An Investigation of the Source of a Low-Q, Low-Frequency Impedance Disrupting Bunch Coalescing in the Fermilab Main Ring

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Abstract

Recent studies of bunch coalescing in the Fermilab Main Ring have indicated the likelihood of a low-frequency, low-Q resonator being responsible for the distortion of the coalesced bunch at high beam intensities. Numerical simulations have shown that a sufficiently high longitudinal impedance is sufficient to account for the observed bunch break-up. A survey of possible offending beam components has been made, and measurements of the longitudinal impedance of these components, including a variety of kicker magnets and coalescing cavities in the Main Ring have been carried out.

I. INTRODUCTION

The coalescing process in the Fermilab Main Ring consists of adiabatically lowering the rf voltage so that a series of bunches effectively debunches, followed by a phase space rotation and recapture in a somewhat larger bucket. In this manner, a high intensity bunch can be constructed out of a series of lower intensity bunches. [1] However, it has been observed that the efficiency of this process degrades as the number of protons in the ensemble increases. In particular, experiments have indicated that charges which arrive at later times in a series of bunches are being pushed out of the buckets, and the overall coalescing efficiency has been observed to decrease nearly linearly with total intensity. [2]

In order to explain these results, the existence of a low-Q, low-frequency resonator has been hypothesized, which can account for several of the details of the observations. [3] In this paper we extend the earlier analyses with a theoretical simulation of the effect, and present the results of bench measurements of various beamline magnets, which were proposed as candidates for the source of the offending longitudinal impedance.

II. RESONATOR MODEL

Since the leading edge of the bunch train is unaffected during coalescing, it is assumed that the resonator Q is such that the resonator fields have decayed away within one revolution period (20.9 μS). Moreover, the resonator period is ostensibly considerably longer than the series of bunches (200 nS), since the deceleration appears to increase roughly linearly towards the end of the ensemble. A feasible candidate would be a resonance between a few hundred kHz to a few MHz. For such a case, the voltage applied to the beam can be modelled by a simple RLC circuit.

During the brief period of passage of the bunch series, the voltage is primarily due to the buildup of charge on the capacitance C, and analysis of the required voltage puts the estimate of C at about 40 pF, for an average bunch current of 200 mA. Q is expected to be in the range of 1 - 5 and hence R ~ 1 kΩ. In order to make quantitative estimates, we consider the time domain solution of the induced voltage using standard Laplace methods,

$$V(t) = f(t)u(t) - f(t-\Delta)u(t-\Delta)$$

where

$$f(t) = I_o R\left(1-\cos\left[\omega_r t\right]e^{-\frac{Rt}{2L}}\right) + I_o \omega_r\left(L - \frac{R^2 C}{2}\right)\sin\left[\omega_r t\right]e^{-\frac{Rt}{2L}}$$

u(t) is the Heaviside function, and Δ is the total bunch length. For times short with respect to $1/f_r$, the voltage rises linearly with time.

III. THEORETICAL SIMULATION

Particle tracking simulations have been carried out using the ESME code. [3] In this work, the protons are assumed to be at an intensity of 10^{10} per bunch. In Fig. 1(a) and (b), the results of a coalescing simulation are shown for the case of zero impedance. With increasing time (toward the top of the plot), the bunches first begin to debunch, then rotate and are finally recaptured into a single high intensity peak. In Fig. 1 (c) and (d), a low Q ~ 10 resonator with ω_r ~ 1 MHz, and a shunt impedance of 200 kΩ was assumed. It is clear from this study that such a low Q resonator would have an effect close to that observed, provided its shunt impedance were high enough. As a result of parametric studies, it has been found that total ring impedance levels below about 10 kΩ are insufficient to produce substantial deceleration of the trailing bunches.

Of the various beam components in the Main Ring, the most suspect of containing low Q resonances are the coalescing cavities themselves, or any of the variety of ferrite or ferromagnetic kicker magnets in use. Direct beam loading measurements of the cavities suggest that their combined impedance is less than 100 Ω [4], so attention has been focussed on bench measurements of the kicker magnets' impedance.

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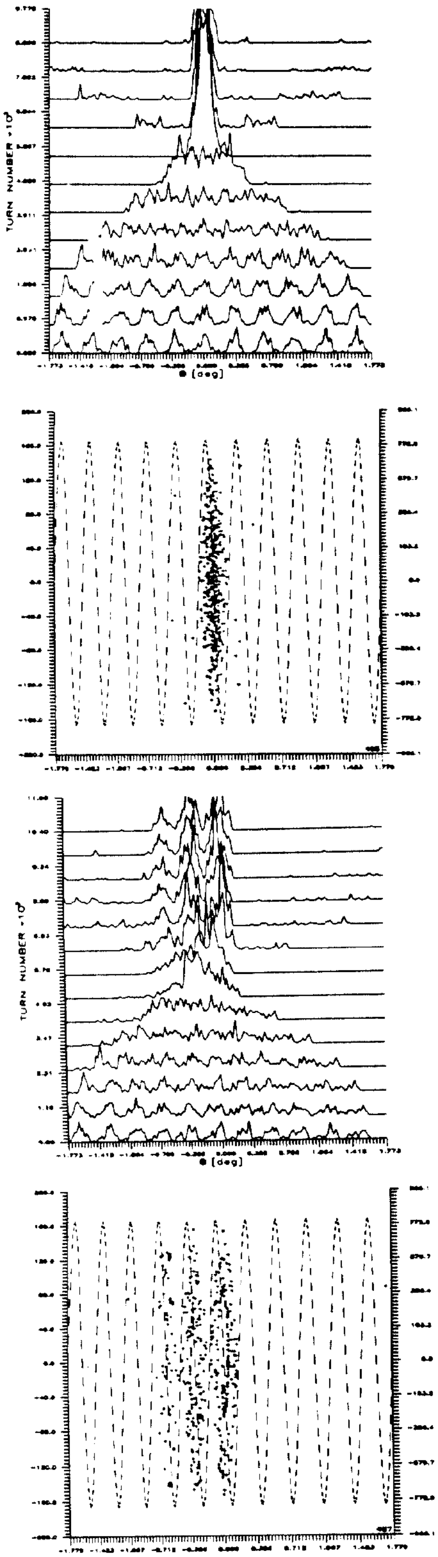

Fig. 1 (a) Plot of bunch current versus arrival time for successive times during the coalescing cycle. Time increases toward the top of the plot. (b) is the corresponding phase space plot. In case (a) and (b), no impedance is assumed. In (c) and (d), a large ~100kΩ impedance is assumed, which causes deceleration of trailing bunches in the ensemble.IV. Kicker Magnet Measurements

IV. KICKER MAGNET MEASUREMENTS

The inventory of kicker magnets in the Main Rng is shown in Table 1. They fall into two classes (a) C-frame magnets and (b) H-frame magnets, with either ferrite or tape-wound-steel as magnetic materials. The H-frame magnets are particularly suspect because of bus lines that may be closely coupled to ferrite materials. A sketch of a typical H-frame device (the C-48 kicker) with associated busswork is depicted in Fig. 2. The bus bars form a coupled transmission line that is effectively terminated in a capacitance at the upstream and downstream ends. In addition, the power feed circuitry applies a short circuit to the input of one bus bar, while 25 Ω occurs across the other. Similar situations occur in the other kicker magnets. The characteristic impedance of the individual lines is measured to be ~ 70 Ω, and due to the presence of the magnetic material, the phase velocity is about 0.7 c. The primary capacitance of interest is at the upstream end, since it can affect trailing bunches. A direct measurement places this value at about 80 pF.

Table 1. Kicker Magnet Types in the Main Ring

Location	Type	Magnetic Material
B-48	H	Tape-wound-steel
A-11	C	Ferrite
F-14	H	Ferrite
C-48	H	Ferrite
E-17	C	Tape-wound-steel

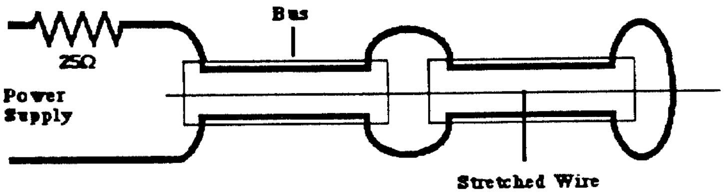

Fig. 2 Sketch of the C-48 kicker magnet. The bus bars form a ferrite loaded transmission line which comprises a low-Q resonator.

The longitudinal impedance of this kicker was measured with a stretched-wire [5] of characteristic impedance 356 Ω, as shown in Fig. 2. Resistor matching networks at the ends provided a wideband match from DC to about 800 MHz, which permits the extraction of the longitudinal impedance from the transmission loss. The measured frequency response of the kicker, including the power feed circuitry, is shown in Fig. 3.

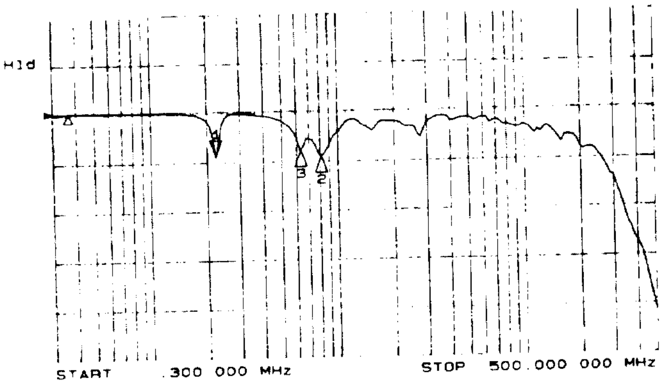

Fig. 3 Transmission response of the kicker from stretched-wire measurements. Absorption peaks indicate impedance maxima. Several low-Q resonances are observed.

The results indicate several low-Q resonances, though due to the requirement that the resonant frequency be less than the inverse bunch length in seconds, it is likely that only the lowest frequency mode can have an appreciable effect. It is noteworthy to observe that the impedance becomes large at high frequencies, likely due to losses in the low conductivity wall coatings and magnetic materials of the kicker, though this impedance is not expected to play a role in the coalescing process.

To determine the quantitative effect such a resonator may have on the beam, we apply the simple resonator model of Sec. II to a time domain measurement of the voltage developed between the kicker bus and the beam pipe for a given input current. The resonator model can be made to fit well the measured voltages, as shown in Fig. 4 (a) and (b). The voltage is observed to rise first linearly on the capacitor, then saturate as the inductance of the ferrite becomes important during the first half cycle. The bunch train exits the kicker before the full voltage of the resonator has built up, giving rise to a maximum voltage of about 15 volts. Other kicker types were found to have a similar order of magnitude response, which leads to the conclusion that about 100 Volts can be accounted for by the kickers.

V. DISCUSSION AND SUMMARY

We have confirmed theoretically that a low-Q resonator of sufficiently high impedance can explain the experimental observation that increasing bunch intensity leads to decreasing coalescing efficiency. In particular, the deceleration of trailing bunches points to a resonant frequency in the MHz range with an approximate shunt impedance of 1 - 5 kΩ. Measurements of the several kicker magnet types employed in the main ring suggest such a resonator may indeed exist, but the magnitude of the measured voltages falls a factor of 10-100 below the expected values based on simulations. While it can be expected that there is some uncertainty in both the measurements and the simulations, it does not appear likely that the kicker magnets are alone responsible for the decrease in coalescing efficiency.

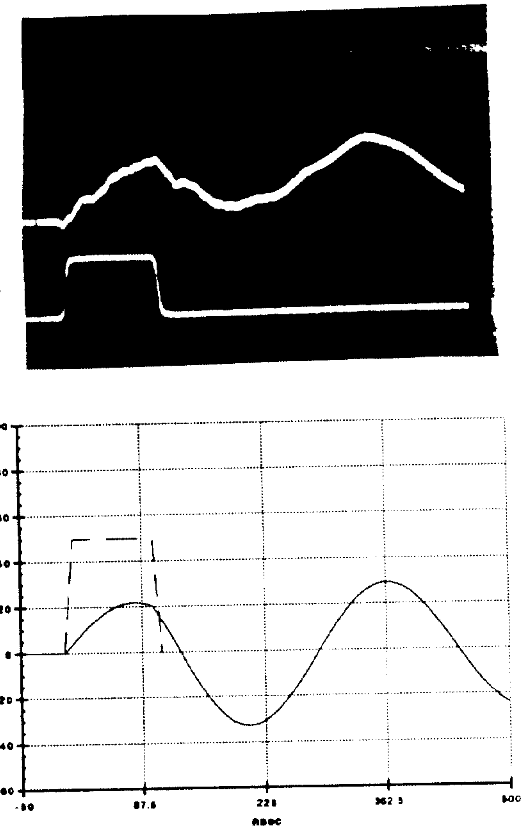

Fig. 4(a) Measurement of induced kicker voltage corresponding to a peak current of 200 mA. and (b) the corresponding resonator model with C=460 pF, L= 5.4 μH and R=7.5 Ω.

In future work, we plan to investigate the source of impedance with direct beam measurements, and to continue to make bench measurements of suspect beamline components. It may be the case that the total impedance is a sum of a large number of small, roughly equal contributions, which would suggest that the most appropriate solution is the development of a feedback system to combat the decelerating voltages around the entire ring.

VI. REFERENCES

[1] J. Griffin, et. al.,"RF Exercises Associated with Acceleration of Intense Antiproton Bunches at Fermilab", IEEE Proc. Nucl. Sci., NS-30, 4, (1983) p.2627

[2] P. Martin,K. Meisner, D. Wildman, Proc. IEEE Particle Accel. Conf., (1987), p. 1527

[3] J. Griffin, "Bunch Coalescing", Proc. of the Fermilab III Workshop on Beam Instabilities (Batavia, Ill., 1990)

[3] J. MacLachlan, "Fundamentals of Particle Tracking for the Longitudinal Projection of Beam Phasespace in Synchrotrons", Fermilab FN-481, 1988

[4] D. Wildman, Private Communication

[5] P. Colestock, et. al., These Proceedings.

[6] X. Lu, G. Jackson, These Proceedings