Transition Crossing in the Fermilab Main Ring, Past and Present.

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Abstract

A recent installation of passive mode dampers in the Booster [1] has eliminated most of the longitudinal emittance blowup of intense bunches due to coupled-bunch instabilities. As a result, high intensity effects (negative-mass instability) dominate the present transition crossing in the Main Ring for the high-intensity cycles. A negative-mass stability limit is derived for transition crossing in the Main Ring and recent observations of high frequency signals around transition is presented. Finally, some predictions about the effect of the negative mass instability on the transition in the Main Ring with the future upgrades are attempted.

I. Introduction

In past years, coupled-bunch instabilities in the Fermilab Booster were responsible for longitudinal emittance blowup in very intense bunches. As a result, high intensity (larger than 2.0×10^{10} p) Booster bunches transferred to the Main Ring had large longitudinal emittance (0.18–0.20 eV-sec). In that case, our measurements showed that nonlinear phenomena were responsible for the emittance blowup around transition in the Main Ring [2]. Recent installation of passive mode dampers in the Booster cavities has eliminated most of the longitudinal emittance blowup. In fact, the longitudinal emittance blowup in the Booster has been reduced by a factor of 3. Now, a 2.5×10^{10} Booster bunch transferred to the Main Ring has an emittance of 0.06 eV-sec. In this case, the blowup at transition in the Main Ring has increased to a factor of 2.8–3.2 resulting in final longitudinal emittances of 0.18–0.22 eV-sec after transition. We attribute this emittance blowup to a negative-mass instability at transition. High frequency negative-mass signals have been observed up to 7 GHz.

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II. Experimental Observations

For the experimental observation of the high frequency signals, we used a wall-current monitor with a flat frequency response up to 6 GHz located in the Main Ring tunnel. The signal from the wall monitor was brought upstairs and was amplified with a 4-8 GHz amplifier. It was then brought to an rf switch panel with a switch gate determined by an HP 8112A pulse generator triggered by a Main Ring beam synchronized clock. This was necessary in order to reduce the noise in the signal since there were only 84 consecutive bunches out of 1113 in the Main Ring cycle used for our observations. Finally, the signal was viewed on a HP8566B spectrum analyser set at the zero-span mode.

In Fig. 1, we display the observed signals around transition at frequencies 4, 5, and 6 GHz for proton bunches with initial emittance 0.07 eV-sec and 2.3×10^{10} p. The units on the vertical axis are 5 db per division and on the horizontal axis 2 msec per division. The transition time is marked with an arrow. As seen in Fig. 1, the signals are getting stronger and more persistent with increasing frequency as expected from the negative-mass instability. In this case, the longitudinal emittance after transition was 0.25 eV-sec corresponding to a blowup of 3.6. Next we used a phase mismatch at injection to blowup the longitudinal emittance of the bunches with initial emittance of 0.06 eV-sec and intensity 1.8×10^{10} p. In Fig. 2, we display the signals observed at 5.0 GHz, with two different longitudinal emittances before transition. As expected, the 5.0 GHz signal is smaller for the bigger longitudinal emittance, and dies away faster compared to the signal in the case with the smaller emittance. The emittance blowup at transition is also much smaller for the bigger initial emittance (a factor of 2 compared with 3.7).

III. Negative-Mass Blowup

Hardt [3] proposed a theory of negative-mass blowup tha takes into account of Landau damping. In the absence of space charge, the spectral coefficient of the bunch for revolution harmonic k is $|c_k| = N_b^{-1/2}$ due to the statistical fluctuation of the N_b particles in the bunch. As a result of

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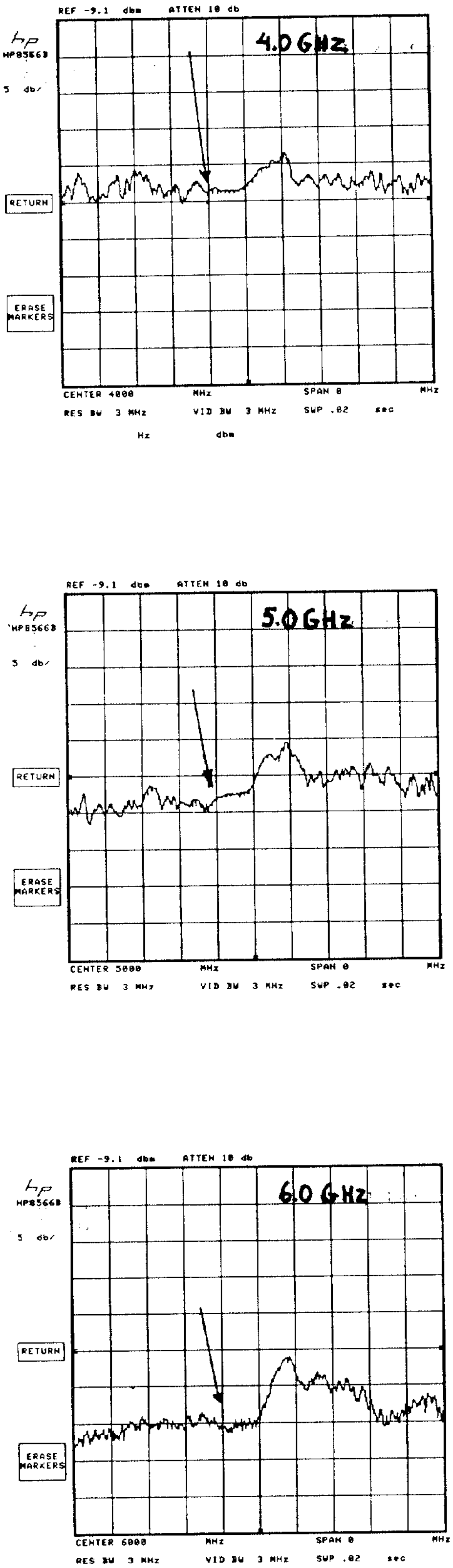

Figure 1: *Negative mass signals at different frequencies for bunches with emittance of 0.07 eV-sec and* 2.2×10^{10} *p.*

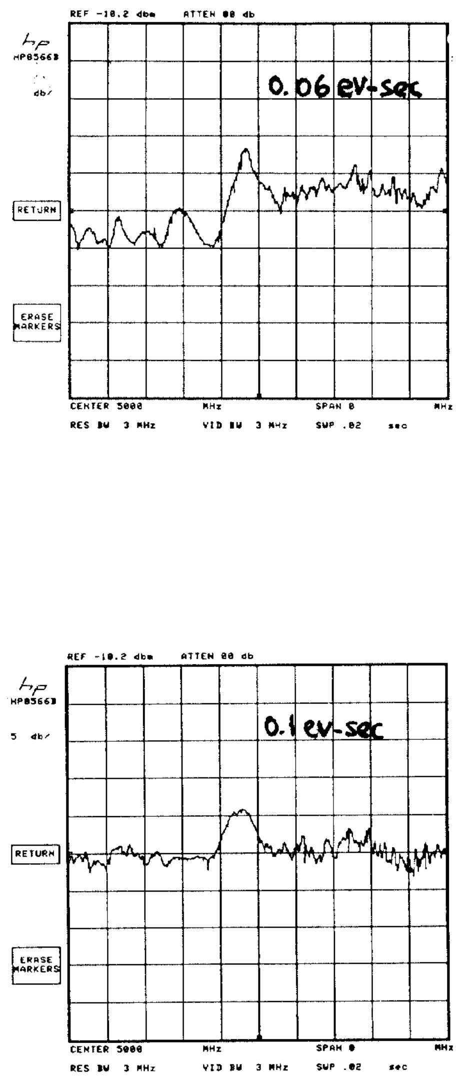

Figure 2: *Negative mass signals observed around transition at 5.0 GHz for bunches with the same intensity and different longitudinal emittances.*

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space charge, a blowup becomes significant when $\sum |c_k|^2$ grows to unity. Here the summation is over all the longitudinal modes of the bunch when the total bunch length $2\hat{\phi}$ in rf radian at transition is an integral number of the harmonic wavelength. As is well-known, the time-integral growth due to space charge after transition for revolution harmonic k is proportional to k. However, the space-charge parameter $g_0 = 1 + 2\ln(b/a)$, where $a \approx 0.5$ cm and $b \approx 3.5$ cm are, respectively, the beam and beam pipe radii, starts to drop when $k \sim \gamma R/b$, $R = 1000$ m being the the mean radius of the Main Ring. In fact, it drops to one-half of its value when $k_{\frac{1}{2}} \approx \gamma R(1.6/b + 0.52/a)$. Therefore the integrated growth has a maximum, which occurs at $k_c = k_{\frac{1}{2}}/\sqrt{3}$. In our case, this corresponds to 1.6×10^6 or 78 GHz. After summing up all the bunch modes, we have

$$\xi k_{\rm eff} \left(\frac{r_p}{R}\right)^2 \left(\frac{E_0^{5/2}}{h^{1/3}\omega_0^{4/3}\gamma^{2/3}}\right) \left(\frac{N_b^2 g_0^2 |\tan\phi_s|^{1/3}}{A^{5/2}\dot{\gamma}^{7/6}}\right) = cE_c \ , \tag{1}$$

where E_c is the maximum allowable time integrated growth at harmonic $k_{\frac{1}{2}}/\sqrt{3}$, and is given by

$$E_c = \frac{1}{2}\left[\ln N_b - \ln\left(\frac{k_{b\frac{1}{2}}\sqrt{8\pi}}{3\sqrt{\frac{1}{2}\ln N_b}}\right)\right] \ , \tag{2}$$

$k_{b\frac{1}{2}} = k_{\frac{1}{2}}\hat{\phi}/\pi h$, and $k_{\rm eff} = 3\sqrt{3}k_{\frac{1}{2}}/16$. When the critical coefficient $c < 1$, there is no blowup due to negative-mass instability. In the above, the coefficient $\xi = 2^{-17/6}3^{13/6}\pi^2\Gamma(2/3)(1-\pi/4)$, A is the bunch area in eV-sec, E_0 is the proton rest energy, and r_p is the classical proton radius.

The highest intensity in our measurement was $N_b = 2.2 \times 10^{10}$ protons per bunch. The transition gamma is $\gamma = 18.85$, the rate of acceleration across transition is $\dot{\gamma} \approx 90\ \text{s}^{-1}$ at the synchronous angle $\phi_s = 60°$. The blowup coefficient c for various bunch areas at such high bunch intensity are given in Table 1. The non-adiabatic time is 3.4 msec.

IV. Conclusion

A negative-mass instability is dominating the transition crossing in the Main Ring with the present emittances and intensities. The experimental data are in agreement with the negative mass instability threshold. In the next collider run, Main Ring is expected to accept bunches with intensity up to 4.0×10^{10} p. The emittance of these bunches is expected to be 0.11–0.12 eV-sec. (following the Booster longitudinal emittance vs intensity curves). In this case, the calculation in Table 2 shows that the instability threshold c remains about 1; i.e., things will not become worse than now. If the Booster emittance remains at 0.06 eV-sec, however, c becomes 5. Then, the blowup around transition will become much worse than now and there will be more beam loss.

Bunch Area (eV-s)	Bunch Length (ns)	c	E_c
0.040	0.438	4.07	9.88
0.050	0.490	2.34	8.83
0.060	0.537	1.49	9.78
0.070	0.580	1.02	9.74
0.080	0.620	0.73	9.71
0.100	0.693	0.42	9.66
0.120	0.759	0.27	9.61
0.140	0.820	0.18	9.57
0.160	0.876	0.13	9.54
0.180	0.929	0.10	9.51
0.200	0.980	0.08	9.48
0.220	1.027	0.06	9.46
0.240	1.073	0.05	9.44

Table 1: Negative-mass blowup coefficient vs bunch area at bunch intensity 2.2×10^{10} per bunch.

Bunch Area (eV-s)	Bunch Length (ns)	c	E_c
0.040	0.438	13.06	10.19
0.050	0.490	7.52	10.13
0.060	0.537	4.79	10.09
0.070	0.580	3.27	10.05
0.080	0.620	2.35	10.02
0.100	0.693	1.35	9.96
0.120	0.759	0.86	9.91
0.140	0.820	0.58	9.88
0.160	0.876	0.42	9.84
0.180	0.929	0.32	9.81
0.200	0.980	0.24	9.79
0.220	1.027	0.19	9.76
0.240	1.073	0.15	9.74

Table 2: Negative-mass blowup coefficient vs bunch area at bunch intensity 4.0^{10} per bunch.

Acknowledgment

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References

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