EFFECT OF BUNCH SHAPE ON ELECTRON-PROTON INSTABILITY

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Abstract

The instability caused by the electron cloud effect (ECE) may set an upper limit to beam intensity in proton storage rings. This instability is potentially a major obstacle to the full intensity operation, at 1.5e14 protons per pulse, of the Spallation Neutron Source (SNS). High intensity experiments have been done with different sets of parameters that affect the electron-proton (e-p) instability, of which bunch intensity and bunch shape are considered as two main factors. In the experiment, the phase and amplitude of the second harmonic RF cavity are used to modify the bunch shape. Analysis is made on the experimental results to understand the impact of bunch shape on beam stability. Benchmark of the e-p model is ongoing to address the threshold of bunch shape more accurately.

INTRODUCTION

Since e-p instability was first observed and identified in Los Alamos Proton Storage Ring (PSR) in 1991, there are a number of other high intensity proton rings, such as SNS and CERN SPS, being considered to be potentially subject to the same issue. Due to the similarity of the SNS ring and PSR, electron cloud effect (ECE) was studied in the design stage of SNS, and led to the decision to coat every piece of vacuum chamber with Titanium Nitrate (TiN) and to install electron collector at high loss regions. However, electron cloud built-up is not eliminated, although might be reduced. Since the first observation of e-p instability in 2006[1], several high intensity runs were dedicated to characterize the dependence of instability on parameters such as beam intensity, transverse betatron tune, RF voltage and bunch shape. In this paper, we will focus on the new test for potential controls including RF voltage and 2nd harmonic RF that introduce changes of bunch shape.

To keep the sole dependence of the instability on bunch shape, we will choose the experiment on October 2008 as a sample to show the bunch shape's change. The other similar high intensity experiments were done in July 2009 and we will use them all to calibrate the ORBIT electron cloud module.

RING CONDITIONS AND SPECTRUM ANALYSIS

For the experiment done on October 2008, the ring was set to the nominal work point (Q_x=6.23, Q_y= 6.2) and chromaticity is natural (ξ_x=-8.2, ξ_y=-7.2). With this configuration, the instability is not shown in bunched beam mode, i.e., 1.03e14 protons per pulse was extracted with low loss. Two of the three first harmonic cavities (RF 1.1 & 1.3) were in phase with an amplitude of 9 kV and 10.5 kV, respectively. The only dual harmonic station (RF 2.1) has a voltage of 10.5 kV. In the experiment, the variables are the phase of RF 2.1, voltage of RF 1.1 & 1.3 and the chromaticity. Since the chromaticity is not an feasible control to change bunch shape and the voltage scanning had only two effective data sets, we will mainly introduce the phase scanning of RF 2.1 in this paper.

Raw data was exported from the four channels of a BPM in the ring. The time interval of data points is 0.4 ns. Proton bunch occupies 2/3 of the 248 m circumference and the revolution period is 963.2 ns. Therefore, every revolution records ~ 2408 data points.

Fast Fourier Transform (FFT) is performed on the raw data of every revolution, which gives the frequency spectrum of the instability. Our previous calculation shows that the frequency of e-p instability should be within 20 to 200 MHz. Figure 1 shows an example of the spectrum, which reveals information such as the time that instability begins, the frequency, the propagation of instability and etc.

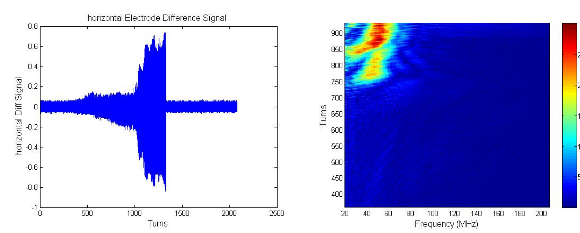

Figure 1: A typical spectrum of the unstable beam caused by e-p instability (RF 2.1 phase = -5^{o}). The graph on the left shows the BPM difference signal and graph on the right is the FFT spectrum corresponding to the left. The damping and re-rising of the fast growth oscillation is because electrons cloud accumulates to a big enough amount that repulse the secondary electrons back into the wall.

While the phase of the dual harmonic RF is scanned from -35^{o} to 15^{o}, or, say, from in phase to out of phase by 50^{o}. The bunch shape revolves and instability comes out and become stronger and stronger referred to the FFT peak. A brief summary of different data sets is shown in Table 1.

In Table 1, "First Plane" stands for the transverse plane on which instability first occurs. "Time" is the estimate beginning time of the instability. f_{instab} represents the frequency of the instability and $1/\tau$ is the growth rate of the first fast growth oscillation as showed in the first plot of Figure 1. The oscillation damps after electron cloud accumulation saturates to repulse the secondary electrons back into the wall and re-rises thereafter because the electrons restart to accumulate at a different position of proton bunch with a different growth rate.

Table 1: Spectrum Analysis of the Phase Scanning

RF2.1 Phase	-35^o	-25^o	-5^o	5^o	15^o
Instability	No	Yes	Yes	Yes	Yes
First plane	------	Hor	Hor	Hor	Hor
Time (ms)	------	0.86	0.7	0.7	0.67
f_{instab} (MHz)	------	40-60	40-60	30-50	30-45
$1/\tau$ (ms^{-1})	------	25.45	15.50	18.05	15.62

BUNCH SHAPE EFFECT ON ELECTRON CLOUD ACCUMULATION

An explanation of the cause of e-p instability [2] is that a high density of electrons exist in the vacuum chamber and interacts with the proton beam and leading to a transverse mode coupling instability between proton and the oscillating electrons trapped in the proton potential well. For the bunched beam, the initially motionless electrons gain energy after traveling across the vacuum chamber with a decreasing longitudinal proton density, and lose energy if the bunch density is increasing. Therefore, initial electron accumulation usually happens on the trailing edge of the proton bunch due to multipacting mechanism. The amount of energy gain depends on multiplication of the slope of bunch trailing edge and the current itself. Therefore, the slope of the trailing edge at the beginning of instability might be a good signal for the initial electron accumulation, consequently the e-p instability.

BCM waterfall data was taken in the experiment as a direct measurement of the beam current. The turn near the end of injection was sampled out to study. To find the slope of the trailing edge, a trail function, the Boltzmann Function in our case, is used to fit the trailing edge of the longitudinal density distribution:

$$y = \frac{A_1 - A_2}{1 + e^{(x - x_0)/dx}} + A_2$$

Where $A_{1,2}$ is the bottom/top limit and the slope is

$$y^{(1)} = \frac{A_2 - A_1}{4dx}$$

Fitting result and the slope are showed in Figure 2, where ph1, ph2, ph3 and ph5 correspond to -35^o, -25^o, -5^o and 15^o of RF 2.1 phase. The 5^o case is absent because of a broken BCM file.

Although the direct observation shows that the flatter the trailing edge, the stronger the instability, we cannot simply relate these two physics quantities because the mechanism is much more complicated. Figure 3 shows the energy gain of a normally incident electron when it travels across different positions at the proton bunch tail, with only a constant coefficient omitted. After striking the wall, secondary emission electrons are produced depending on the primary initial energy with quantitative dependence as shown in Figure 4 [3] .

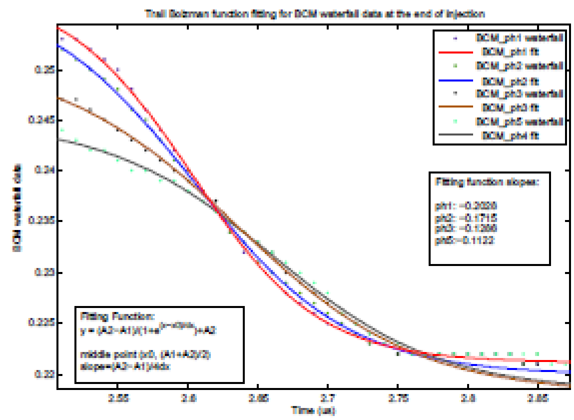

Figure 2: Slope comparison for the phase scanning data. Instability is sensitive to the slope of the trailing edge. Slope threshold of instability is between [-0.2, -0.19] taking into account of the results from voltage scanning.

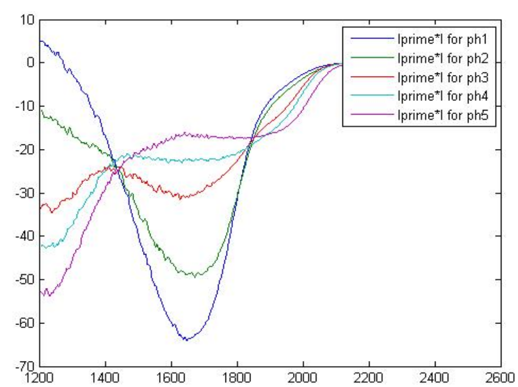

Figure 3: Indication of energy gain along the trailing edge. Calculated from derivative of current times current.

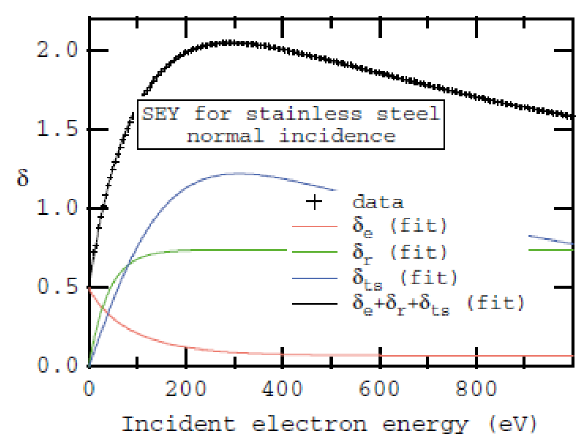

Figure 4: SEY dependence on the incident energy of primary electron. The maximum of SEY depends on the vacuum chamber material (stainless steel in this example).

This process continues up to a point when the electron density is comparable with the proton density. The accumulation of electrons often happens at the high proton beam loss spots such as the stripper foil and high

SEY area such as the ceramic and aluminium part of vacuum chamber. The number of electron accumulated can be calculated by integrating the SEY as the proton bunch passes by.

The maximum SEY factor depends on the properties of material used. Since we only have one node of the electron cloud module in ORBIT code [4], its value in the ORBIT is actually an average, which is difficult to estimate. However, we can use the experimental result to find the average maximum SEY. Since the growth rate is proportional to the square root of neutralization factor (electron line density/proton line density) [5], the experiment should show the same relationship. Therefore, We can adjust the maximum SEY until the experimental growth rate versus the number of electron accumulated agree with the theory.

This part of benchmarking of the SNS electron cloud model is in progress. The calibrated model can be used to predict the threshold of bunch shape and SEY value beyond which the instability begins to occur. It is important for the SNS power ramp-up and future upgrade.

CONCLUSION

In this paper, we have analyzed the experimental result of the effect of bunch shape on electron cloud generation. The observation of experimental result agrees with the qualitative explanation [2] and some quantitative information can be abstracted from the analysis, such as the e-p frequency and trailing edge slope threshold. The next step is to implement the experimental beam distributions into the electron cloud module of ORBIT to calibrate the model, and perform more accurate quantitative analysis thereafter.

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