Experimental Study of the Main Ring Transition Crossing

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Abstract

The longitudinal emittance increase and the particle loss through transition as a function of the initial emittance in the Main Ring was studied. A phase mismatch at injection was used to change the initial longitudinal emittance and measurements were taken for different intensities and RF voltages around transition. The results of our measurements are in good agreement with simulation results from ESME and indicate that nonlinear effects dominate the transition crossing in the Main Ring under the present operating conditions ($\epsilon_L \geq 0.14$ eV-sec).

Introduction

A number of different experiments were proposed as part of the Fermilab III Instabilities Workshop in order to study the transition crossing in the Main Ring. Due to time limitations and operational restrictions only one of the experiments was actually performed. The results and analysis presented here are preliminary.

We used an injection mismatch to deliberately blow up the longitudinal emittance in the MR 29 cycles, and measured the increase in bunch emittance and the particle loss through transition as functions of the initial bunch emittance. The experiment was repeated for different intensities (2, 4 booster turns) and for different rf voltages around transition. The purpose of the experiment was to distinguish the mechanism that is responsible for emittance growth and particle loss across transition.

Two mechanisms can lead to the growth of bunch emittance and particle loss across transition. The first one is nonlinearity, which is due to the nonlinear terms in the expansion of the momentum compaction factor or the orbit length as a power series in the momentum spread. With these nonlinear terms, particles of different momenta cross transition at different times. The spread in crossing time is called the *nonlinear time* [1], which is proportional to the momentum spread and depends on the Johnsen's nonlinear coefficient [2] in the momentum compaction factor. After those particles with larger momenta than the synchronous particle cross transition and before the rf phase is switched, they are outside the accelerating bucket and drift away forming a tail in the longitudinal phase space. Those particles with lower momenta than the synchronous particle also develop into a tail after the rf phase is switched because they cross transition much later. These tails can lead to emittance growth and particle loss. The second mechanism is microwave instability because the phase-slip parameter $\eta = 1/\gamma_T^2 - 1/\gamma^2$ is vanishingly small near transition and therefore cannot provide enough Landau damping to stabilize the growth of the microwave amplitudes. However, these two mechanisms are very different.

If nonlinear effect dominates at transition crossing, we expect the effect to increase with initial bunch emittance ϵ_L and the rf voltage $V_{\rm rf}$ at transition. This is because a bigger ϵ_L or a bigger $V_{\rm rf}$ at constant $\dot{\gamma}_T$ implies larger momentum spread, which enhances the time difference between the fastest particle and the synchronous particle in crossing transition. In fact, according to [1], we have

$$\frac{\Delta\epsilon_L}{\epsilon_L} \propto \epsilon_L^{\frac{1}{2}} V_{\rm rf}^{\frac{2}{3}} \ . \tag{1}$$

On the other hand, if microwave instability dominates at transition crossing, we expect its effect to decrease with initial bunch emittance and rf voltage at transition. This is because both larger ϵ_L and $V_{\rm rf}$ imply larger momentum spread near transition, which in turn provides more Landau damping for stabilization. We obtain from [3] and [4] that

$$\frac{\Delta\epsilon_L}{\epsilon_L} \propto \epsilon_L^{-3} V_{\rm rf}^{-1} \ . \tag{2}$$

When the bunch emittance is sufficiently small, the dominant effect should be microwave instability. However, when the bunch emittance is sufficiently large, nonlinearity should dominate. As a result, we expect to see the variations of emittance growth and particle loss as functions of initial bunch emittance to follow curves as indicated in Figure 1. Also microwave effect is intensity dependent while nonlinear effect is not.

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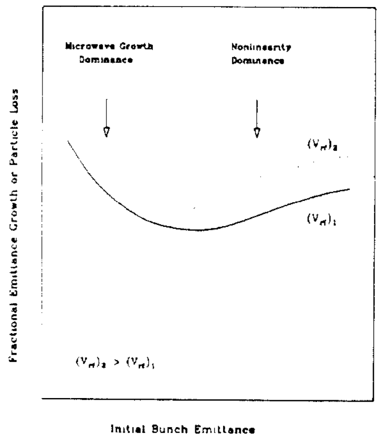

Figure 1: *Schematic plot of fractional growth of bunch emittance and particle loss across transition versus initial bunch emittance at different transition rf voltages.*

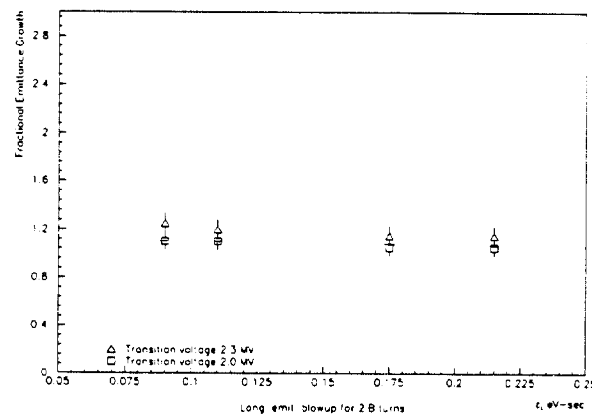

Figure 2: *Change in bunch area as a function of initial bunch emittance for the first set of measurements and 2 booster turns.*

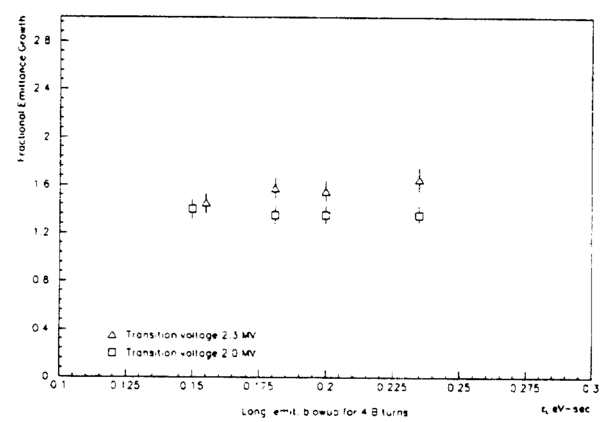

Figure 3: *Change in bunch area as a function of initial bunch emittance for the first set of measurements and 4 booster turns.*

Preparation and setup

We found that the most effective way to increase the emittance at injection in the MR was through phase mismatch. We started with 0° phase error and tuned the rf voltage at injection so as to minimize the bunch length oscillations measured by the BLMON, a bunch-length monitor which is not well-calibrated. The absence of synchrotron oscillations before transition was checked by taking mountain range pictures at 0.32 sec into the cycle i.e., 60 ms before transition.

The longitudinal emittance was calculated by measuring the bunch length (from mountain range pictures), the rf voltage and the rf phase at two places before transition (60, 30 ms) and at two places after transition (60, 150 ms). The particle loss through transition was measured with the intensity monitor IBEAMM. An injection phase error was then introduced and the measurements were repeated. The phase error varied between 0° and 40°. As mentioned before, measurements were taken at two different intensities, i.e., for 2, 4 booster turns corresponding to 0.9×10^{10} and 1.6×10^{10} ppb respectively.

A second set of measurements were taken at a later time using a modified 29 cycle with a 0.5 sec long front porch after transition (40 GeV) in order to measure the emittance after transition of a stationary bucket instead of an accelerating one. We also used 14 out of 16 Booster cavities with the remaining cavities shorted in order to reduce emittance blowup due to coupled bunch instabilities in the Booster and to start with smaller long. emittance. This time mesurements were taken for 4 Booster turns corresponding to an intensity of 1.4×10^{10} ppb. The phase error varied between 0° and 30° and measurements were taken for three different transition voltages.

Results and Conclusions

The results of our first measurement are summarized in Figs. 2 and 3, where we have plotted the growth in bunch area through transition as functions of the initial emittance for two different intensities and two transition voltages. The results of our second measurement are plotted in Fig. 4 where the growth in bunch area through transition is shown as function of the initial emittance for one intensity (4 Booster turns) and three transition voltages. The errors in all the figures indicate mainly the uncertainty in estimating the bunch length.

Figures 2 and 3 show clearly that both the fractional growth in emittance and particle loss increase with V_{rf} at transition. As a result, we concluded that nonlinear effect dominates the Main Ring at transition, at these emittances. However, a closer look at Figs. 2 and 3 reveals that the fractional growth in emittance stays roughly constant with the initial bunch emittance at V_{rf} = 2.0 MV for 4-booster-turn injection, and even de-

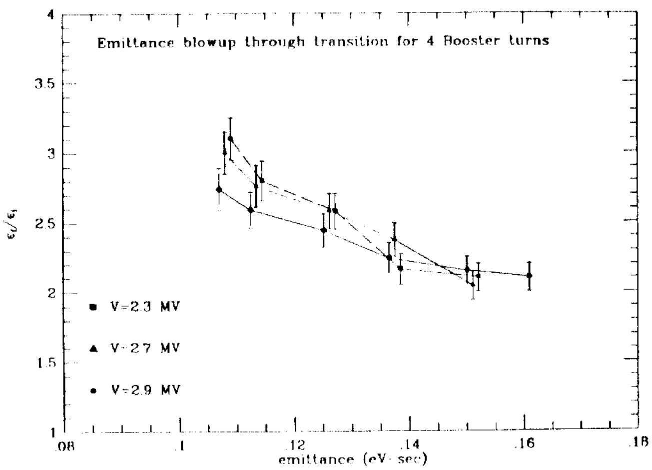

Figure 4: *Change in bunch area as a function of initial bunch emittance for the second set of measurements and 4 booster turns.*

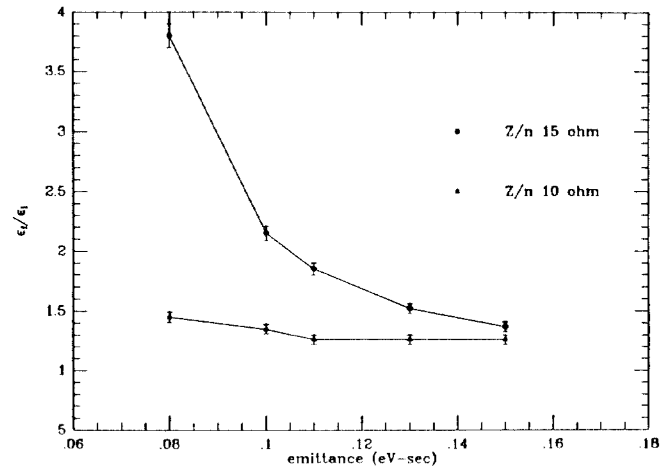

Figure 5: *Change in bunch area as a function of initial bunch emittance for two values of Z/n as predicted by ESME.*

creases slightly with ϵ_L at both $V_{\rm rf} = 2.0$ MV and 2.3 MV for 2-booster-turn injection. The 4-booster-turn results are understandable. A $\Delta\epsilon_L/\epsilon_L$ constant with ϵ_L at $V_{\rm rf} = 2.0$ MV implies that there is some contribution from microwave instability. At $V_{\rm rf} = 2.3$ MV, the bunch becomes much more microwave stable and therefore $\Delta\epsilon_L/\epsilon_L$ increases with ϵ_L due to nonlinear effect in the region 0.15 eV-sec $< \epsilon_L <$ 0.23 eV-sec. In the same ϵ_L region and at the same $V_{\rm rf}$, a 2-booster-turn (lower intensity) bunch should be much less affected by microwave growth than a 4-booster-turn bunch. We should expect more nonlinearity dominance so that the fractional growth of emittance should increase more rapidly with ϵ_L than the 4-booster-turn results. However, as depicted in Fig. 2 the fractional growth of emittance decreased slightly with ϵ_L instead. This contradiction may have arised from errors in the measurement.

With our second measurement we were able to start with smaller initial bunch emittance for about the same intensity and to approach the area of microwave dominance as is shown in Fig. 4. Clearly the emittance growth is bigger for the smaller transition voltage as expected from the microwave instability, up to about 0.14 eV-sec where the growth levels out and remains almost costant. The signature of the microwave instability at small emittances and at these intensities reveals the existance of an appreciable ($Z/n > 10$ ohms) longitudinal impedance in the Main Ring. Some ESME simulations were done with a broadband (Q=2) high frequency impedance and with the same intensity as in our last set of measurements. The results of the simulations are plotted in Fig. 5 where the fractional growth in bunch area is plotted as a function of the initial bunch emittance for two values of Z/n. The results of our second set of measurements along with the ESME simulations indicate, that for emittances smaller than 0.14 eV-sec and intensities bigger than 1.4×10^{10} ppb, microwave instability dominates the transition crossing in the Main Ring, and can lead to a large emittance blowup for emittances smaller than 0.12 eV-sec.

References

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[4] K.Y. Ng *"Some Estimation Concerning Crossing Transition of the Main Injector", FNAL-TM1670, 1990.*