TRANSIENT BEAM LOADING DUE TO THE BUNCH TRAIN GAP AND ITS COMPENSATION EXPERIMENTS AT BEPC-II AND ALS*

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Abstract

Non-uniform bunch fill patterns in storage rings, driven by the need to provide gaps for beam aborting and ion clearing cause a large beam loading change in the RF cavities. The induced turn-periodic transient in the cavity voltage modulates longitudinal beam properties along the train, such as synchronous phase and bunch length. We have carried out beam based experiments on the BEPC-II at IHEP and on the ALS at LBNL, using bunch-by-bunch diagnostic capabilities of the coupled-bunch feedback systems to study this transient effect. A modulated bunch filling pattern with higher charge density around the gap has been demonstrated to be effective in partially compensating this transient modulation. Details of the experimental setups and data analysis will be presented.

INTRODUCTION

Fill patterns in a storage ring are typically non-uniform both by design, such as beam abort and ion clearing gaps, and due to difference in injection and bunch lifetime. This non-uniformity can cause a large beam loading change to the RF cavity and feedback control system. The induced cavity voltage change can also cause the longitudinal beam dynamics to change, leading to bunch-to-bunch variation in synchrotron frequency and synchronous phase. In the Jefferson Lab electron-ion collider design (JLEIC), due to the different bunch train structure and RF system response between the electron and the ion rings, such modulation would result in shifting of the collision point and lead to reduced luminosity. We have studied the longitudinal beam stability in steady state by a MathCAD model [1] with open loop (Robinson model [2]) and closed feedback loops (Pedersen [3-4], Koscielniak [5] and Heifets models [6]). We also carried out beam loading experiments in BECP-II at IHEP and ALS at LBNL. The beam gap transient detection and its compensation by modified bunch charge distribution techniques have been investigated experimentally. We have used longitudinal bunch-by-bunch feedback system to measure synchronous phase transient and bunch currents and diagnose beam loss due to instability, which had previously limited the current in BECP-II.

BEAM CAVITY INTERACTION

The fundamental beam-cavity interaction can be modelled by a parallel RLC resonant circuit as shown in Fig. 1. Note the definition of the beam synchronous phase ϕ

phase ϕ_B, angle between beam current $\overrightarrow{I_B}$ and the vertical line of cavity voltage $\overrightarrow{V_C}$, where ϕ_B=90° is on crest and ϕ_B=180° is at a zero crossing. The equations in

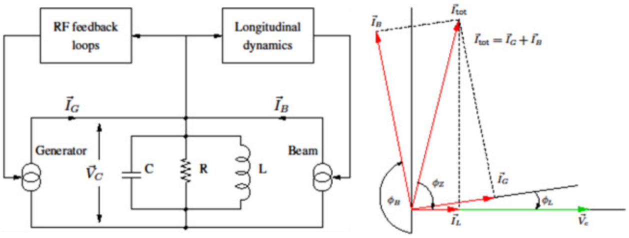

Figure 1: RLC circuit model of cavity-beam interaction (left) and their vectors' diagram (right).

Ref. [8] give the basic steady-state relationships of tuning angle ϕ_Z, loading angle ϕ_L with generator current $\overrightarrow{I_G}$ and RF current $\overrightarrow{I_L}$ and $\overrightarrow{I_B}$ by:

$$I_G = \frac{I_L + I_B sin\emptyset_B}{cos\emptyset_L} \tag{1}$$

$$tan\emptyset_Z = tan\emptyset_L + \frac{I_B}{I_L}(tan\emptyset_L sin\emptyset_B + cos\emptyset_B) \tag{2}$$

When ϕ_L=0, the optimum detuning ω_D<0 (above transition energy) will give a minimum klystron reflected power:

$$\omega_D = \frac{\omega_{rf}}{2Q_L}\frac{I_B}{I_L}cos\emptyset_B = \frac{\omega_{rf}}{2V_C}\frac{I_B R}{Q}cos\emptyset_B \tag{3}$$

$$\omega_D = \omega_{cav} - \omega_{rf} = \frac{1}{\tau}tan\emptyset_Z \qquad \tau = \frac{2\mathrm{Q_L}}{\omega_{\mathrm{rf}}} \tag{4}$$

where τ is the cavity damping time.

Any uneven ring filling pattern represents a periodic amplitude modulation of the $\overrightarrow{I_B}$ from turn to turn, i.e. the beam signal has power at the revolution harmonics in the frequency domain. These components interact with the detuned cavity impedance producing both amplitude and phase modulations of cavity voltage $\overrightarrow{V_C}$, which in turn, influences the longitudinal parameters of individual bunches or even the stability of the whole bunch train.

BEAM LOADING TRANSIENT

A gap in the bunch train can cause the bunch vector voltage change from the N^{th} to the 1^{st} bunch with N_g empty buckets between the head and the tail [9]:

$$\tilde{V}_b{}^N - \tilde{V}_b{}^1 = -2\mathrm{kq}\frac{sin\frac{1}{2}N_g\overline{\theta_b}}{sin\frac{1}{2}\overline{\theta_b}}\frac{sin\frac{1}{2}(N-1)\overline{\theta_b}}{sin\frac{1}{2}(N+N_g)\overline{\theta_b}} \tag{5}$$

Here, $\overline{\theta_b} = \Delta\overline{\omega}T_b = \frac{tan\emptyset_Z + i}{\tau}$, $k = \frac{1}{4}\omega_{rf}\frac{R}{Q}$ is loss factor of the cavity, and q is the bunch charge. The phase variation between the $\mathrm{N^{th}}$ and the 1^{st} bunches is:

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$$\Delta\theta_{1N} \approx \frac{Re\left(\tilde{V}_b{}^{N} - \tilde{V}_b{}^{1}\right)}{V_C \cos\emptyset_B} \tag{6}$$

For a short gap T_g time interval or a short train T_b compared to the whole ring T_r, the maximum phase transient (6) can be approximated by:

$$\Delta\theta_{1N} \approx \frac{-2kI_B T_g}{V_C \cos\emptyset_B} \tag{7}$$

We have used the analytical formulae (1)-(7), MathCAD model[1], and Dimtel fast feedback and beam diagnostic program using a small signal Pedersen model [3], to simulate, setup and measure the beam transient parameters.

High beam loading conditions (beam current I_b is large relative to the generator current I_g) in combination with mandatory abort and ion clearing gaps often lead to large synchronous phase transients. Active compensation of these transients is impractical, since it requires very high peak power [11]. For a fixed *Ib* and V_c, this transient is related to the cavity's R/Q and the number of cavities only. In order to mitigate this problem one can attempt to increase the cavity stored energy by lowering the R/Q but achievable with limitation. Alternatively, a scheme of adding additional bunch charge at the head and tail of the bunch train in order to compensate the missing charge in the gap was proposed [10], but it was not experimentally verified until it was brought up again by Rimmer in 2016.

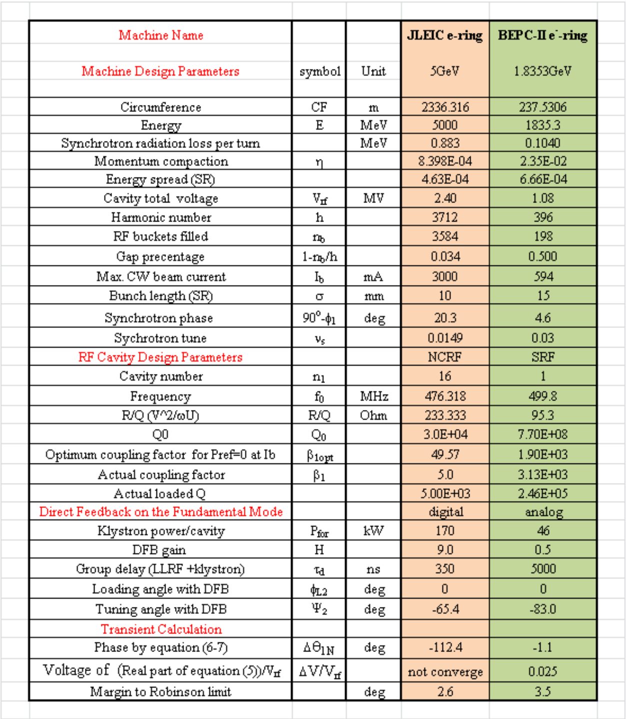
EXPERIMENT PARAMETERS AND MEASUREMENT SETUPS

Two experiments have been carried out, the first one was at the BECP-II, IHEP in December 6-10, 2016, after the machine had reached the highest luminosity on April 05, 2016 by gradually reducing the filling gap space. The second experiment was done in the ALS at LBNL in May, 2017. Table I lists experiment parameters set up at the BEPC-II and the simulated design parameters for the JLEIC e-ring for comparison. Due to incompletely detuned 3rd harmonic cavities during the ALS experiment, the simulation model could not include the 3rd harmonic voltage, the experiment parameters at ALS are not listed here for comparison.

Considering the 40-meter gap length of the JLEIC collider's electron ring, the transients on the phase and cavity voltage at 5GeV would be much worse, indicating possible beam instability. To demonstrate the modulated fill-pattern compensation scheme, we intentionally set up the machine experiment at BEPC-II with increased gap length and reduced cavity voltage in order to increase the phase transient as estimated in Eq. (7).

In addition, to investigation the beam loss problem at BECP-II, the transfer functions of the direct feedback systems were carefully characterized in open and closed loop conditions before the beam operation. In the open loop, the klystron loading angle can be directly measured by the tuning angle. In closed loop, the loop gain H, group delay τ_d, cavity loaded Q_L and center loop resonant frequency ω_{rf} can be precisely measured or fitted. The circuit gain and delay setting curves can be also prepared for the control. In Figures 2 and 3, we show Robinson diagrams from the MathCAD program for the BEPC-II experiment.

Table 1: Machine Design Parameters for JLEIC e-ring and Experiment Parameters for BECP-II



Machine Name			JLEIC e-ring	BEPC-II e^--ring
Machine Design Parameters	symbol	Unit	5GeV	1.8353GeV
Circumference	CF	m	2336.316	237.5306
Energy	E	MeV	5000	1835.3
Synchrotron radiation loss per turn		MeV	0.883	0.1040
Momentum compaction	η		8.398E-04	2.35E-02
Energy spread (SR)			4.63E-04	6.66E-04
Cavity total voltage	V_{rf}	MV	2.40	1.08
Harmonic number	h		3712	396
RF buckets filled	n_b		3584	198
Gap precentage	$1-n_b/h$		0.034	0.500
Max. CW beam current	I_b	mA	3000	594
Bunch length (SR)	σ	mm	10	15
Synchrotron phase	$90^o-\phi_1$	deg	20.3	4.6
Sychrotron tune	ν_s		0.0149	0.03
RF Cavity Design Parameters			NCRF	SRF
Cavity number	n_1		16	1
Frequency	f_0	MHz	476.318	499.8
R/Q (V^2/ωU)	R/Q	Ohm	233.333	95.3
Q0	Q_0		3.0E+04	7.70E+08
Optimum coupling factor for Pref=0 at Ib	β_{1opt}		49.57	1.90E+03
Actual coupling factor	β_1		5.0	3.13E+03
Actual loaded Q			5.00E+03	2.46E+05
Direct Feedback on the Fundamental Mode			digital	analog
Klystron power/cavity	P_{for}	kW	170	46
DFB gain	H		9.0	0.5
Group delay (LLRF +klystron)	τ_d	ns	350	5000
Loading angle with DFB	ϕ_{L2}	deg	0	0
Tuning angle with DFB	Ψ_2	deg	-65.4	-83.0
Transient Calculation				
Phase by equation (6-7)	$\Delta\Theta_{1N}$	deg	-112.4	-1.1
Voltage of (Real part of equation (5))/V_{rf}	$\Delta V/V_{rf}$		not converge	0.025
Margin to Robinson limit		deg	2.6	3.5

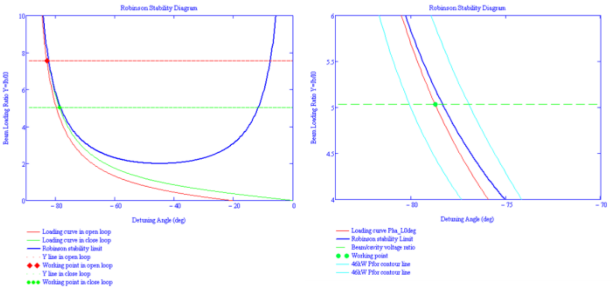


Figure 2: Robinson diagrams in y-ϕ_z plots [1][7] for the working point setup.

The DFB closed loop moves the beam load line $y=I_B/I_L$ down (from red dash line to green dash line) away from the instability area (left plot, inside of "U" shape marked by blue curve). Right plot is a zoom-in view of the working point on the red closed-loop's loading line. The cyan line is the contour of the 46kW klystron available power boundary. We can convert the y-ϕ_z plots in Fig. 2 into the plots into y-ϕ_L plots.

The left plot of Fig. 3 shows the working point under the Robinson blue line (stable) on the close loop y line (green) and within the contour line of 46kW power limit. The zoom-in view on the right plot indicates that the steady state working point has a 3.5 degree margin to the Robinson limit line (blue) when the load angle transient follows the effective tuning line (red).

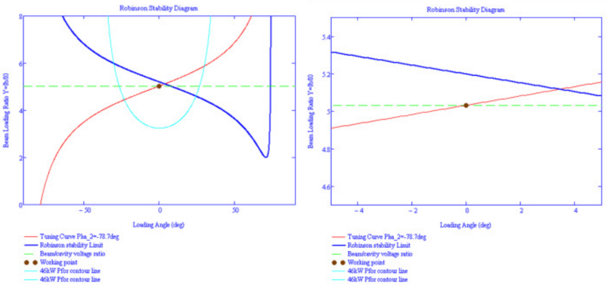


Figure 3: Robinson diagrams in y-ϕ_L plots.

EXPERIMENT RESULTS AT BECP-II

The first experiment has demonstrated the modified fill scheme can partially compensate the synchronous phase transient as shown in Fig. 4, where 99 bunches were evenly filled with every other bucket at 7mA bunch current. The peak-to-peak phase transient is still quite small at about 2.2°. Then the uniform fill current was reduced to 4.5mA in order to be able to double the current on the first 22 and last 22 bunches while keeping total beam current constant.

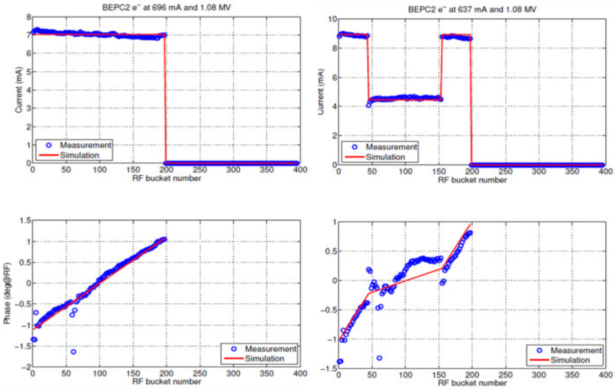


Figure 4: Bunch fill pattern (above) and phase transient (bottom) between even (left) and modified type filling (right). The phase transient in the middle of the train has been partially reduced from 1.0° to 0.5° by this modified fill.

As can be seen in Fig. 4 the phase transient in the middle part of the fill pattern was not in zero slope, since the extra charge in the "ears" was lower than the charge removed from the gap, the gap transient was not fully compensated. Some features observed around bucket 60 are due to beam-excited modes propagating in the nearby vacuum chamber. Agreement between small Pedersen signal simulation and measurement is reasonable.

The beam loss events in BEPC-II have been recorded by the RF bunch to bunch phases. Two feedback processing channels were used to capture the beam loss transients. One channel was set up to differentiate BPM sum amplitude, generating bunch-by-bunch loss trigger signal. This signal, together with the pre-trigger acquisition feature was used to capture the motion before and after the beam current loss event. The captured beam loss events have been analysed as shown in Fig. 5. Before the beam loss, the bunch phase has fairly large steady-state excursions around 5° p-p, 0.6° rms with ~20ms period. The exponential phase runaway is a typical signature of high beam loading Robinson limit. As predicted in Fig.3 with the cavity parameters in Table 1, a slightly negative loading angle ϕ_L would increase the current limit; moving in the positive direction only 3-4° will cause the beam loss as shown in Fig. 5 right. The direct loop gain of H=0.5 would give ~33% more margin than the open loop. The trend of all bunch phases moving together is another signature of Robinson instability onset.

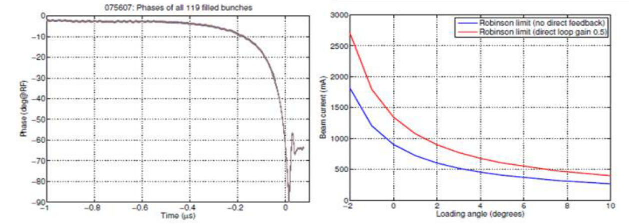


Figure 5: Exponential beam phase run-away during the beam abort (left) and calculated maximum Robinson-stable beam current as the function of loading angle (right).

EXPERIMENT RESULTS AT ALS

The ALS can tolorate larger RF and beam transients without a direct feedback, makes it a more attractive choise for testing fill pattern modulation scheme than at BEPC-II. Measured synchronous phase transients are shown in Fig. 6. This scheme leads to a reduction of phase transient in uniform filled part of the train from 3° to ~0.3°. However it does not affect the overall peak-to-peak transient. This transient reshape normally has no effect on the light source users, the compensated transient on the JLEIC collision limunosity could be a benifit. Other possible effects due to the increased bunch charges, like reduced lifeltime or single bunch instabily have not been studied yet.

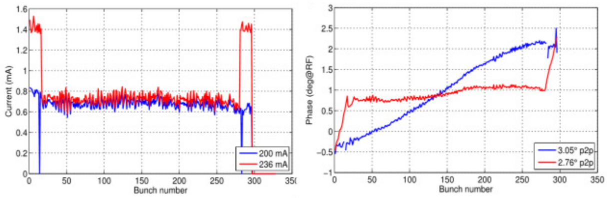


Figure 6: The experiment data at ALS.

CONCLUSIONS

Mitigation of transient beam loading by modified bunch filling has been experimentally verified at two machines, BECP-II and ALS. The charge density modulations can shift bunch phase and cavity voltage transients to the ends of the bunch train, removing transient behaviour in the uniform filled central section. Excellent benchmark agreement between experimental data, analytical and simulation tools has been achieved. Such tools can be used for the future feedback system designs and guide the IHEP in improving the BECP-II SRF cavity direct feedback systems in order to achieve still higher luminosity.

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