NSLS2 TRANSVERSE FEEDBACK SYSTEM DESIGN

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Abstract

A diffraction-limited storage ring like NSLS2 requires stringent beam stability. Even with careful design of vacuum component to limit the geometric impedance, due to resistive wall impedance and fast-ion effect, transverse instabilities will happen at low current (~15mA). An active transverse feedback system has been designed to cure the coupled bunch instability. The system will have less than 200 micron seconds damping time at 500mA to suppress the fast-ion instabilities, which is severe in vertical plane due to small beam size.

INTRODUCTION

Bunch-by-bunch feedback systems have been proved effective to cure the coupled bunch instabilities. Third generation light sources and particle colliders need to run at high beam current to get the desired brightness and luminosity. Even with careful design of the vacuum chamber and other methods to cure the instabilities, there may be residual betatron oscillation or synchrotron oscillation. An active feedback system is straight forward to achieve the design current and required stability. Those methods to increase the tune spread by introduce non-linear field (like Chromaticity or Octupole magnets) may limit the dynamic aperture, which is not suitable especially at top-off operation. Active feedback has no side effect on the dynamic aperture and typically helps to suppress the injection transient.

Feedback systems are generally composed of three parts: RF front end to detect the transverse position error signal or longitudinal phase information; digitizer to sample and filter the error signals, as well as feedback gain control, phase adjustment etc; corrector module including high power amplifier and kickers. Shunt impedance of the kicker should be sufficient to kick the beam effectively with reasonable power. With the recent development of digital technology, especially the FPGAs (Field Programmable Gate Array), there is no reason to select digital feedback processors other than FPGA based. In a digital feedback loop, one can easily get rid of the DC offset as well as revolution harmonics by using digital filters. The digital delay adjustment avoids the use of long cables to do one-turn delay. The feedback digitizer itself is a powerful diagnostic tool with large memory to store the bunch-by-bunch position/phase information. Bunch oscillation and unstable modes can be revealed by transient measurements. The digitizer can be used to measure the tune of each individual bunch, or to clean unwanted bunches.

Treating the bunch as a rigid particle, the central motion of beam position/phase can be written as damped harmonic oscillation with external force. Eq (1) gives the oscillations in longitudinal plane, transverse plane is similar.

$$\ddot{\tau} + 2d_r\dot{\tau} + \omega_s^2\tau = f(t) = f^{wk} + f^{fb} \qquad (1)$$

Where

$$f^{fb} = -\frac{\alpha e}{E_0 T_0} V^{fb}(t)$$

with,

$$V^{fb}(t) = -jG^{fb}\tau \approx -\frac{G^{fb}}{\omega_s}\dot{\tau}$$

f^{wk} – wake force from the past bunches,
f^{fb} – kick force from the feedback system.

Beam stabilization requires the damping rate (radiation damping + feedback damping) be larger than the wake field excitation rate. Be aware that the wake field caused coupled bunch instability growth rate is proportional to the beam current. More feedback gain is needed for higher beam current. However, active feedback gain is not infinite, it’s limited by the high power amplifier. Besides, with too much gain, the noise in loop might be amplified too much to excite the beam.

Instability growth rate has been estimated for the NSLS-II storage ring, see next section for more information. It shows that for transverse (especially vertical plane), feedback system is mandatory to achieve the designed goal of 500mA and preserve the low emittance < 1 nm.rad. Longitudinal instability in not expected to be a problem because of the use of superconducting RF cavity. The baseline design of NSLS-II will have feedbacks for horizontal and vertical planes. Some major parameters related to the transverse feedback are listed in Table 1.

Table 1, main parameters for NSLS-II feedback system

Parameter	Value	Unit
E	3	GeV
f_{rf}	499.68	MHz
h	1320	
f_{rev}	378.55	kHz
T_{rev}	2.64	μs
Q_X/Q_Y	33.36/16.28	
f_X/f_Y	136/106	kHz
$\varepsilon_x/\varepsilon_Y$	0.9/0.008	nm.rad
τ_x/τ_Y	54/54 (w/o DW)	ms
	23/23 (3 DW)	ms
Resolution	3	μm

τ_{FB}	200	μs
Dynamic range	+/- 0.5 (V)	mm
	+/- 1.5 (H)	mm
R_{Shunt}	>10	kOhm
Power	2*500	W
Stripline length	30	cm

INSTABILITY SOURCES

Transverse coupled bunch oscillations are driven by high-Q wake fields. Bunches generate these wake fields by interacting with the surroundings. Main contributions to the transverse coupled bunch instability include:

- Cavity like structures and discontinuities in the chamber;
- Resistive wall of the surrounding chamber;
- Ion and fast-ion instabilities.

For the modern collider machine and 3rd generation light source, beam emittance and size are getting smaller. With smaller vertical gap of vacuum chamber (in-vacuum undulator, small gap IDs), resistive wall and ion instabilities are the main issues affecting running at high current. Discontinuity in the vacuum chambers can cause wake field while beam passing through. The wake field will act back on the beam itself and cause instabilities. Impedance and wake fields for various components in NSLS2 storage ring have been calculated using GdFidl[1].

Resistive Wall

Resistive wall impedance in the ring can be written as:

$$Z_{//}(\omega) = (1-i)\frac{C}{2\pi b}\sqrt{\frac{\mu\omega}{2\sigma}}$$
$$Z_{\perp} = \frac{2c}{\omega b^2}\cdot Z_{//} \qquad (2)$$

Where C is the ring circumference; b is the chamber radius (height if the chamber is not round); μ is magnetic permeability of pipe material; σ is conductivity of pipe material and ω is the angular frequency.

Eq. (2) assumes the same chamber pipe shape all around the ring, which is not true for the real machine. One should replace the ring circumference C with chamber length L. Since the resistive wall impedance depends strongly on chamber height (for transverse resistive wall ~$1/b^3$). Third generation light sources will have many small gap insertion devices, vertical resistive wall impedance and corresponding instability growth rate are expected to be large.

Knowing the impedance, transverse coupled bunch instability growth rate can be calculated from:

$$\tau_g^{-1} = \frac{eI_0\omega_0\beta}{4\pi E}\left\{\sum_{n=1}^{\infty}\mathrm{Re}\left[Z_T(\omega_{\mu,n}^{-})\right] - \sum_{n=0}^{\infty}\mathrm{Re}\left[Z_T(\omega_{\mu,n}^{+})\right]\right\} \qquad (3)$$

Where

$$\omega_{\mu,n}^{+} = n\omega_{RF} + (\mu\omega_{rev} + \omega_{x,y})$$
$$\omega_{\mu,n}^{-} = n\omega_{RF} - (\mu\omega_{rev} + \omega_{x,y})$$

n = 0, 1, 2,... and μ = 0, 1, 2, ..., Harmonic Number -1; μ is called the mode number.

As a simple estimation for NSLS2, assume there are 100 meter 7mm gap ID chambers with Aluminum material, the vertical growth rate can be calculated from Eq. (2) and (3) for different modes. The strongest unstable mode (mode -1) has the growth rate about 1300 1/sec (with growth time 0.77ms). It's impossible to damp this by synchrotron radiation damping only (damping time ~23ms with three damping wigglers).

Its worth to note that Eq. (2) stands for single material chamber. For those chambers with coating of different material can refer to [2]. Longitudinal growth rate contributed from resistive wall has been calculated as well. The fastest growth rate is less than 2.5 1/sec (with growth time > 400ms). There expected to be no problem from the longitudinal resistive wall.

Fast-ion

Residual gas in the vacuum chamber maybe ionized and trapped by the beam space-charge potential. Ion trapping is important to electron storage rings. Once happened, it may result in lifetime decrease, emittance growth and coherent beam oscillation etc.

Leaving some buckets empty (ion gap) in the filling pattern is effective and widely used to cure the conventional ions. Ions cannot survive for more than one turn. However, even with the ion gap in NSLS2, ions can still accumulate during one pass of the bunch train, which is called fast-ion instability. Fast-ion can result in tune shift and emittance blow up along the bunch train.

Ions with atomic mass larger than critical mass will be trapped, the critical mass was defined by:

$$A_{crit} = \frac{N_b r_p c T_b}{2\sigma_{x,y}(\sigma_x + \sigma_y)} = \frac{N_b r_p L_{sep}}{2\sigma_{x,y}(\sigma_x + \sigma_y)} \qquad (4)$$

Where N_b is number of particles per bunch;

$$r_p = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_p c^2}$$

is proton classical radius ~ 1.5×10^{-18} m; A is atomic mass of ion; T_b (or L_{sep}) is bunch separation and σ_x σ_y the RMS beam size.

Critical mass depends on the beam size, which varies along the ring. Figure 1 shows the critical mass in one super cell of NSLS2 storage ring. For the calculation, we use horizontal and vertical emittance of 0.9/0.008 nm.rad respectively and relative energy spread 0.09%.

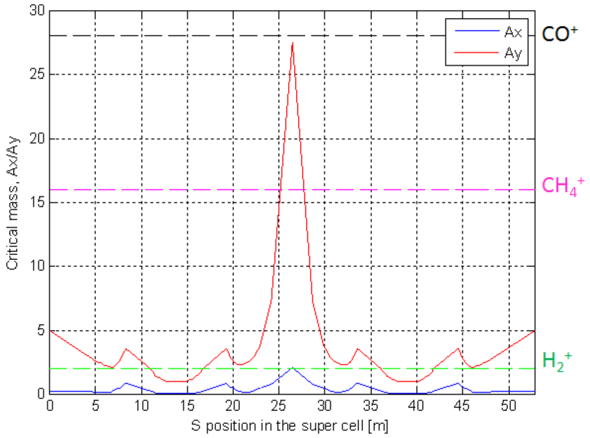

Figure 1, Ion trap critical mass in NSLS2 supercell (start from center of long ID).

We can see from the plot, at short ID, vertical beam size is small, the strong beam force can over focus ions and cause the ions motion to become unstable. That's why the critical mass is highest in vertical at the short ID. Horizontally almost all the ions are trapped, even H_2^+ captured in most of ring. Vertically $CH4^+$ and CO^+ will be captured in most part of the ring, while H_2^+ will be trapped at dispersion region.

Ion oscillating frequency can be written as:

$$\omega_{ion} = 2\pi f_{ion} = \left[\frac{2N_b r_p c}{A\sigma_{x,y}\left(\sigma_x + \sigma_y\right)T_b}\right]^{1/2} \qquad (5)$$

CO^+ (A=28) is considered to be the dominant ion in the NSLS2 ring. At 500mA, evenly filled in 1040 bunches, the ion frequency is around 20MHz in horizontal plane and ~50MHz vertically. Ion frequency will shift as the bunch current is varied.

Ion oscillation frequency will be different from Eq (5) due to: non-linearity of electron potential; beam density variation at different transverse position; beam size variation along the ring and bunch-to-bunch current variation etc. Considering the ion oscillation spread, fast ion instability growth rate can be analytically expressed as:

$$\frac{1}{\tau} \approx \frac{r_e c \beta_y \lambda_{ion}}{3\gamma\sigma_y\left(\sigma_x + \sigma_y\right)}\frac{1}{\Delta\omega_i / \omega_i} \qquad (6)$$

Where $\Delta\omega_i$ is the ion oscillation frequency spread along the ring. Select $\Delta\omega_i/\omega_i$ =30% matches the simulation result well; β_y is average beta function and λ_{ion} is ion density

$$\lambda_{ion} = \frac{n_b N_b}{K_B T}\sigma_{ion} p$$

Assume single bunch train of 1040 bunches, CO+ ion density of 1nTorr at the end of train is $5.3\text{x}10^4$ m^{-1}, ion oscillation frequency spread ~30%, beam size 100µm/10 µm, average vertical beta function ~10m, the calculated rise time is ~13us. (If use 0.3nTorr CO, and 250 bunches per train, the growth time ~200µs, which is close to the simulation [3]).

The bunch-by-bunch feedback system is designed to have the damping time less than 200 µs, which is about 75 turns of NSLS2 storage rings.

BPM AND STRIPLINE KICKER

Normal multi-chamber RF BPM design [4] will be adopted as the transverse feedback pickup. Sensitivity and signal strength of the BPM has been analyzed. The detection will be at three times RF frequency, where the BPM button has peak signal. However, the antechamber structure will decrease the cutoff frequency to less than 1GHz even with RF shielding. To avoid the possible trapped TE mode, dedicated BPM housed in non antechamber structure will be used.

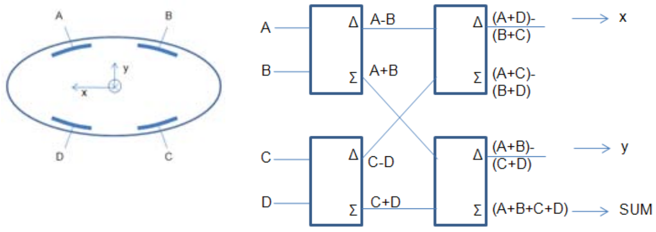

Figure 2, hybrid network to get the position error signal in RF front end.

Assume BPM buttons with sensitivity Kx = Ky =10mm, the hybrid output from the RF front end with small position offset ΔX is (Figure 2)

$$(V_A+V_D) - (V_B+V_C) = 4*\Delta V$$

while,

$$\Delta X = K_x \frac{(V_A + V_D) - (V_B + V_C)}{(V_A + V_B + V_C + V_D)} = K_x \frac{\Delta V}{V_0}$$

$$\Delta V = \frac{1}{K_x} \cdot \Delta X \cdot V_0$$

Where V_0 is the signal strength with the beam passing through the center, and ΔV is signal strength change with position offset ΔX.

The NSLS2 button BPM has about -7dBm at 500MHz with 500mA full current, which corresponding to 0.1Vrms. With 1µm offset and Kx=10mm, the output signal from the hybrid network is:

$$4 \cdot \Delta V = 4 \cdot \frac{1}{K_x} \cdot \Delta X \cdot V_0 = 0.04mV$$

This corresponds to -75 dBm.

In the real machine, transverse feedback doesn't need to have the sensitivity to detect 1µm beam oscillation. Depending on the location of BPM, the vertical beam size is typically around 10 μm (horizontal beam size is 10 times larger, no detection sensitivity problem), feedback control needs to have 30% beam size resolution which is ~3 μm. (Don't like the orbit feedback which has small bandwith, the users will see these kind of slow beam movement; but for the betatron oscillation, user's experiments typically cannot seen it, effect of betatron oscillation is 'effective' emittance/beamsize increase. If the oscillation can be controlled <30%, the effective beamsize change is less than (1^2+30%^2)-1 = 9%, which is negligible.) With 3 μm beam position offset, the output from the hybrid has -65dBm signal.

Noise of the BPM button signal and hybrid outputs can be estimated from thermal noise. With 250MHz bandwidth and temperature ~20 degC, the noise floor is about -90 dBm. Considering detection resolution of 3 μm, which has -65dBm output at the hybrid, there is 25dB noise figure budget in the feedback loop.

BPM signal output has maximum amplitude around ~1.5GHz. NSLS2 normal RF BPM gives -7dBm at 500MHz with 500mA. If the bunch feedback detection frequency is selected to be 3*f_{rf}, ~6dB more signal can be gained. Figure 3 shows the BPM button signal power at 500mA. The cable loss value was based on 100 feet LDF2-50 3/8'' Heliax cable.

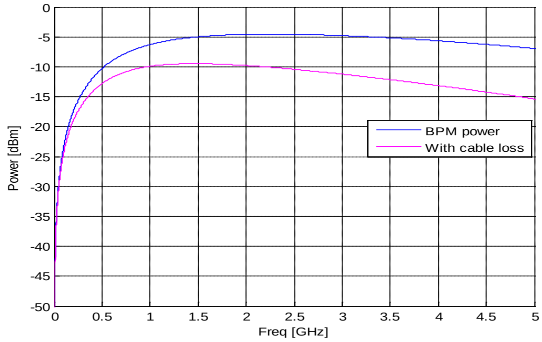

Figure 3, BPM button output signal power (with and without cable loss)

The high power amplifiers and stripline kickers are the feedback actuators. They are the most expensive parts of the system. Design of the kicker should provide sufficient shunt impedance while minimizing the beam impedance. Stripline has been proved effective as transverse kicker. It has higher shunt impedance at lower frequency, which is suitable if the main instability contribution is from resistive wall and ions. Required power can be calculated if the stripline shunt impedance, damping time and initial oscillation amplitude are known.

$$\Delta\theta = -\frac{2\alpha}{f_{rev}}\cdot\frac{\Delta x}{\sqrt{\beta_m\cdot\beta_k}} = -2\cdot\frac{1}{\tau}\cdot T_{rev}\cdot\frac{\Delta x}{\sqrt{\beta_m\cdot\beta_k}}$$

$$V_\perp = \Delta\theta\cdot\frac{E}{e} = -2\cdot\frac{1}{\tau}\cdot T_{rev}\cdot\frac{E}{e}\cdot\frac{\Delta x}{\sqrt{\beta_m\cdot\beta_k}} \qquad (7)$$

in which, $\Delta\theta$ is deflecting angle while beam passing through; $V_\perp$ is transverse deflecting voltage; E is the beam energy; α/τ are feedback damping rate/time; Δx is initial beam oscillation amplitude; β_m/β_k – beta function at BPM and kicker.

From Panofsky-Wenzel theorem, electric field and magnetic field have the same kick effect when the power is fed to the stripline kicker from the downstream port:

$$\Delta\theta \approx \frac{\Delta p_\perp}{p_{//}} = \frac{V_\perp}{E/e} = \frac{2\int_{stripline} E_\perp dt}{Energy/e}$$

Kicker shunt impedance is defined as:

$$R_{shunt} = \frac{V_\perp^2}{2P} \qquad (8)$$

Taking shunt impedance 10 kOhm, which is not hard to get with 30-cm stripline, the required damping time of 200μs, β_m=12/10m and β_k = 7/21 m (vertical/horizontal). Figure 4 plots required power at different initial oscillation amplitude.

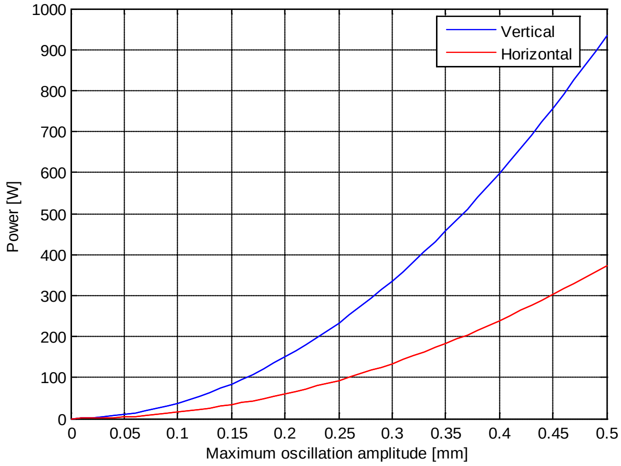

Figure 4, required power vs. initial oscillation amplitude for NSLS2 feedback.

To damp an oscillation of up to +/- 0.5mm in the vertical plane, we need 1000W power (2*500W) which is commercially available.

Its worth to mention that bunch might never have chance to get large oscillation if the feedback is always on. In this case the needed power is really small. Full power may be needed only for machine study purpose, if the feedback loop is switched off and the instability is allowed to grow.

Transverse shunt impedance of stripline with opposite electrode distance d and length l can be written as:

$$R_\perp = 2Z_c\left(\frac{2g_\perp l}{d}\right)^2\left(\frac{\sin kl}{kl}\right)^2 \qquad (9)$$

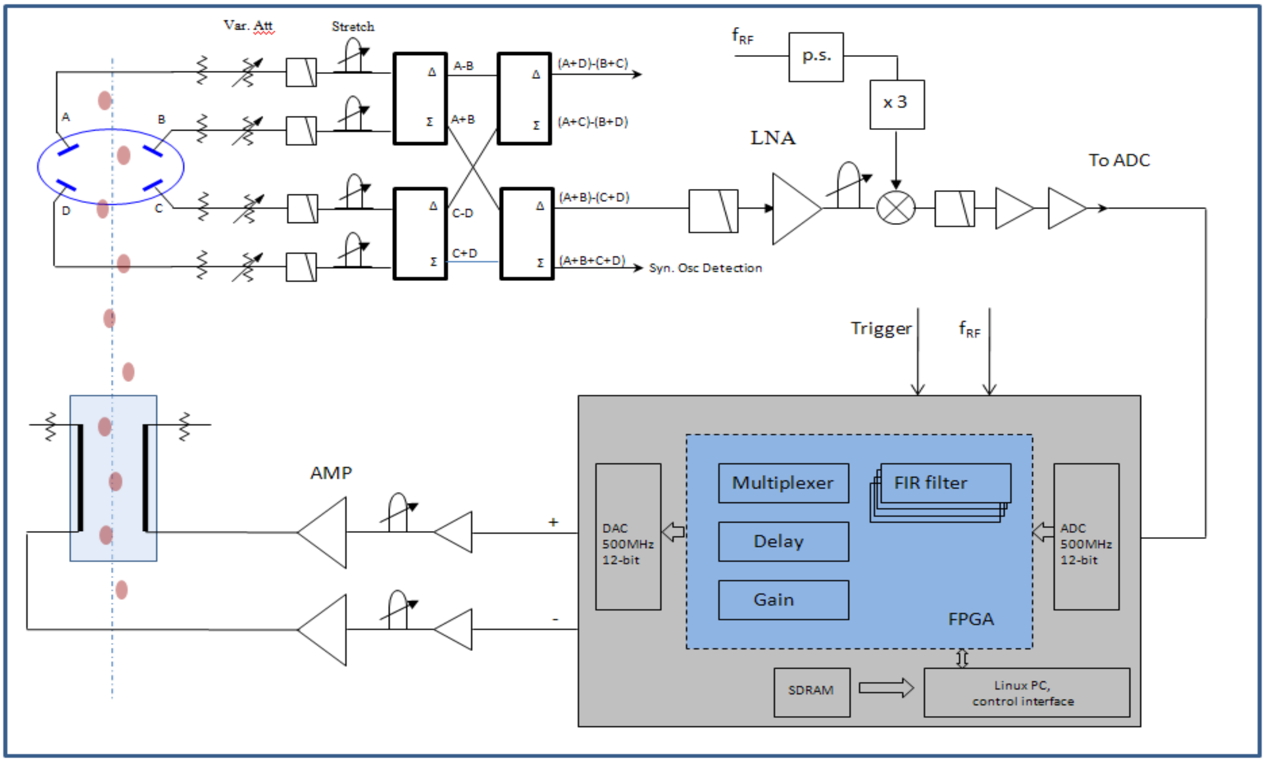

Figure 5, Layout of NSLS2 transverse feedback system for vertical plane

With longer stripline kicker, the shunt impedance is bigger at low frequency but the bandwidth decreases. To separate between bunches in case the instability mode around 250MHz happens; stripline electrodes typically select less than half of the bunch space, which is 30cm with 500MHz RF frequency.

A two plate 30cm stripline in round chamber has been designed with shunt impedance > 10kOhm till 200MHz [5]. Field uniformity is within 5% in 10mm range.

SUMMARY

NSLS2 transverse feedback system has been designed to cure the instabilities with growth rate as fast as 200µs. BPM detector signal strength and sensitivity has been analyzed. Normal RF BPM proves sufficient to be used as feedback pickup. RF front end will generate the low-noise bunch-by-bunch position information to be fed to digitizer. The detection frequency was selected to 3*Frf due to higher signals at that frequency. Commercial 500MHz FPGA based digitizer will be used. See Figure 5 for the layout. Stripline kicker design shows >10kOhm shunt impedance with 30cm electrode, beam impedance of the kicker is under investigation. Future work will deal with feedback system during the top-off injection, single high-current bunch in hybrid fill mode, bunch clearing and tune measurement using the feedback digitizer. NSLS2 storage ring might need positive chromaticity. The feedback behavior at positive chromaticity needs to be investigated.

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