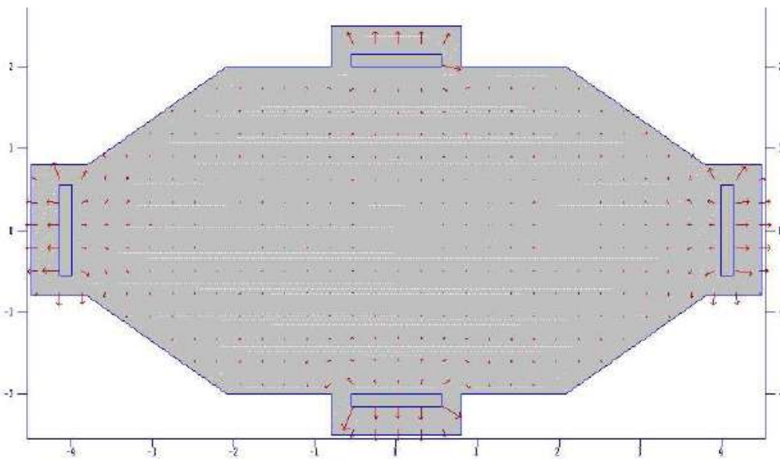
Design of the stripline BPM



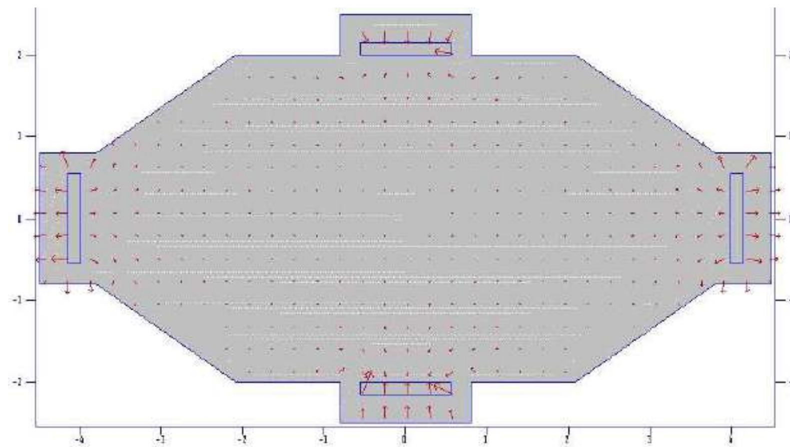
electric field for dipole1mode



electric field for dipole2 mode



electric field for sum mode



electric field for quad mode

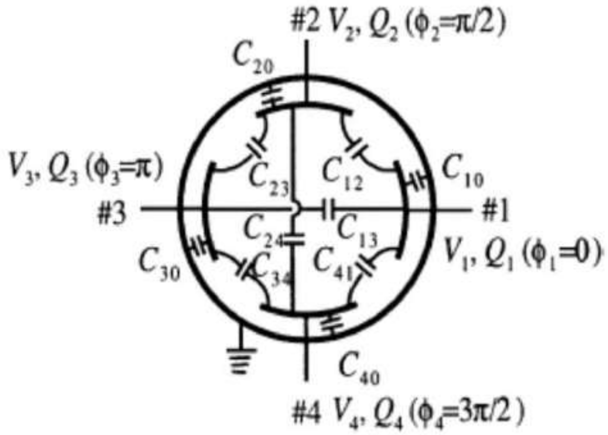
Design of the stripline BPM

final sizes of the HLS II stripline BPM

Parameter	Value /mm
l	183.8
t	1.5
h_x	4
h_y	3.5
W_x	11
W_y	11

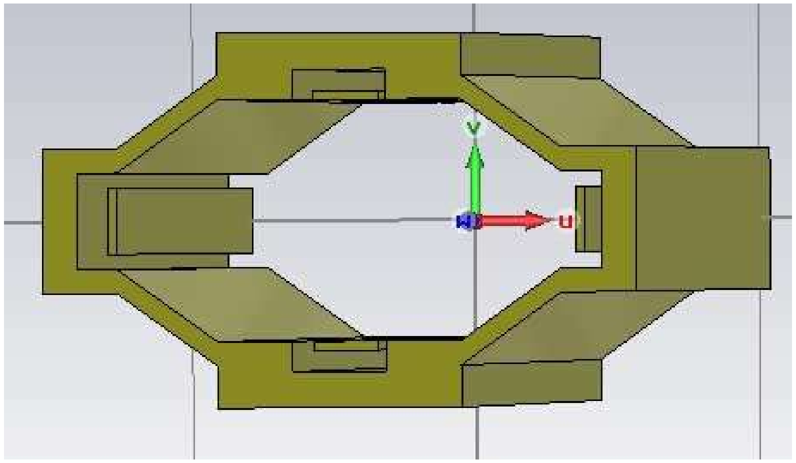
$Z_{dipole1}=Z_{dipole2}=50.18\Omega$, $Z_{sum}=50.98\Omega$, $Z_{quad}=50.47\Omega$

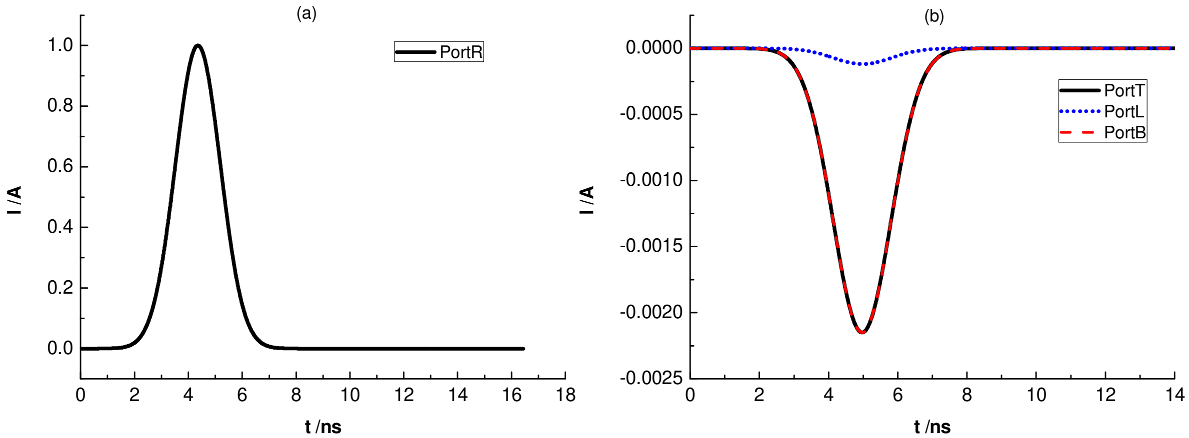
Design of the stripline BPM



$$K_{12} = C_{12} / C_{10} = Q_2 / \sum_i Q_i$$

$$K_{13} = C_{13} / C_{10} = Q_3 / \sum_i Q_i$$





K_{RL}=0.01% **K_{TB}=0.93%**

K_{RT}=K_{RB}=0.21%

Coupling coefficients of the stripline BPM were very small and are no more than 1%.
Coupling influence can be neglected.

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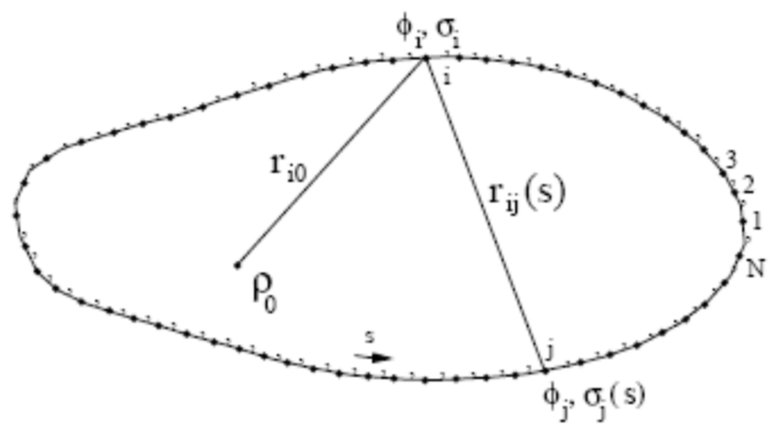
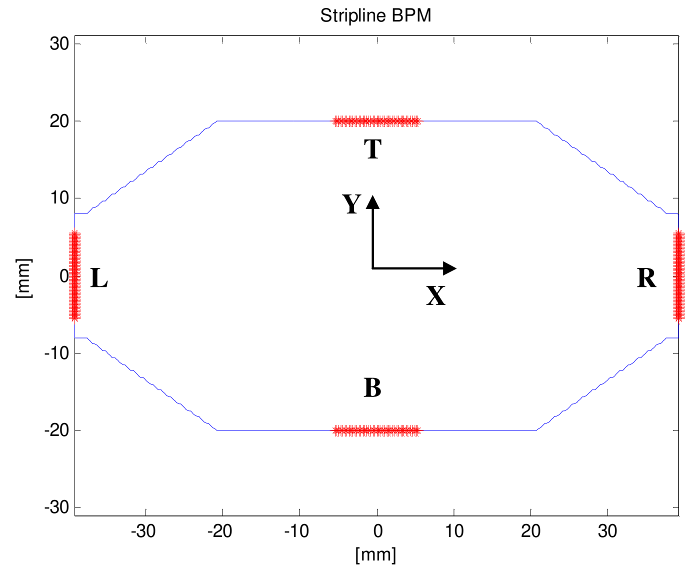
Calibration of the stripline BPM

Simulated calibration:

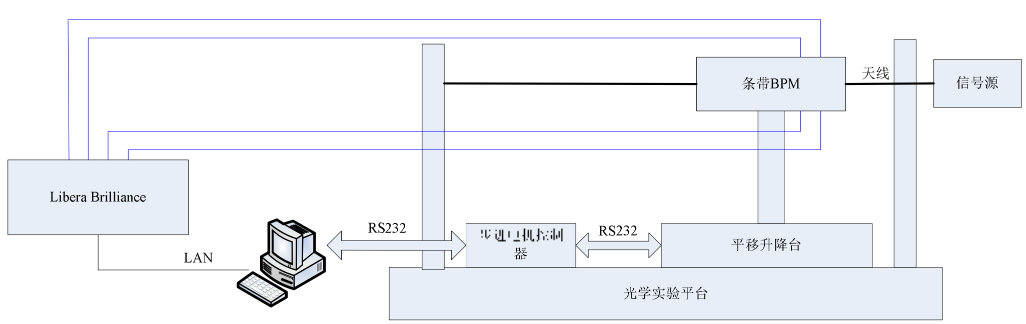
Stripline BPM is modeled using **boundary element method**[3, 4] by Matlab code

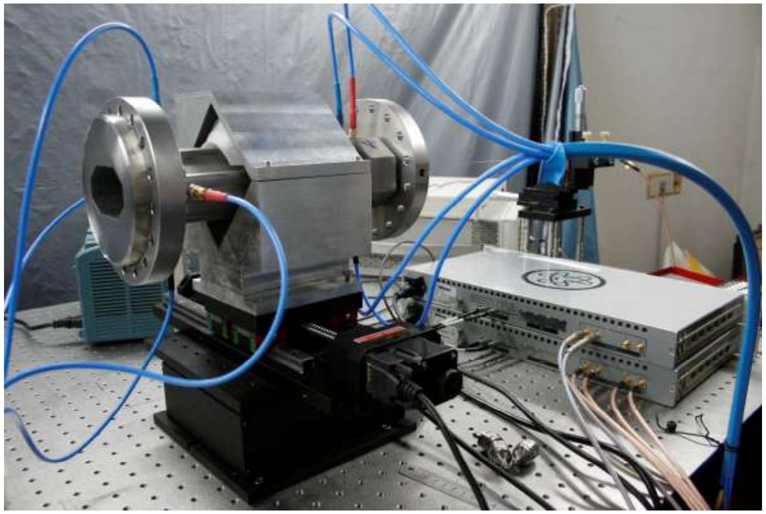




Offline Calibration:

Stripline BPM is calibrated with **wire scanning method**





Calibration of the stripline BPM

1. normalized position (U, V)

- difference/sum method:

$$U_{\Delta/\Sigma} = \frac{V_R - V_L}{V_R + V_L} = \boxed{S_{x,\Delta/\Sigma}} \cdot x$$

$$V_{\Delta/\Sigma} = \frac{V_T - V_B}{V_T + V_B} = \boxed{S_{y,\Delta/\Sigma}} \cdot y$$

- log-ratio method:

$$U_{\ln} = \ln \frac{V_R}{V_L} = \boxed{S_{\ln,x}} \cdot x$$

$$V_{\ln} = \ln \frac{V_T}{V_B} = \boxed{S_{\ln,y}} \cdot y$$

measuring beam position

2. sum signal(SUM):

$$SUM = V_R + V_L + V_T + V_B$$

measuring beam current

3. transverse quadrupole signal(Q):

transverse quadrupole component

- difference/sum method:

$$Q_{\Delta/\Sigma} = \frac{(V_R + V_L) - (V_T + V_B)}{(V_R + V_L) + (V_T + V_B)} = Q_0 + \boxed{S_{Q,\Delta/\Sigma}} \cdot (\sigma_x^2 - \sigma_y^2 + x^2 - y^2)$$

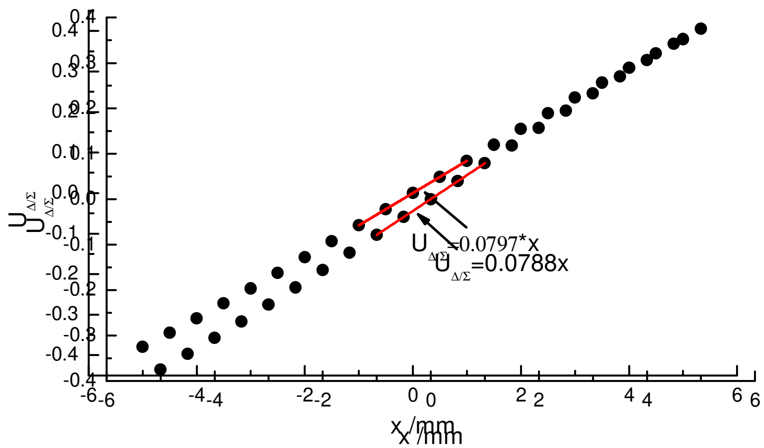
- log-ratio method:

$$Q_{\ln} = \ln \frac{V_R V_L}{V_T V_B} = Q_0 + \left[\boxed{S_{Q,\ln}} \left(\sigma_x^2 - \sigma_y^2\right) + k\left(\sigma_x^2 - \sigma_y^2\right)\right]$$

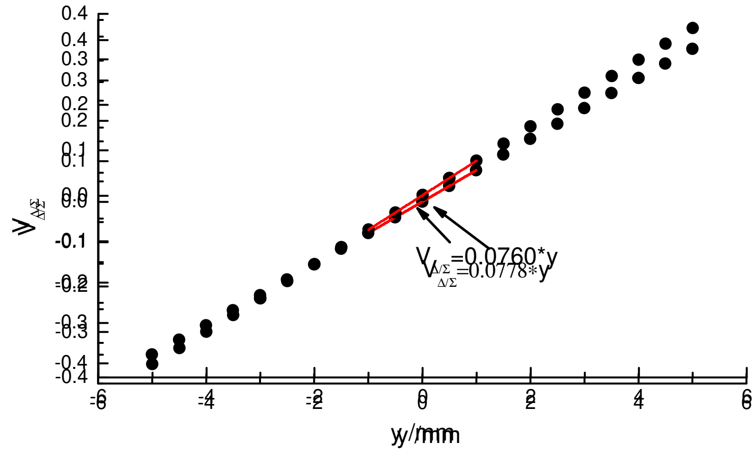
measuring beam transverse quadrupole oscillation, transverse dimension, etc

Calibration of the stripline BPM

Position sensitivities-Simulated calibration
Position sensitivities-Offline calibration

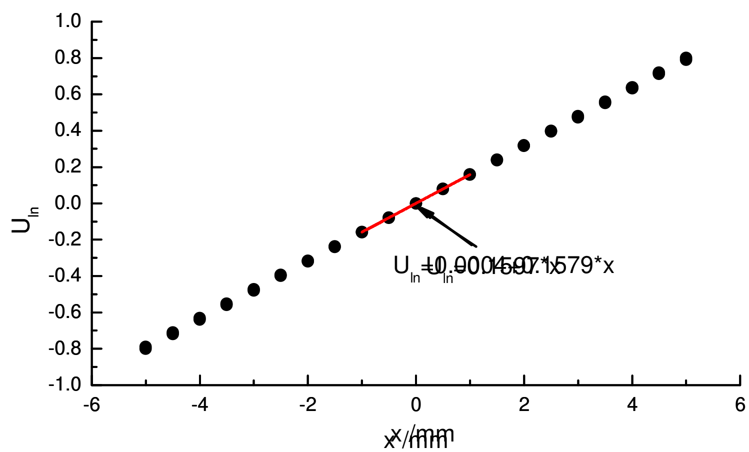


horizontal direction

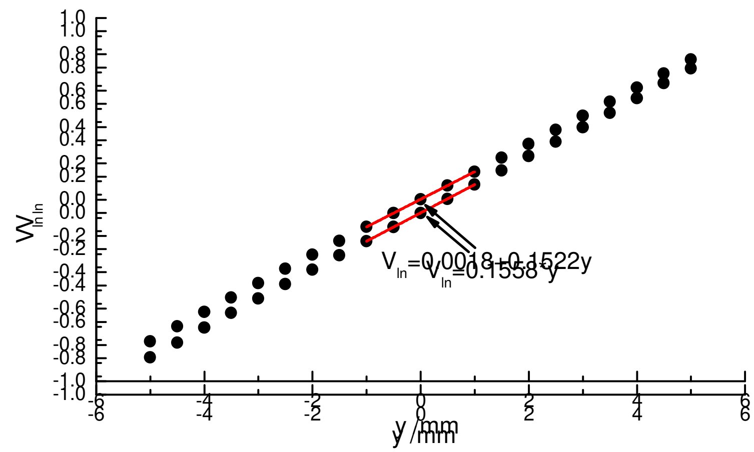


vertical direction

Sensitivity curves calculated with difference/sum method



horizontal direction
horizontal direction



vertical direction
vertical direction

Sensitivity curves calculated with log-ratio method
Sensitivity curves calculated with log-ratio method

条带BPM的标定

Position sensitivities comparison between simulated calibration andoffline calibration with difference/sum method

Position sensitivities	Simulated calibration	Offline calibration
S_x /mm^{-1}	0.0797	0.0788 /1.13%
S_y /mm^{-1}	0.0778	0.0760 /2.31%

Position sensitivities comparison between simulated calibration andoffline calibration with log-ratio method

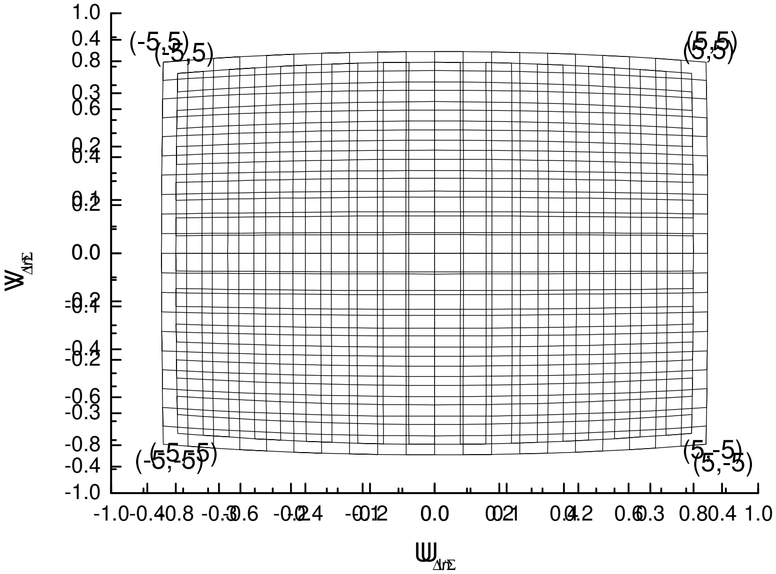
位置灵敏度	模拟仿真值	离线标定值
S_x /mm^{-1}	0.1597	0.1579 /1.13%
S_y /mm^{-1}	0.1558	0.1522 /2.31%

Whether difference/sum ratio(Δ/Σ) method or log-ratio method is used, errors do not exceed 3% compared with simulation results.

Calibration of the stripline BPM

Simulated calibration - difference/sum method

Offline calibration - difference/sum method

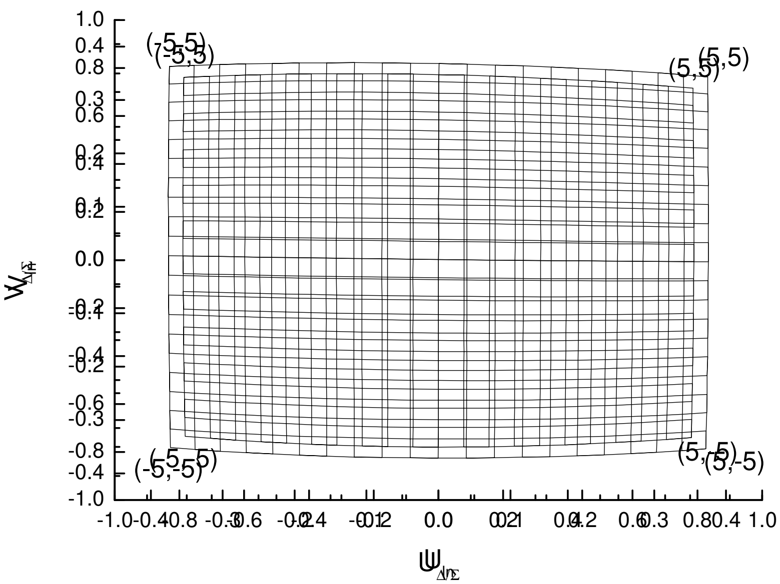


$$\begin{cases} x = 6.2627U_{ln} - 0.0155U_{ln}^3 + 0.0689U_{ln}V_{ln}^2 \\ y = 6.4190V_{ln} + 0.5884U_{ln}^2V_{ln} - 0.2200U_{ln}^3 \end{cases}$$

$$\begin{cases} x = 12.5076U_{\Delta/\Sigma} + 4.5229U_{\Delta/\Sigma}^3 + 0.6202U_{\Delta/\Sigma}V_{\Delta/\Sigma}^2 \\ y = 12.8177V_{\Delta/\Sigma} + 5.3315U_{\Delta/\Sigma}^2V_{\Delta/\Sigma} + 2.7477V_{\Delta/\Sigma}^3 \end{cases}$$

Offline calibration - log-ratio method

Simulated calibration - log-ratio method



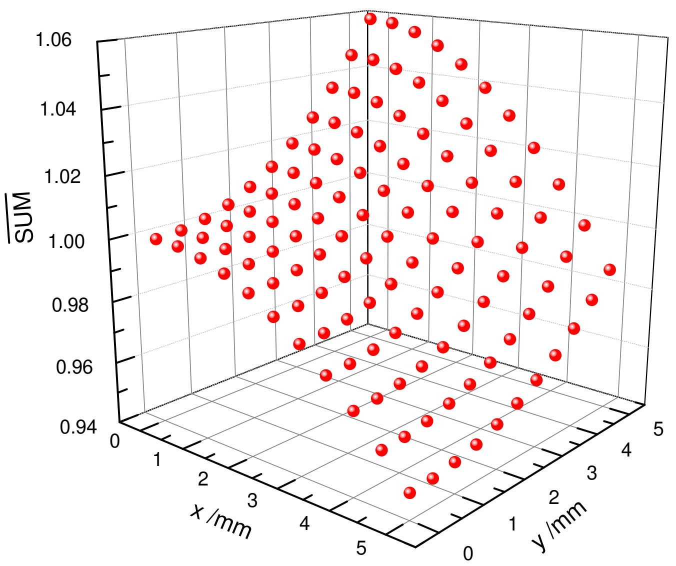
$$\begin{cases} x = -0.0034 + 6.3342U_{ln} - 0.0024V_{ln} + 0.0003U_{ln}^2 - 0.0239U_{ln}V_{ln} + 0.0011V_{ln}^2 \\ \quad + 0.0009U_{ln}^3 + 0.0055U_{ln}^2V_{ln} + 0.0674U_{ln}V_{ln}^2 - 0.0060V_{ln}^3 \\ y = -0.0133 + 0.1003U_{ln} + 6.5624V_{ln} - 0.0340U_{ln}^2 + 0.1082U_{ln}V_{ln} + 0.0484V_{ln}^2 \\ \quad - 0.0011U_{ln}^3 + 0.5207U_{ln}^2V_{ln} + 0.0084U_{ln}V_{ln}^2 - 0.2093V_{ln}^3 \end{cases}$$

$$\begin{cases} x = -0.0034 + 12.6510U_{\Delta/\Sigma} - 0.0046V_{\Delta/\Sigma} + 0.0006U_{\Delta/\Sigma}^2 - 0.1013U_{\Delta/\Sigma}V_{\Delta/\Sigma} + 0.0051V_{\Delta/\Sigma}^2 \\ \quad + 4.7161U_{\Delta/\Sigma}^3 + 0.0495U_{\Delta/\Sigma}^2V_{\Delta/\Sigma} + 0.6045U_{\Delta/\Sigma}V_{\Delta/\Sigma}^2 - 0.0570V_{\Delta/\Sigma}^3 \\ y = -0.0133 + 0.2004U_{\Delta/\Sigma} + 13.1075V_{\Delta/\Sigma} - 0.1492U_{\Delta/\Sigma}^2 + 0.4593U_{\Delta/\Sigma}V_{\Delta/\Sigma} + 0.2102V_{\Delta/\Sigma}^2 \\ \quad + 0.0629U_{\Delta/\Sigma}^3 + 4.7007U_{\Delta/\Sigma}^2V_{\Delta/\Sigma} + 0.0701U_{\Delta/\Sigma}V_{\Delta/\Sigma}^2 + 2.9285V_{\Delta/\Sigma}^3 \end{cases}$$

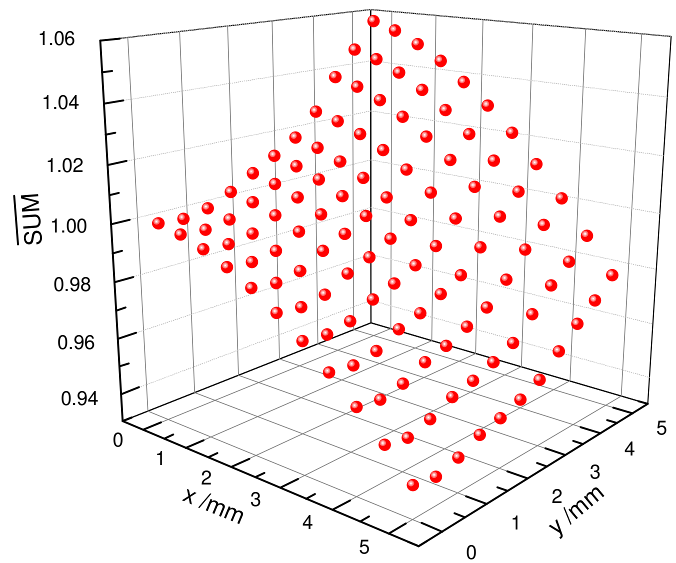
Calibration of the stripline BPM

Sum signal calibration

- **Simulated calibration**



- **Offline calibration**

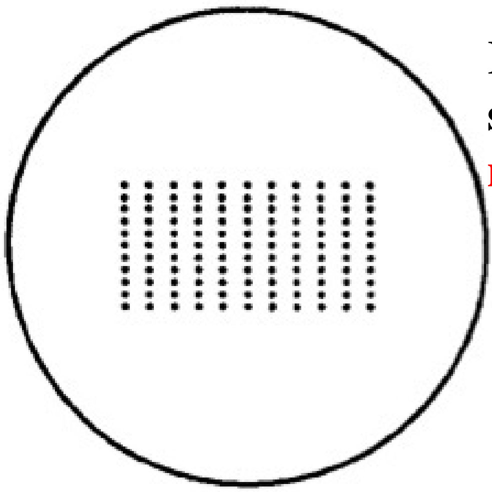


the normalized sum signal from (0 mm, 0 mm) to (5 mm, 5 mm) is no more than **±6%,** the normalized sum signal can be used to measure beam current.

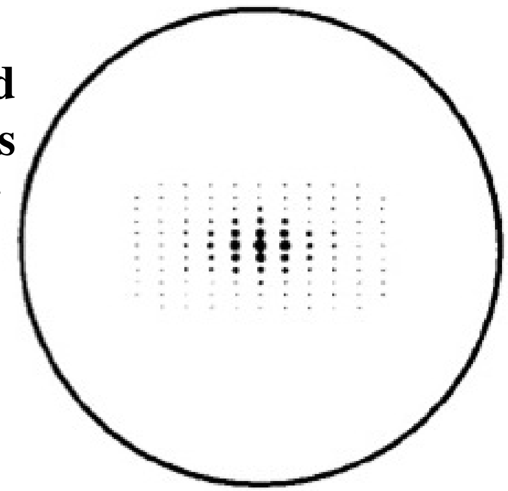
$$\overline{SUM} = 1.0010\text{-}0.0028x\text{-}0.0002y\text{-}0.0021x^2\text{-}0.0001xy+0.0022y^2$$

Calibration of the stripline BPM

The shape of bunch in the HLS II storage ring is Gaussian distribution, in order to calibrate transverse quadrupole signal of the gaussian bunch, The gaussian weighted method of a two-dimensional grid structure is used to simulate the gaussian bunch[5].



Reference point is selected, electrode induced signal generated by surrounding point is multiplied by the weight A and added together



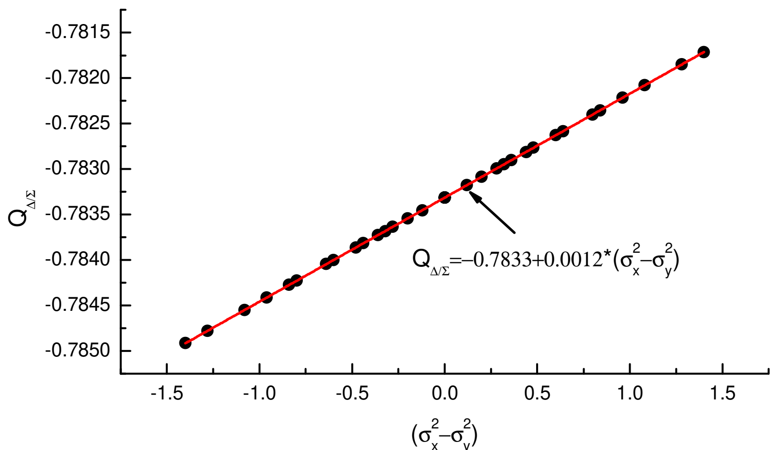
$$A=\frac{1}{2\pi\sigma_x\sigma_y}\times\exp\left(-\frac{1}{2}\left((\frac{x-x_0}{\sigma_x})^2+(\frac{y-y_0}{\sigma_y})^2\right)\right)$$

antenna width and **grid spacing** in offline calibration have influence on the result, through analysis, **0.2mm antenna diameter** and **0.2mm grid spacing** are selected to have little effect

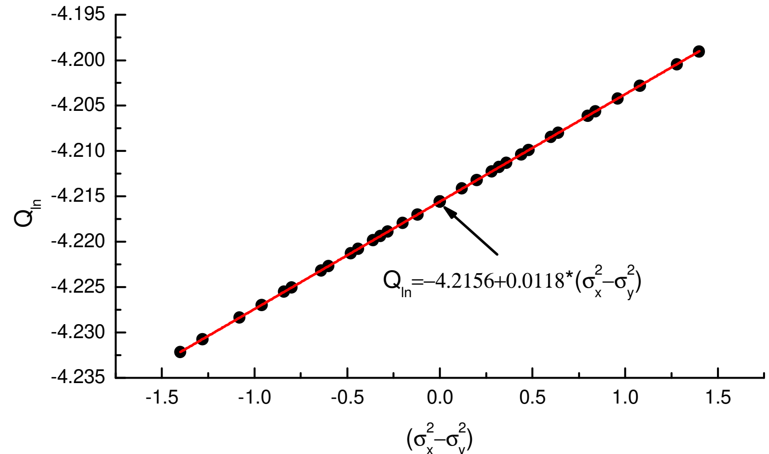
Calibration of the stripline BPM

Maintaining bunch same position, changing the transverse dimension

Bunch position (x_0, y_0) is set to be (0, 0), transverse dimension (σ_x, σ_y) changes from (0.2mm, 0.2mm) to (1.2mm, 1.2mm) and step length is 0.2mm. The following graphs show transverse quadrupole signal varying with (σ_x^2-σ_y^2)

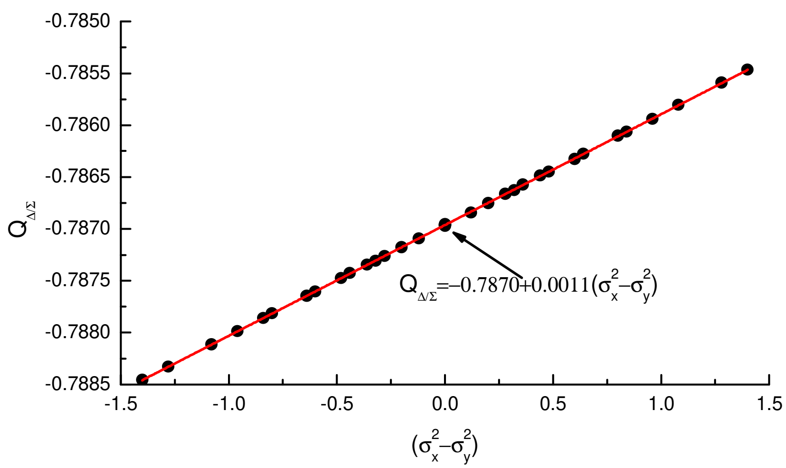


difference/sum method

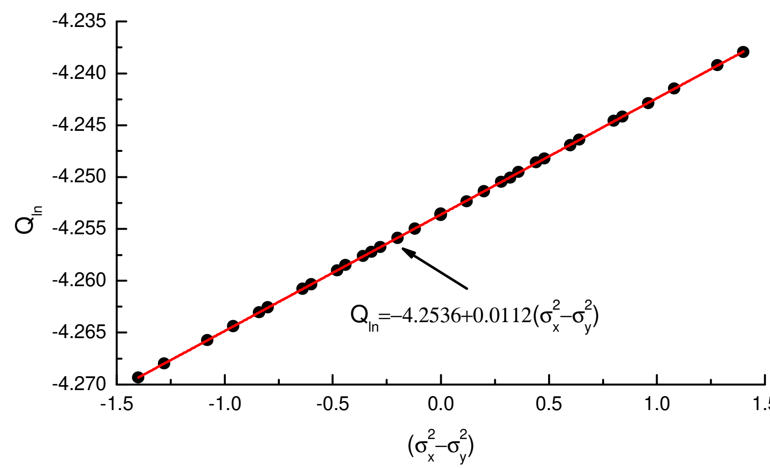


log-ratio method

Simulated calibration



difference/sum method



log-ratio method

Offline calibration

Calibration of the stripline BPM

Transverse quadrupole signal sensitivities comparison calculated with difference/sum method and log-ratio method

Transverse quadrupole signal sensitivity	simulated calibration	offline calibration
$S_{Q,\,\Delta/\Sigma}$	0.0012	0.0011 /8.3%
$S_{Q,\,\ln}$	0.0118	0.0112 /5.1%

Changing bunch position and transverse dimension and Polynomial formulas are obtained by fitting transverse quadrupole signal with variables (x_0, y_0, σ_x, σ_y)

Bunch position (x_0, y_0) changes from (0.2mm, 0.2mm) to (1.2mm, 1.2mm). Transverse dimension (σ_x, σ_y) changes from (0.2mm, 0.2mm) to (1.2mm, 1.2mm) and step length is 0.2mm.

$$Q_{\Delta/\Sigma}=-0.7870+0.0011\left(\sigma_x^2-\sigma_y^2\right)+0.0011x_0^2-0.0011y_0^2+0.0006x_0+0.0004y_0$$

$$Q_{\ln}=-4.2537+0.0053x_0^2-0.0057y_0^2+0.0111\sigma_x^2-0.0112\sigma_y^2+0.0066x_0$$
$$+0.0041y_0+0.0002\sigma_x+0.0001x_0y_0+0.0001x_0\sigma_y+0.0001\sigma_x\sigma_y$$

$(\sigma_x^2-\sigma_y^2)$

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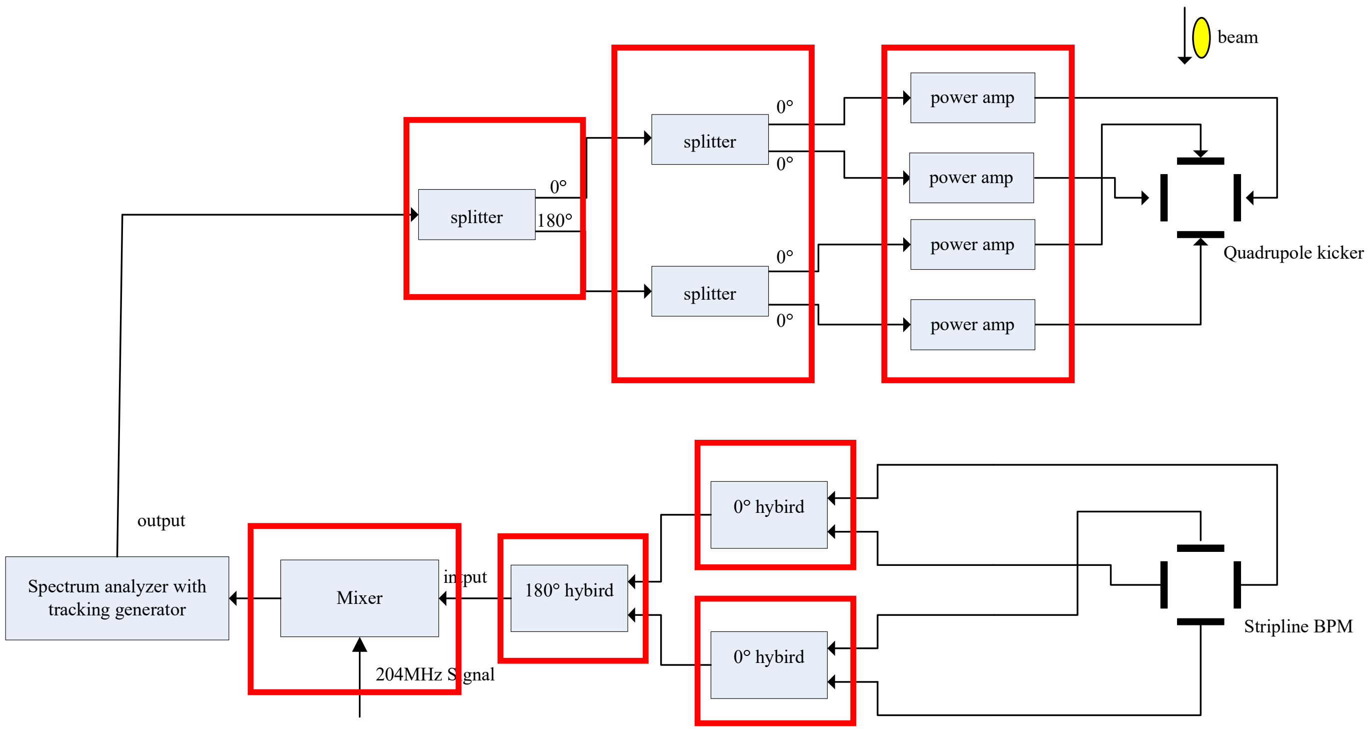
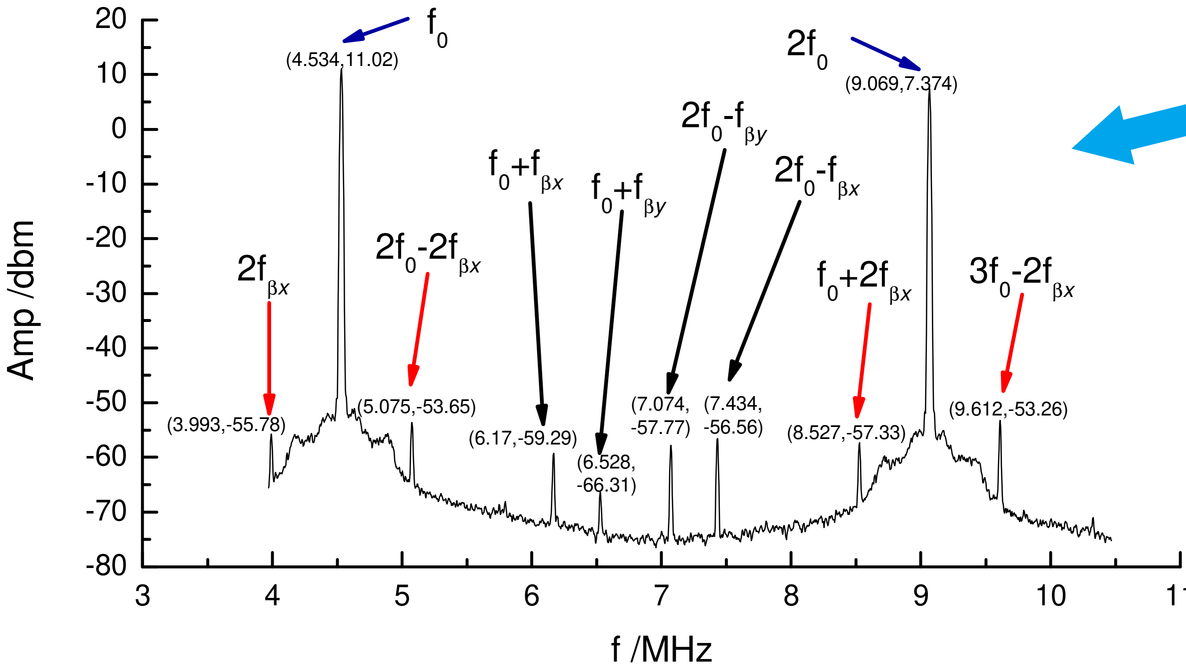
Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring



As the beam is never perfectly centred neither in the kicker, some other frequency lines appear at the dipole mode frequencies. In order to accurately measure the spectral response of sweep excitation, **the horizontal and vertical feedback system are close** and longitudinal feedback system is still open.

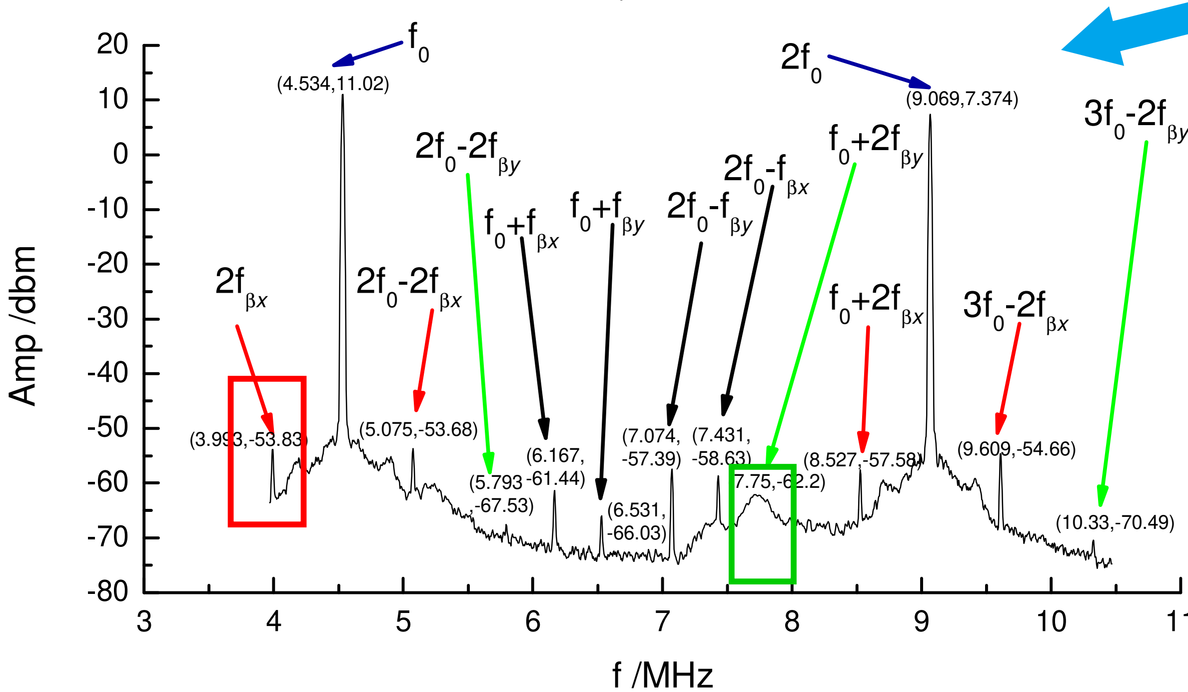
Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring



- **Multi-bunch**, beam current is 114.67mA, **turn off excitation**

Corresponding transverse oscillation spectrum peaks:

- **Horizontal dipole oscillation**
- **Vertical dipole oscillation**
- **Horizontal quadrupole oscillation**



- **Multi-bunch**, beam current is 114.67mA, **turn on excitation**

Corresponding transverse oscillation spectrum peaks:

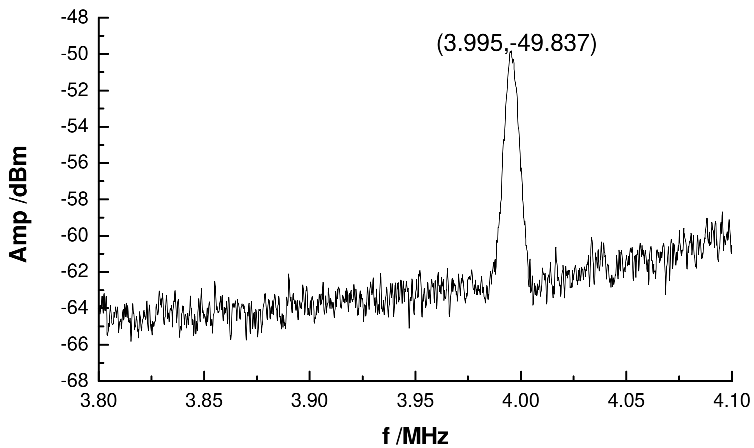
- **Horizontal dipole oscillation**
- **Vertical dipole oscillation**
- **Horizontal quadrupole oscillation**
- **Vertical quadrupole oscillation**

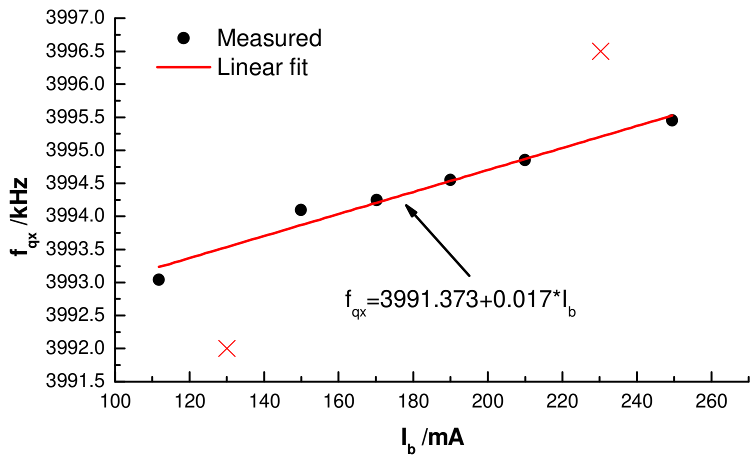
Beam is excited at frequencies close to $2f_{\beta x}$ and $f_0+ 2f_{\beta y}$ in order to induce **horizontal and vertical quadrupole oscillation**

Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring

- **Multi-bunch**, horizontal direction, **turn off excitation**

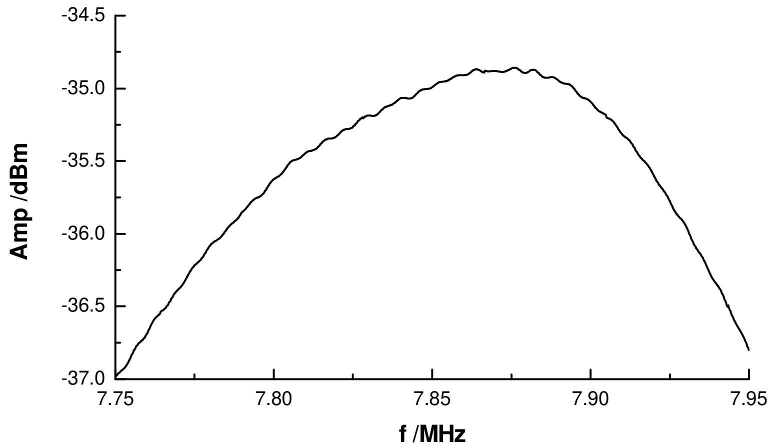
Beam current is 249.55mA

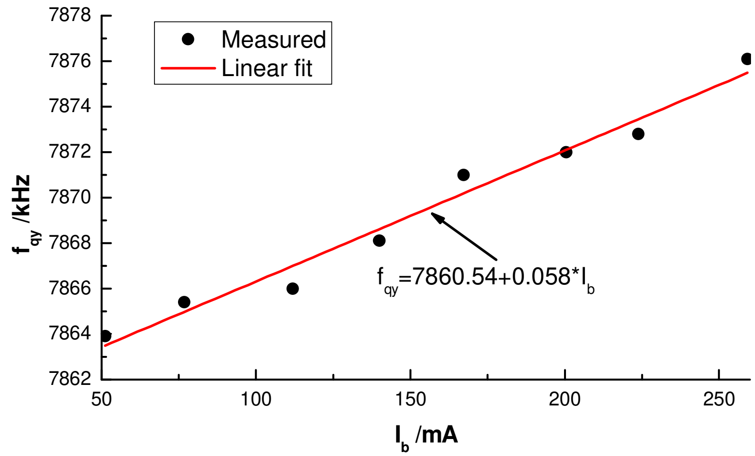




- **Multi-bunch**, vertical direction, **turn on excitation**

Beam current is 259.12mA

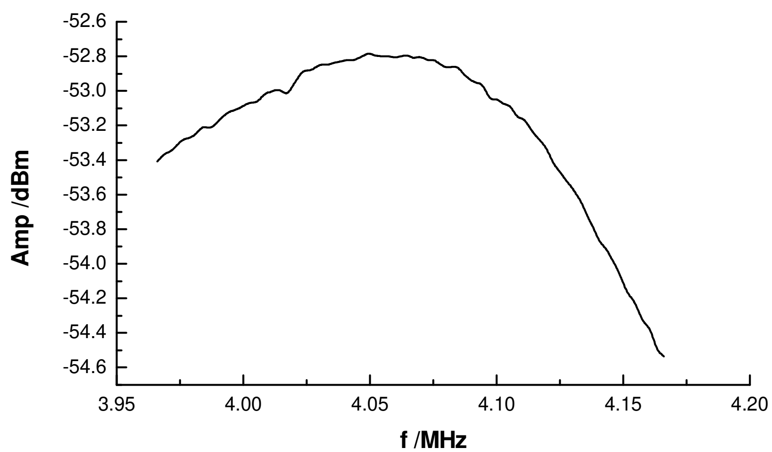


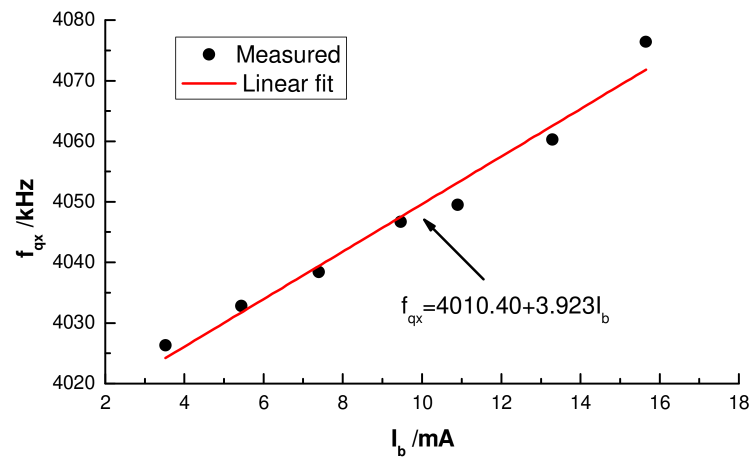


Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring

➢**Single bunch**, horizontal direction, **turn on excitation**

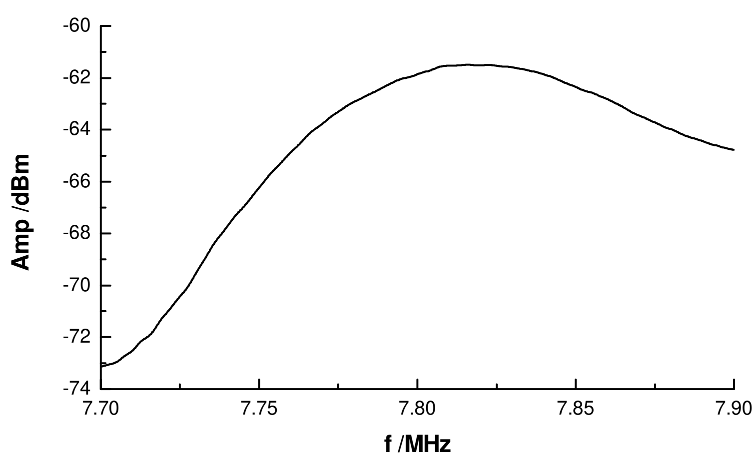
Beam current is 11.90mA

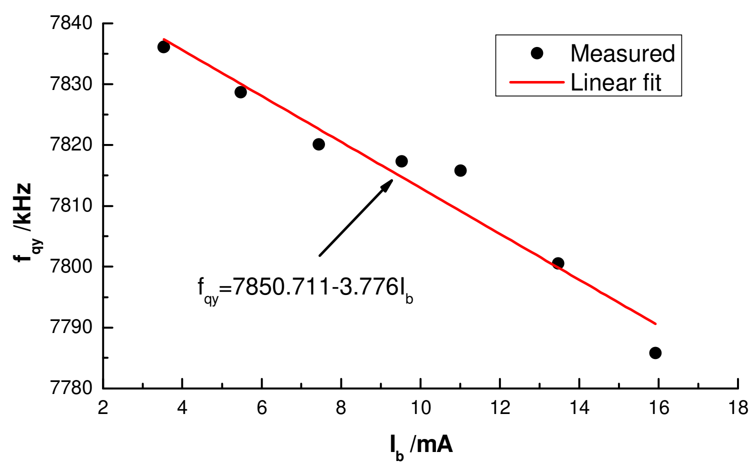




➢ **Single bunch**, vertical direction, **turn on excitation**

Beam current is 11.01mA

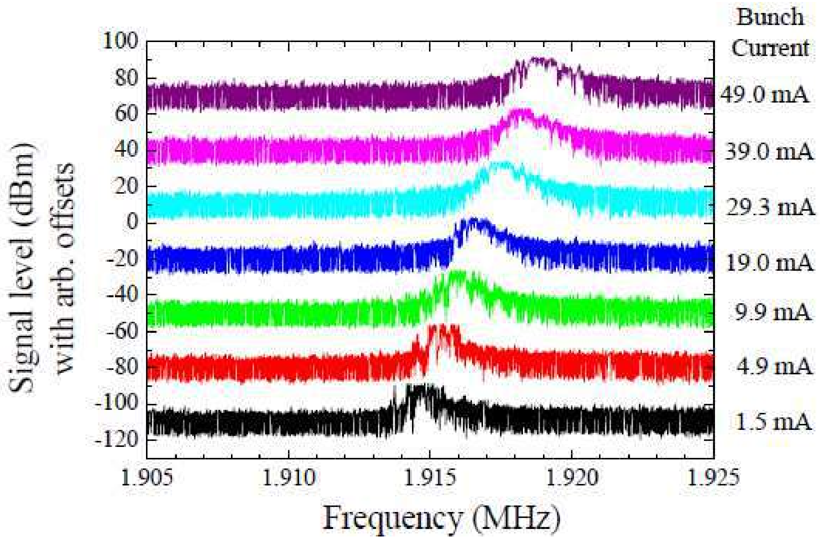


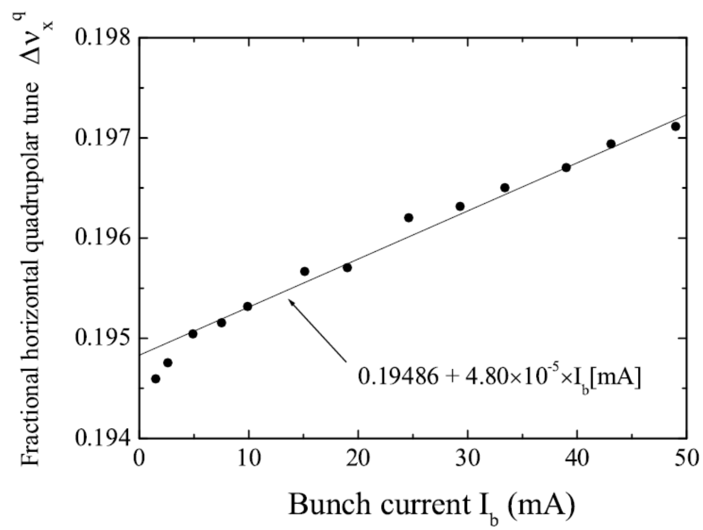


Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring

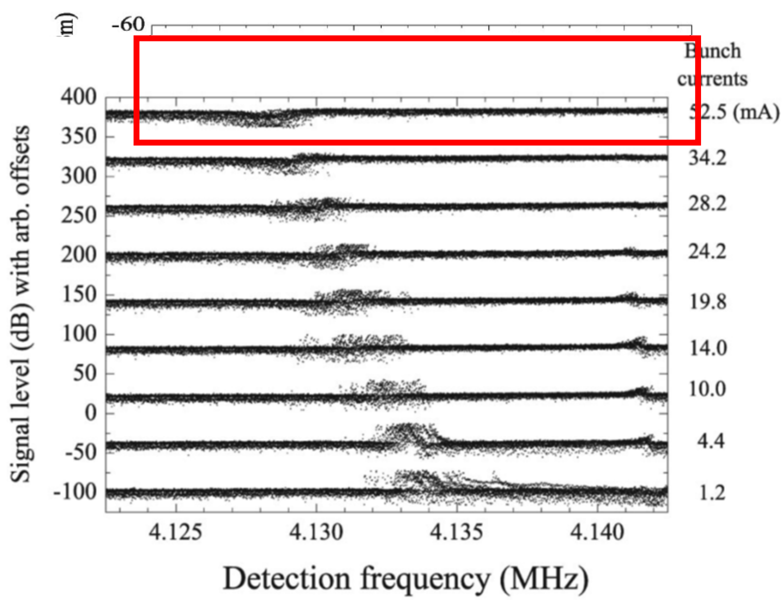
Refer to reference[6], the transverse quadrupole oscillation is excited and detected in the KEK Photon Factory storage ring, the results are as follows:

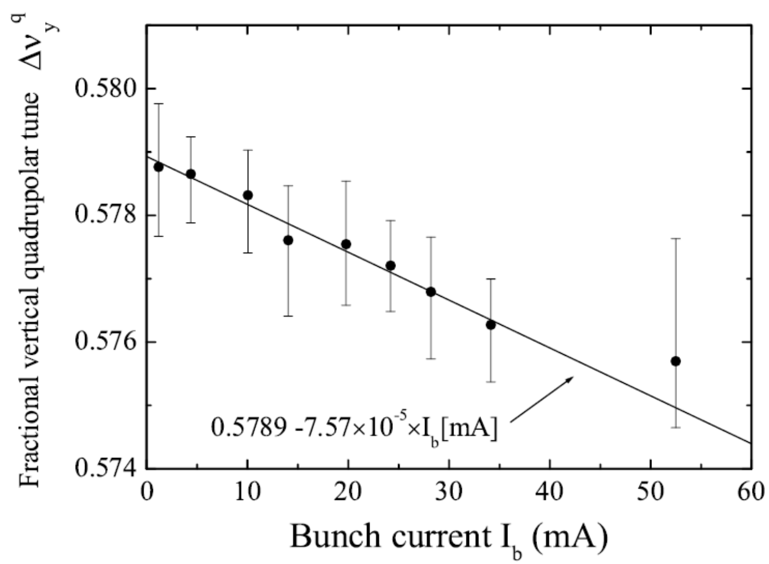
Single bunch, horizontal direction, **reference frequency is $2f_{\beta x}$**





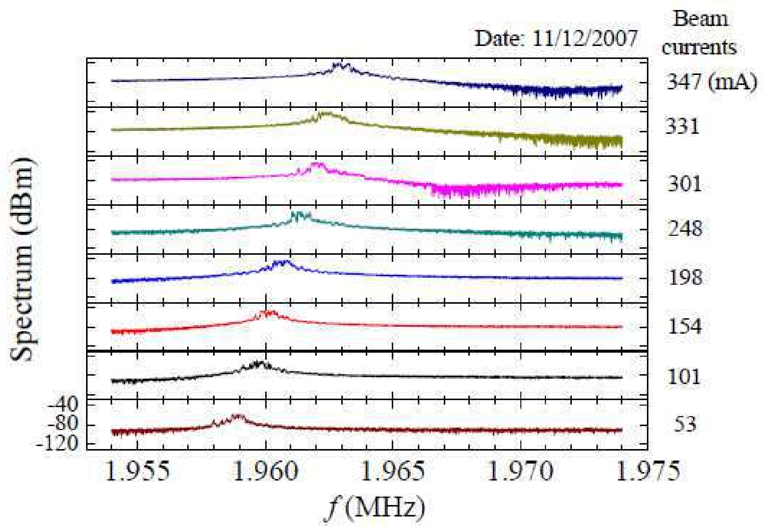
Single bunch, vertical direction, **reference frequency is $3f_0 + 2f_{\beta y}$**

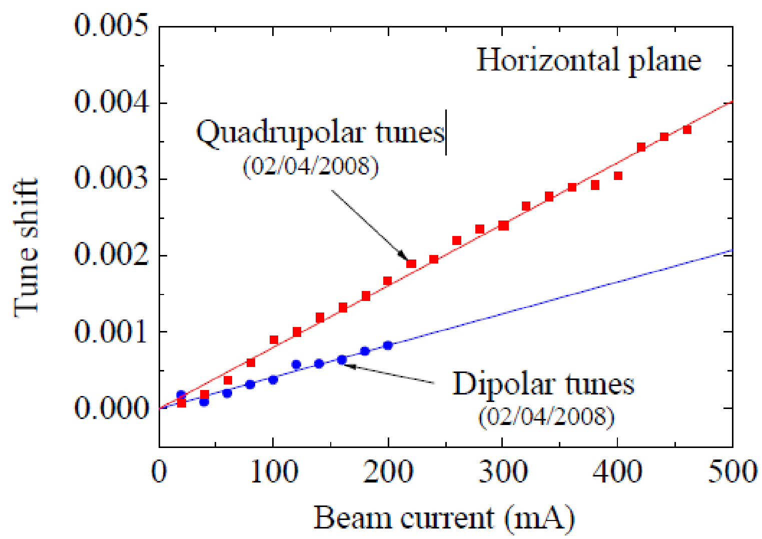




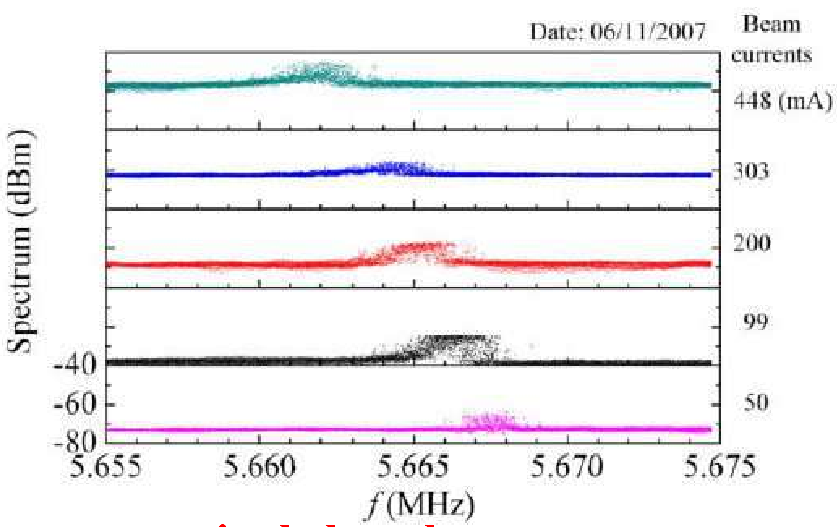
Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring

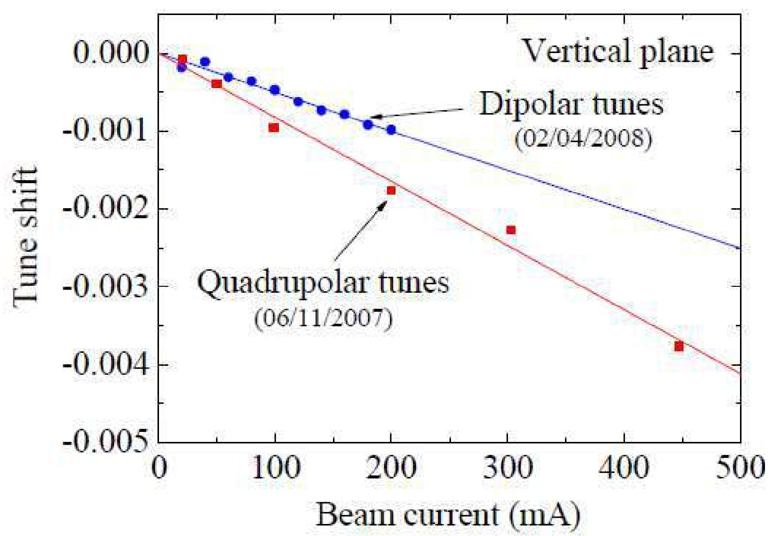
Multi-bunch, horizontal direction, **reference frequency is $2f_{\beta x}$**





Multi-bunch, vertical direction, **reference frequency is $3f_0 + 2f_{\beta y}$**





As the same as single bunch, every measurement result is 10 times superimposed

Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring

Summary of the measured quadrupole tune
shifts under single-bunch and multi-bunch operation

oscillation mode	single-bunch /kHz/mA	multi-bunch /kHz/mA
horizontal quadrupole oscillation	3.923	0.017
vertical quadrupole oscillation	-3.776	0.058

Some studies have shown that short-range transverse quadrupole wakefield has influence on transverse quadrupole oscillation frequency under single bunch[6], so the effect of short-range transverse quadrupole wakefield on transverse quadrupole oscillation frequency under single bunch in the HLS II storage ring is analyzed.

Excitation and detection of a transverse quadrupole mode beam oscillation in the HLS II storage ring

$$\delta\nu_x^q = 2\delta\nu_x^{inc}$$
$$\delta\nu_y^q = 2\delta\nu_y^{inc}$$

$$\frac{\delta\nu_x^{inc}}{I_b} = 0.4325\mathrm{A}^{-1}$$
$$\frac{\delta\nu_y^{inc}}{I_b} = \text{-}0.4165\mathrm{A}^{-1}$$

$$\delta\nu_x^{inc} = -\frac{q_b e}{4\pi E}\sum_j \beta_x(s_j)k_{x,j}^{(2)}$$
$$\delta\nu_y^{inc} = -\frac{q_b e}{4\pi E}\sum_j \beta_y(s_j)k_{y,j}^{(2)}$$

$$\boxed{\begin{aligned}\sum_j \beta_x(s_j)k_{x,j}^{(2)} &= -1.971*10^{16}\,\mathrm{V/C}\\ \sum_j \beta_y(s_j)k_{y,j}^{(2)} &= 1.898*10^{16}\,\mathrm{V/C}\end{aligned}}$$

$$\bar{\beta}_x = \frac{1}{L}\oint_L \beta_x ds = 5.93\mathrm{m}$$
$$\bar{\beta}_y = \frac{1}{L}\oint_L \beta_y ds = 6.25\mathrm{m}$$

$$\boldsymbol{k_x^{(2)} = -3324\mathrm{VpC^{-1}m^{-1}}}$$
$$\boldsymbol{k_y^{(2)} = 3037\mathrm{VpC^{-1}m^{-1}}}$$

The above transverse quadrupole kick factors are reasonable regarding the following points.

1. the signs of $k_x^{(2)}$ and $k_y^{(2)}$ are opposite, which indicate focusing in the horizontal direction and defocusing in the vertical direction, are consistent with theory;
2. $k_x^{(2)}/k_y^{(2)}$=-1.09 is close to theoretical value of -1.

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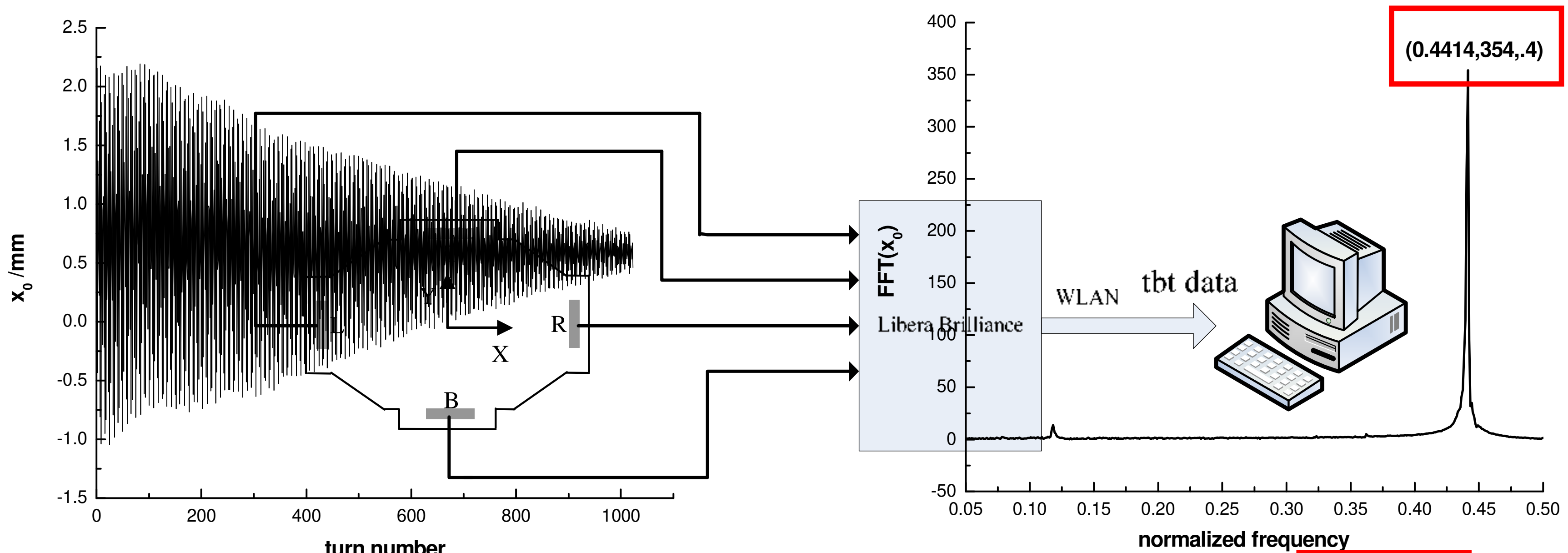
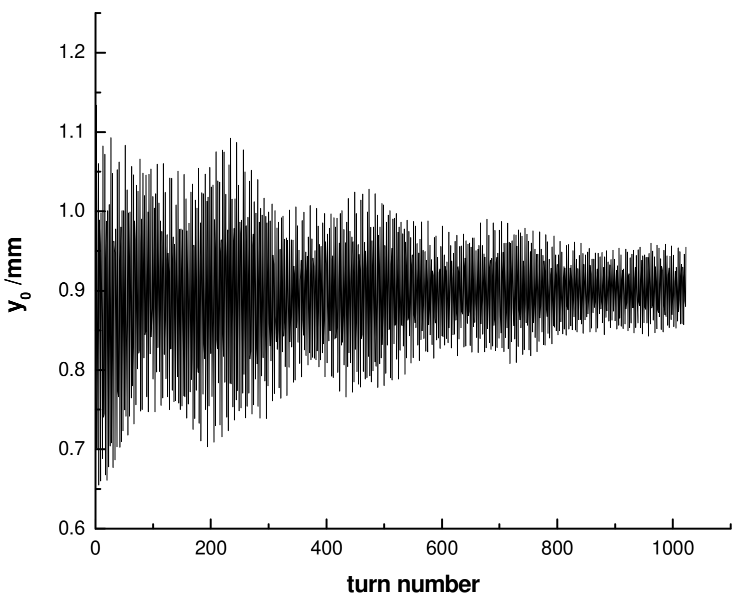
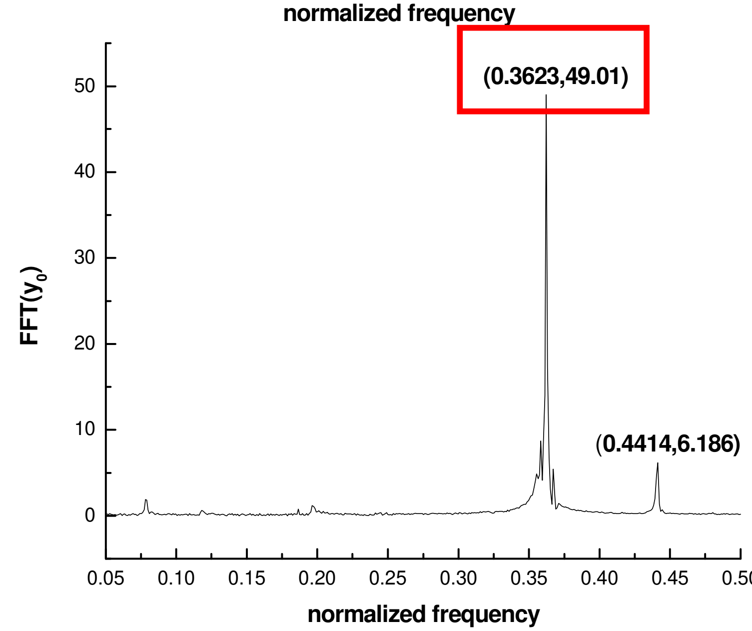
Measurement of injected beam transverse quadrupole oscillation

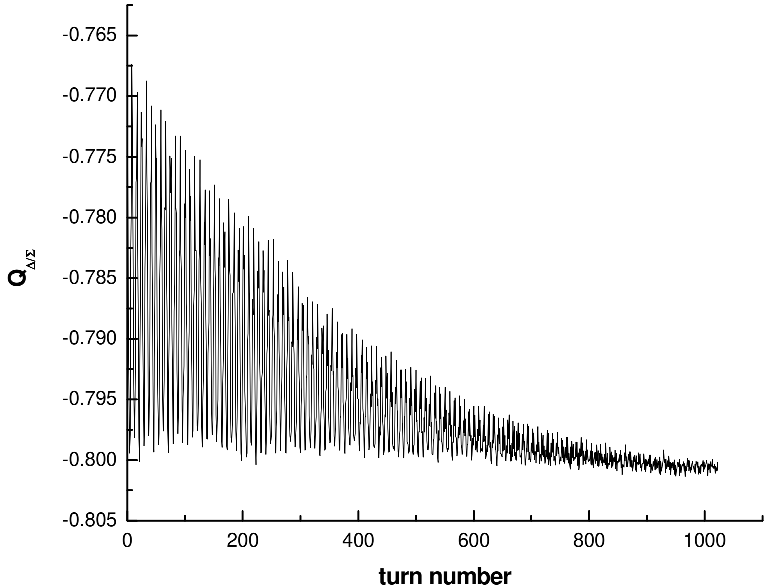
If the beam injected in a machine is not matched to the receiving machine in terms of **Twiss values**, **dispersion**, its transverse quadrupole oscillation will appear as a function of machine turn

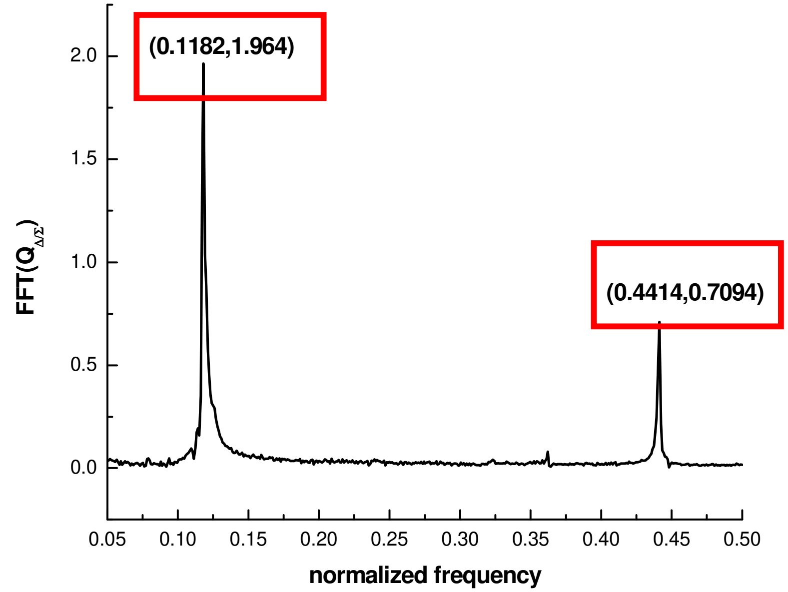


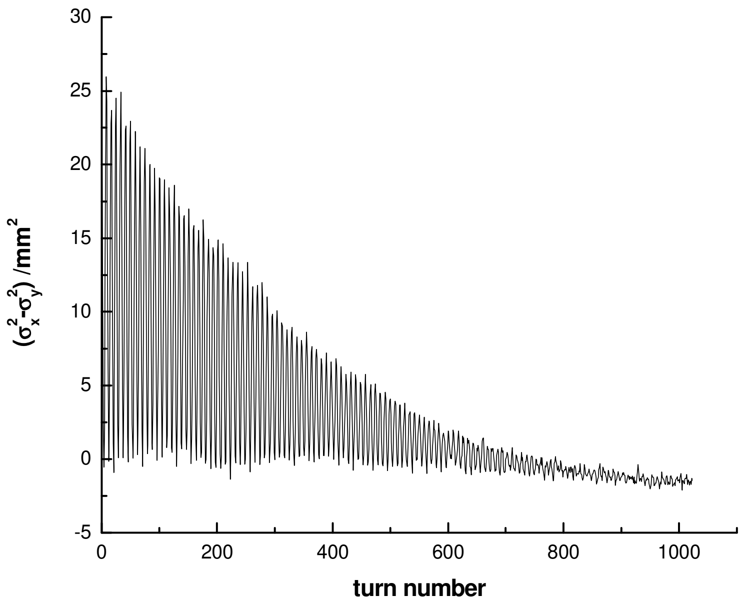


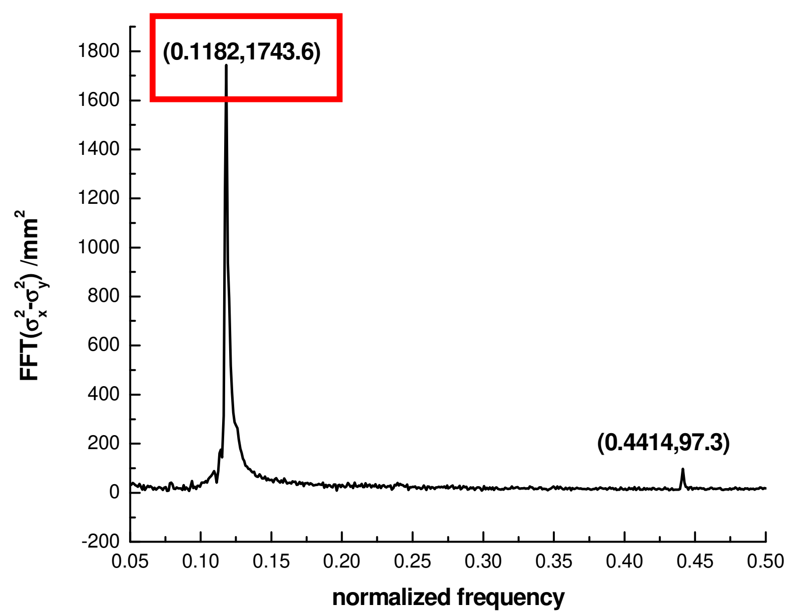


Measurement of injected beam transverse quadrupole oscillation









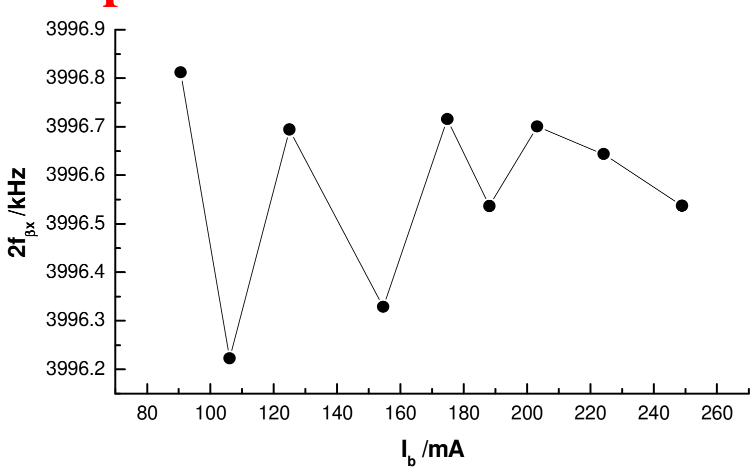
Measurement of injected beam transverse quadrupole oscillation

The oscillation corresponding to normalized frequency $\Delta\nu_Q = 0.1182$ is horizontal quadrupole oscillation. The reasons are as follows:

① The relationship between normalized frequency $\Delta\nu_Q = 0.1182$ and normalized horizontal dipole oscillation frequency $\Delta\nu_x$=0.4414 satisfies $\Delta\nu_Q \approx (1-2\Delta\nu_x)$, there is 0.001 difference due to the space charge effect and short-range transverse quadrupole wakefield;

② When excluding the horizontal dipole oscillation, the spectrum peak corresponding to normalized frequency $\Delta\nu_Q = 0.1182$ is still evident, which ruling out the possibility that this oscillation is harmonic component of horizontal dipole oscillation

The relationship between the horizontal quadrupole oscillation frequency and beam current during the injection is analysed.In order to increase frequency resolution interpolation FFT method is used.



When beam is injected, the horizontal quadrupole oscillation frequency non-linearly changes with the beam current. This phenomenon is incompatible with the experiment result of excitation and dection of multi-bunch beam tansverse quadrupole oscillation. Different beam state in both cases may cause this result.

References

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3. A. Olmos, T. Günzel, et al. BPM design for the ALBA synchrotron[C]. Proceedings of EPAC06, Edinburgh, Scotland, 2006: 1190-1192
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5. Russell J S, Gilpatrick D J, et al. Characterization of beam position monitors for Measurement of Second Moment[C]. Proceedings of PAC95, Texas, USA, 1995: 2580-2582
6. Shogo Sakanaka, Toshiyuki Mitsuhashi, et al. Observation of transverse quadrupolar tune shifts in the Photon Factory storage ring[J]. PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 042801 (2005)

Thank you！