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Impedance of Booster Band II Cavity and Associated Instabilities

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Subject: Impedance of Booster Band II Cavity and Associated Instabilities

1 Summary

Using a single bunch in the Booster, the band II cavity impedance was measured at the first few revolution lines on a long front porch. Fitting an LRC circuit model to these data yielded cavity parameters as a function of tuning current. The results with beam were quite different from the results obtained without beam. The discrepancy may be due to the sparse sampling in frequency for the data taken with the beam.

Using three bunches in the machine, the cavity was tuned to maximize the impedance at the first revolution line. This resulted in a coupled bunch longitudinal dipole instability. The growth rate of the instability is in good agreement with theoretical predictions. Tuning the cavity to about half the RF frequency resulted in growth rates too small to measure. It is not known whether the system was truly stable.

2 Introduction

Under ideal conditions, the Booster will accelerate protons and heavy ions on a pulse to pulse basis. If one is to minimize the complexities of bunch coalescence (shifts in harmonic number) both the band II and band III RF systems need to be operational during heavy ion cycles. Previous work [1] indicates that the presence of the band II system, when viewed as a parasitic resonator, might be highly detrimental to high intensity proton operation. The purpose of this study was to measure the impedance of the band II cavity and the effect of this cavity on proton operation.

3 Impedance Measurements

With a single bunch in the Booster, and a long front porch on the user 3 magnet cycle, a swept filter spectrum analyzer was used to measure the voltage across the wall current monitor and the band II cavity gap at the first few revolution harmonics and as a function of bias current on the cavity. The revolution frequency on the front porch was 850 kHz. Only 1 bias winding in the cavity was used, with no external capacitance on the gap and no power amplifier. Under the supposition that the wall current monitor acted as a pure resistor with R = 3.125Ω, the ratio of the voltages were used to obtain the magnitude of the band II impedance. The data were fitted to an LRC circuit model yielding effective values for the resonant frequency (f_r) , shunt impedance (R_s) and quality factor (Q) of the band II cavity as a function of bias current (I_b). The fit results are summarized in Table 1.

In addition to the best fit parameters, the one standard deviation uncertainty in the fitted value of the shunt impedance (δR_s) is given in column 3 of Table 1. The sudden drop in δR_s at 60 amp bias current occurred when the resonant frequency became larger than the revolution frequency. The errors in f_r and Q became significantly smaller at the same time. One suspects that the sudden drop in the errors is due to the data constraing the impedance on both sides of the peak. Column 6 of Table 1 shows the quantity $R_s f_r/Q$, which is proportional to the integral of the impedance with respect to frequency, which in turn is proportional to the loss factor $k = \pi f_r R_s/Q$ for the fundamental mode [2]. The loss factor is nearly independent of frequency, which is suggested by the following argument.

The loss factor may be written as [2]

$$k = \frac{|V|^2}{4U} \tag{1}$$

$$V = \int E_z(0,0,z)e^{i\omega z/c}dz \tag{2}$$

$$U = \frac{1}{2}\int \epsilon(x,y,z)\mathbf{E}(x,y,z)\cdot\mathbf{E}^*(x,y,z)dxdydz. \tag{3}$$

where $\epsilon(x,y,z)$ is the permitivity tensor as a function of position, $\omega = 2\pi f_r$ and $Re(\mathbf{E}e^{-i\omega t})$ is the electric field for the mode. For lossless materials the electric field satisfies

$$\nabla\times\left\{\mu^{-1}\nabla\times\mathbf{E}\right\} = \epsilon\omega^2\mathbf{E}, \tag{4}$$

where μ is the permeability tensor. If all the material properties are taken as piecewise constant, the boundary conditions at interfaces between different materials are that the transverse component of $\mathbf{E}$ is continuous and the

Table 1: Band II impedance parameters

I_b	R_s	δR_s	f_r	Q	$R_s f_r / Q$
Amp	kΩ	kΩ	MHz		kΩ-MHz
0	2.182	5.206	0.759	2.071	0.800
10	4.607	92.254	0.685	3.835	0.823
20	4.981	60.494	0.736	4.321	0.849
30	5.171	19.329	0.791	5.034	0.813
40	5.796	24.369	0.782	5.056	0.896
50	5.393	34.750	0.634	3.287	1.040
60	1.585	0.050	0.914	1.330	1.090
70	1.429	0.099	1.099	1.459	1.076
80	1.408	0.076	1.292	1.698	1.071
90	1.750	0.032	1.398	2.429	1.007
100	1.802	0.058	1.526	2.691	1.022
110	2.121	0.022	1.613	3.359	1.019
120	2.301	0.035	1.743	3.800	1.055
130	2.428	0.025	1.862	4.216	1.073
140	2.017	0.140	1.921	3.698	1.048
150	2.351	0.003	2.078	4.727	1.034
160	1.778	0.015	2.189	3.675	1.059
170	1.427	0.012	2.291	3.028	1.080
180	1.218	0.001	2.448	2.722	1.095
190	1.159	0.001	2.560	2.643	1.123
195	1.072	¡ 0.001	2.600	2.554	1.091

longitudinal component of $\mathbf{D} = \epsilon\mathbf{E}$ is continuous. If the *shape* of the electric field (eg. a field line plot) does not change with frequency then the loss factor won't either. Personal experience with the Superfish code seems to bear this out.

On the other hand, Bench measurements of the band II cavity impedance [3] indicate that the quality factor of the resonator increases smoothly from 2.7 to 4 as the bias current is increased from 0 to 200 Amps. The data described in this report suggest that the quality factor reaches a peak value of about 4.7 at a bias current of 150 Amps and drops to 2.5 at a bias current of 195 Amps. The error bars on the fits are far too small to account for such a difference. If the impedance of the band II cavity *is not* well modeled by an LRC circuit, the discrepancy could be due to the sparse frequency sampling of the measurements using the beam. (eg. The full width at half max of the impedance line is similar to the frequency spacing of the measured values.) It is difficult to reconcile the nearly constant loss factors with this possibility. More measurements with the beam appear warranted.

4 Instability Measurements

For all measurements there were 2.0E+11 protons per bunch, obtained by integrating under a wall current monitor pulse, and the full length of the bunch was 120° of RF phase. The revolution frequency on the front porch was 850 kHz. The band III gap voltage was 30 kV. Initially, the band II bias voltage was set to 35 Amps, the setting for which the single bunch gap volts was maximized. The filter of the spectrum analyzer was set to a center frequency of 850 kHz, with a resolution bandwidth of 100 kHz and no frequency span. Figure 1 shows a typical plot of the analyzer trace. The signal increases exponentially over the first 40 ms, a clear sign of instability. The e-folding time for the amplitude of the instability is 30 ms. Note that the e-folding time for the analyzer trace is half the amplitude e-folding time, since the analyzer measures power. A mountain range plot of the bunches is shown in Figure 2. From the plot it is clear that the unstable mode is a coupled bunch dipole mode. Figure 3. shows a typical oscilloscope trace of the bunches near saturation (eg. where Figure 1 rolls over). Notice that the width of the three bunches is different. This may be due to an unstable quadrupole mode, or simply the partial filamentation of the dipole mode. No quantitative data for this phenomena were obtained.

Theoretical predictions for the instability were made using a computer code which calculates growth rates in the weak coupling formalism of Sacherer, Besnier, and Zotter. A parabolic line density was assumed. Ball park numbers for the resonator were take to be $R_s = 3$ kΩ, $f_r = 0.85$ MHz, and $Q = 2.5$. The fastest growing mode was a coupled bunch dipole mode with an e-folding time of 31 ms. All other modes had growth rates down by an order of magnitude. When the bias on the cavity was set to 75 amps the instability dissappeared. Theoretical predictions for the dipole mode with a 75 amp bias on the cavity yield e-folding times of order 130 ms, giving a total growth of a factor of 10 in amplitude over the 300 ms porch. This seems small enough to miss. Calculations (with this new code, not ZAP) show that all other modes grow more slowly than the dipole mode. On the whole, the agreement between theory and experiment is quite good.

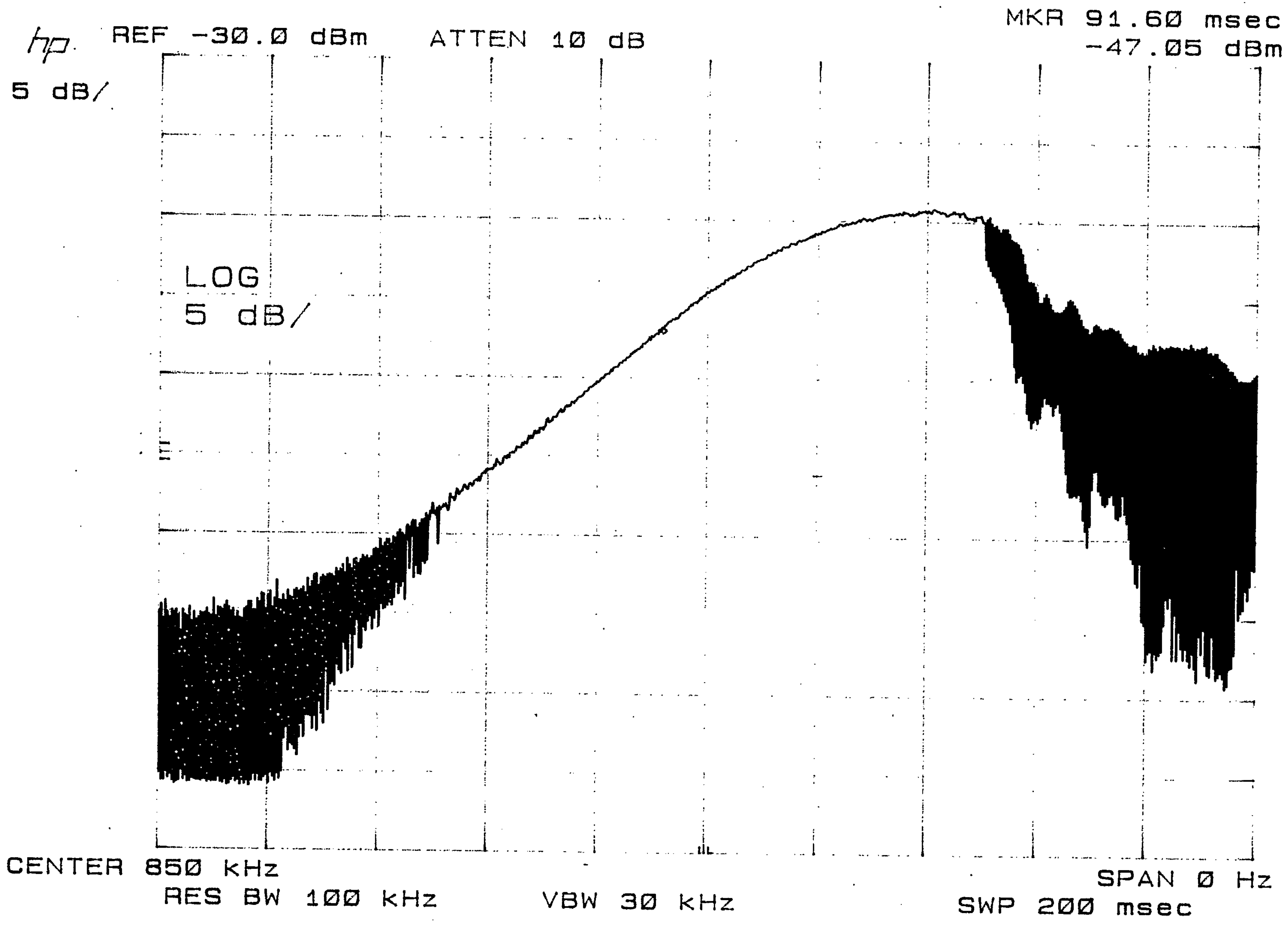
It seems important to point out that the tune shift brought about by the space charge impedance alone is very close to the Landau damping boundary. In other words, it is possible that instabilities have been occurring in the booster all along, they were just too weak to be noticed. Increasing the intensity by a factor ~ 30 may yield some surprises.

5 REFERENCES

1. M. Blaskiewicz, Booster Tech Note # 207, 1992
2. K.L. Bane, P.B. Wilson, & T. Weiland, SLAC-PUB-3528 (1984).
3. A. Ratti *private communication*

Fig 1

F1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ATTEN 10 dB
MKR 91.60 msec
-47.05 dBm
5 dB/
LOG
5 dB/
CENTER 850 kHz
RES BW 100 kHz
VBW 30 kHz
SPAN 0 Hz
SWP 200 msec

F2

Fis 2

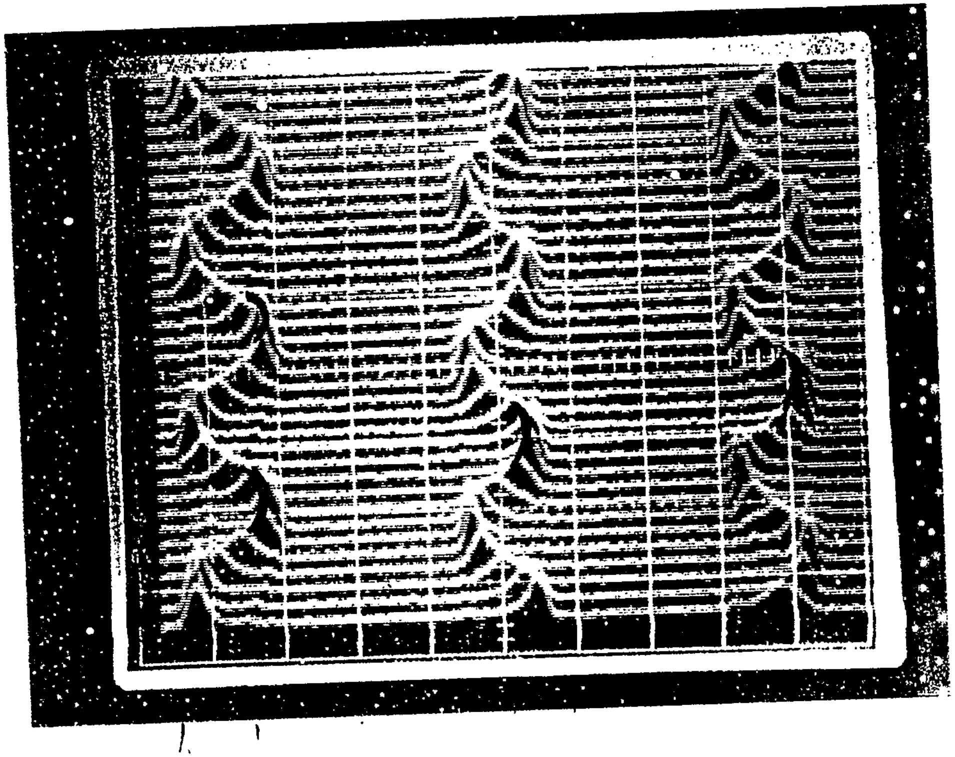
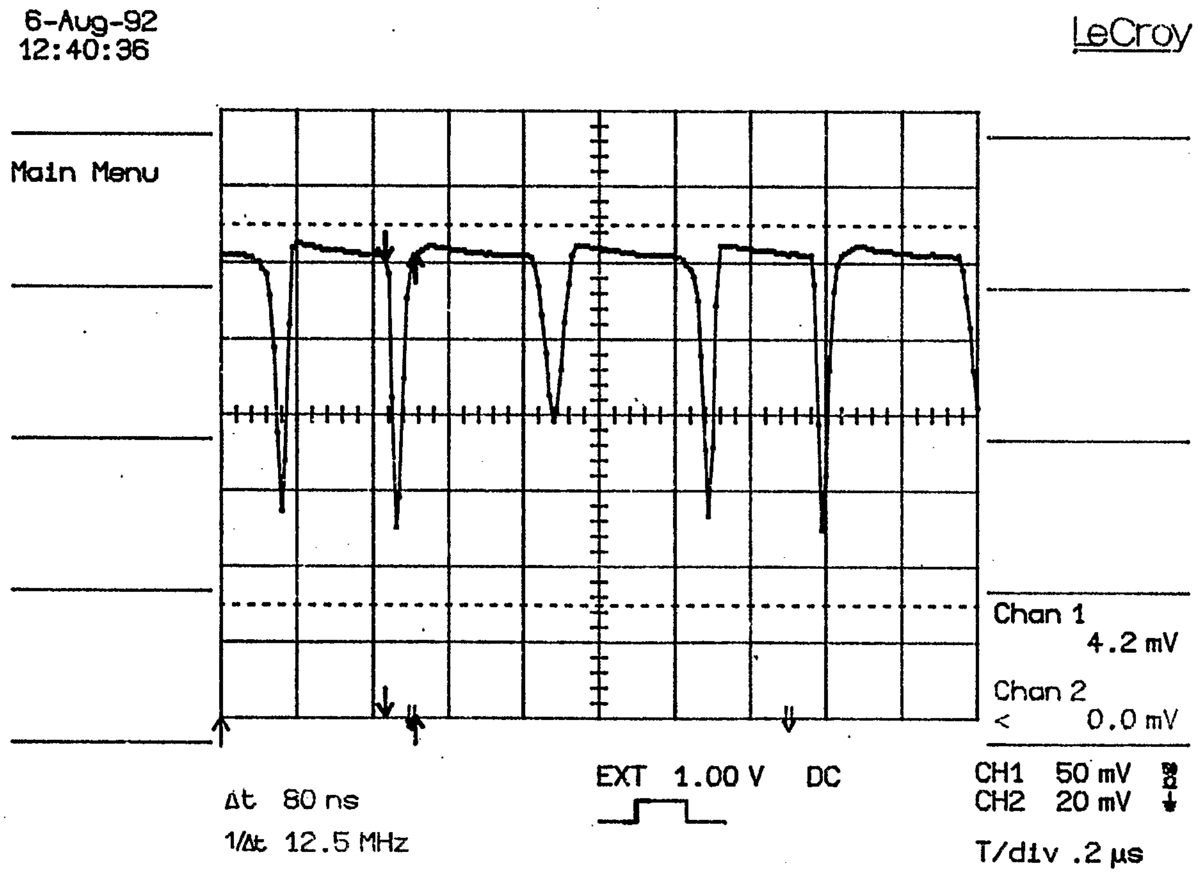


Fig 3



interaction