Measurement of the Resistive Wall Instability in the Fermilab Main Ring

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Abstract

An instability disruptive to high current Main Ring operations is the vertical resistive wall instability. Tunes, chromaticities, and feedback loop gains must be continuously adjusted to preserve the beam intensity at injection. Results of frequency and time domain measurements aimed at understanding the sensitivity of the beam to this instability are presented. The influence of selected accelerator parameters are studied in detail. In addition, the effectiveness of various cures are reviewed.

I. INTRODUCTION

The existence of the vertical resistive wall instability in the Main Ring has been known for some time now [1]. It is an operational problem during fixed target operations where 12 batches of 81 bunches are injected from the Booster and accelerated each Main Ring acceleration cycle. The intensity per bunch is operationally around 1×10^{10}. For reasons not understood, a severe version of this instability occurs predominantly during the warm summer months.

Two feedback loops presently work to stabilize the vertical motion of the beam. The slow damper loop has a megahertz scale bandwidth, and is the most effective of the dampers. The bunch-by-bunch vertical superdamper is a much weaker loop, but has good diagnostics which are utilized in this work. The slow damper is always off for the work presented in this paper.

II. EXPERIMENTAL METHOD

The measurement of vertical betatron oscillations is accomplished by monitoring the output of the Main Ring bunch-by-bunch vertical superdamper reciever. A block diagram of the system is in figure 1. The spectrum analyzer monitors the transverse position signal, which because of the 53 MHz heterodyning superdamper reciever is only sensitive to dipole beam oscillations. Figure 2 contains a plot of the transverse betatron spectrum in the form of an AM modulation pattern around the 53 MHz RF frequency. Taken while the beam was suffering from this instability, note that the n-Q lines (Q=19.42) have 10x more oscillation power than the n+Q lines, as expected from a resistive wall instability [2].

To perform betatron oscillation damping rate or growth measurements, the spectrum analyzer was placed in zero span mode, centered on the lower n-Q line visible in figure 2. The resolution bandwidth was 3 kHz, which is narrow enough to isolate the line without restricting damping rate measurements.

Injection requires the transfer of 12 batches from the Booster, where the beginning of successive batches are separated by either 95 or 599 RF buckets (h=1113). For these studies the Main Ring remained at the injection energy.

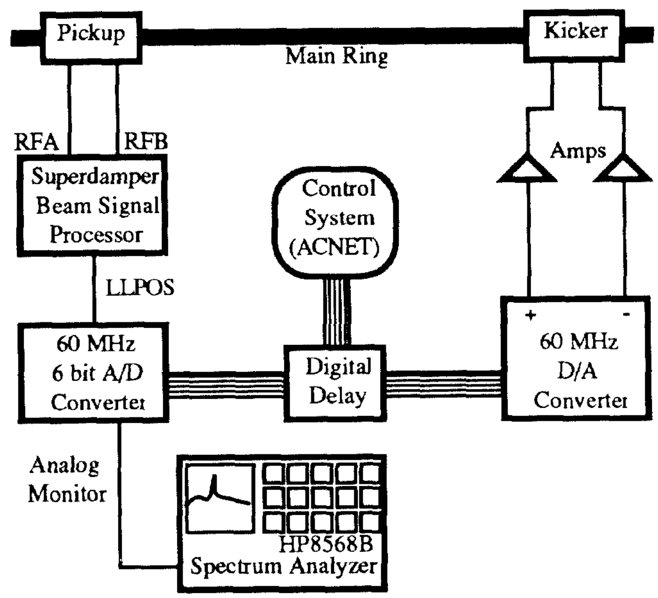

Figure 1: Schematic diagram of the Main Ring vertical bunch-by-bunch superdamper system.

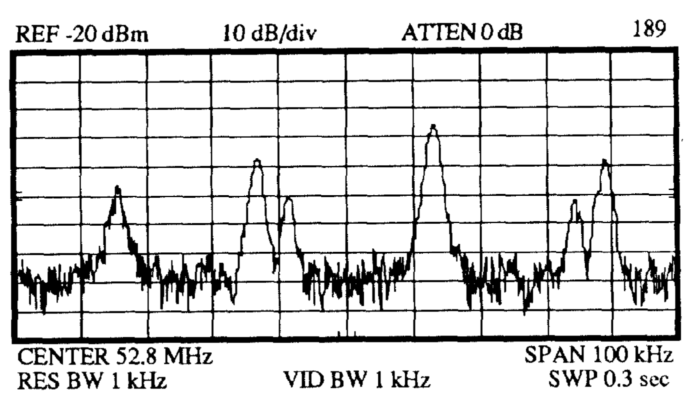

Figure 2: Measured betatron spectrum. The tallest peak corresponds to the RF frequency. The betatron sidebands to either side are visible due to the instability.

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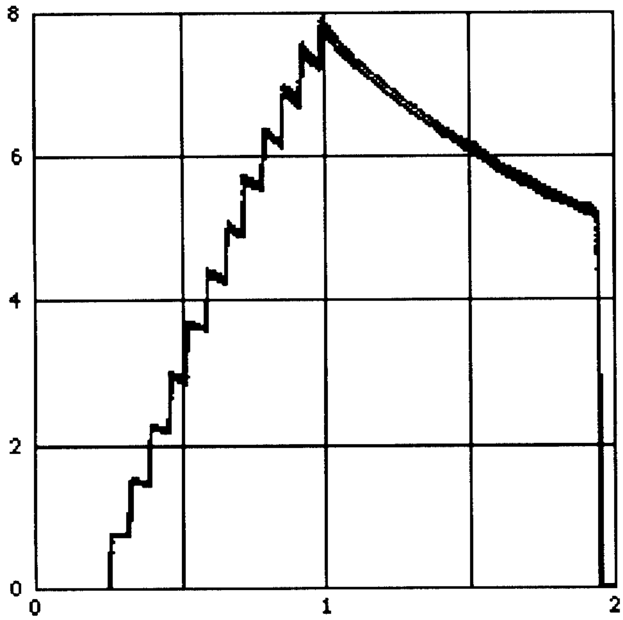

Figure 3: Beam intensity (units of 10^{12}) as a function of time (in seconds) for 4 consecutive injection cycles. During this time the beam was stable.

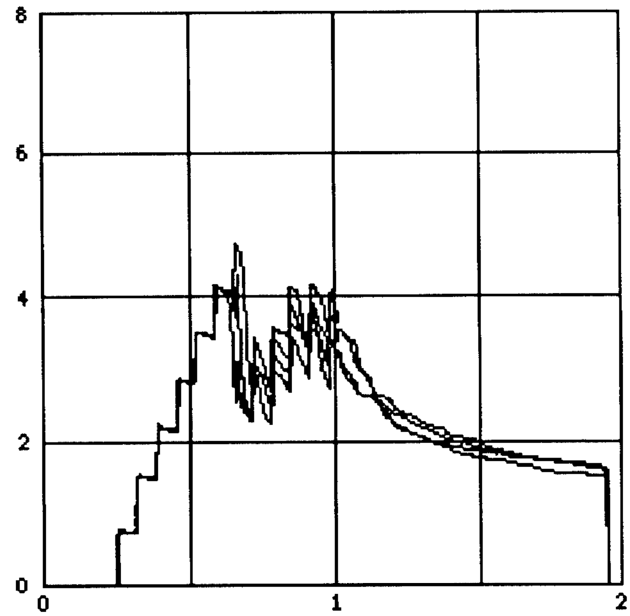

Figure 5: Beam intensity vs. time with the superdamper turned off and the batch spacing set at 599 RF buckets. Under these circumstances the beam clearly goes unstable.

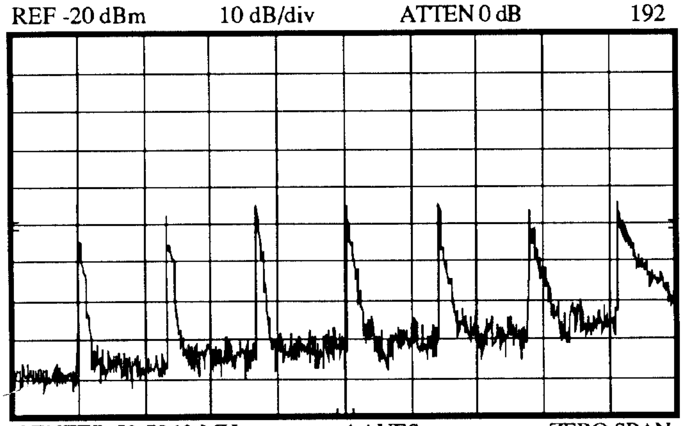

Figure 4: Betatron oscillation amplitude vs. time during the injection cycles displayed in figure 3. Batches 1-7 are shown. The superdamper was on and the batch spacing was 95.

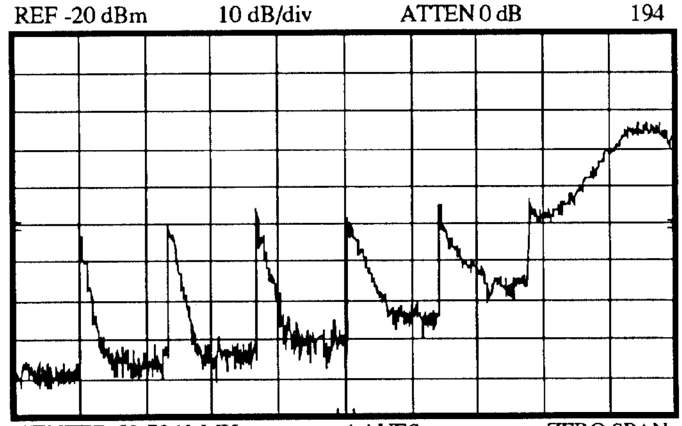

Figure 6: Injection of batches 1 through 7 during the injection cycles displayed in figure 5. Note that batch 6 was marginally unstable, and batch 7 is no longer visible.

III. RESULTS

The first measurements involved the variation of the batch injection spacing, both with the superdamper on and off. Figure 3 and 4 show the beam intensity and average betatron oscillation amplitude as a function of time with the superdamper on and a batch spacing of 95. Note that the damping rate of the betatron oscillation depended on the stored current in the accelerator. When the batch spacing was changed to 599 the damping time was cut in half and the intensity lifetime improved. With the superdamper off injections with either value of the batch spacing were unstable. Figures 5 and 6 show the case of a batch spacing of 599. For a spacing of 95 even batch 5 was unstable.

By studying a number of accelerator parameters it was found that the instability was most sensitive to vertical chromaticity $\xi=\Delta Q/(\Delta p/P)$. With the superdamper on the chromaticity was varied from -40 (stable below transition) to +20. Larger absolute values of chromaticity yielded shorter betatron damping times and intensity lifetimes. Near zero chromaticity the beam was maximally unstable. Table 1 contains a summary of the chromaticity scans.

The RF voltage also played a big role in the damping rate of the injection betatron oscillations. See Table 2 for a summary of the data. The general trend indicates that higher RF voltages cause the beam to be more betatron stable. The superdamper was off during these measurements on batch 6. The batch spacing was 599 RF buckets and ξ=-20.

Chromaticity ξ	Growth Rate (sec^{-1})
-40	-83
-30	-37
-20	-23
-10	-3
0	+11
10	0
20	-20

Table 1: Oscillation growth rate as a function of chromaticity at injection.

RF Voltage (MV/turn)	Growth Rate (sec^{-1})
0.5	-6.8
1.0	-10.4
1.5	-16.4

Table 2: Oscillation growth rate as a function of the RF voltage at injection.

In order to further explore the dependence of betatron stability on the condition of longitudinal phase space, the above studies were repeated with the RF voltage off. After the bunches are injected they immediately begin to shear in phase space. For an injection repetition rate of 15 Hz and a 95 bucket batch delay, only about 10% of the previous batch intensity shears into the aperture of the following injection kick. The resultant injection profile is shown in figure 7.

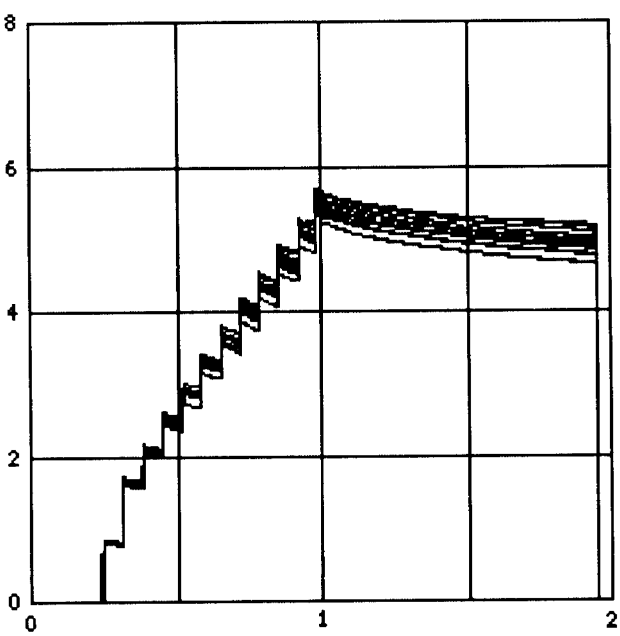

Figure 7: Beam intensity vs. time under the same conditions as the data in figure 5, except the RF is turned off. Because of phase space shearing in the time between transfers, some stored beam is kicked out each batch injection. Therefore, the peak intensity is lower than in the RF-on case.

Even though this data was taken under the same conditions as those in figure 5, note that now the beam is completely stable with a very long lifetime. Unfortunately, since the superdamper reciever depends on the existence of 53 MHz beam structure, no oscillation information was recorded.

IV. Proposed Cures

Under normal circumstances the vertical resisitive wall instability can be suppressed by running with large, intensity dependent chromaticities and with the dampers turned on. Unfortunately, the beam intensity lifetime is sacrificed when the chromaticity is run so large. In addition, the dynamic range of the damper recievers are quite small in power and aperture, requiring constant tuning of attenuators and the closed orbit through the beam position striplines.

It has been calculated that the wall resistance in the Main Ring may be the dominant source of transverse impedance at frequencies below 1 GHz [3]. Recently however it has been discovered that the ferrite loaded window-frame type kicker magnets may actually supply the dominant impedance at low frequencies [4,5]. If true, the best cure for this instability is to fix its source and modify these kicker magnets.

In the mean time a set of studies have been initiated to understand the open loop transfer funtion characteristics of the damper systems. For example, at the location labelled LLPOS in figure 1 the signal path was interupted and a network analyzer installed. Preliminary measurements have been successful. For instance, a peak gain of -35 dB was observed.

Finally, a narrow band n-Q feedback loop is presently under construction. In parallel, better injection oscillation correction controls are being designed. The goal is provide a high gain and sensitivity feedback loop on the dominant resisitive wall betatron mode which can operate throughout the cycle. Since it will be a narrow band analog circuit it will not suffer from the same dynamic range deficiencies of the present dampers. Testing will occur during fixed target operations.

V. References

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