OBSERVATION OF TRANSVERSE INSTABILITIES IN THE FNAL 200 MEV LINAC

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Abstract: Using newly installed Beam Position Monitors in the downstream half of the FNAL Linac, we have observed significant transverse beam instabilities within the 30 μs beam pulse. We can affect the instability so that the peak-to-peak amplitude is as small as 0.5 mm or as large as 8 mm. The effect is largely due to a beam-plasma instability in the ten-meter 750-keV transport line. Other causes are being investigated. Using these instabilities as an analysis tool, the betatron amplitude of the beam has been reduced.

Introduction

Beam Position Monitors (BPMs) have been installed in half of the 200 MeV H^- Linac at Fermilab. These monitors have significantly increased the diagnostic capabilities within this Linac and are providing information to improve the quality of the beam delivered to the accelerator complex.

With this new diagnostic tool, we have discovered that one mode of operation, using relatively high pressure in the 750 keV injection line to neutralize the space charge forces in the beam, has induced a fast (4 MHz) transverse oscillation in the beam position which is propagated through the Linac as a betatron oscillation. It is important to control this oscillation because there is evidence that it degrades the performance to the 8 GeV Booster, into which the Linac injects, by reducing the uniformity of the beam current it, in turn, delivers to the Main Ring.

The instability at 750 keV can be used as a probe to reveal the betatron amplitude at the BPM. We have begun a program to use this information to change the settings and improve the alignment of the 295 quadrupoles, reduce the oscillations and reduce the emittance growth in the Linac.

Mechanical Considerations

Beam-induced RF signals are received by a detector containing four plates, subtending 30° each, in a conventional quadrupole arrangement: at the top, bottom, east and west sides of the cylinder, see Figure 1. The inside diameter (id) of the 93 mm long pickup is 41.0 mm (the id of the nearby drift tubes is 40.0 mm). Machinable ceramic is used to separate the pickup plate from the ground plane. Electrical gaps at the ends of each plate produce the beam signal; the downstream gap is terminated in the characteristic impedance of the transmission line, 50Ω. The difference of signals from opposite plates is proportional to the position of the beam centroid between the plates.

The pickup assembly, mounted to a 250 mm flange, replaces the beam toroid and scraper at an end of a Linac tank. The BPM at the output of an upstream tank is separated from the BPM at the input to a downstream tank by approximately 700 mm.

The response of a pickup is measured by 201 MHz RF on a wire threaded through the pickup on a test stand. The response, linear for small deviations (less than about 6 mm), is 1.428 and 1.335 dB/mm for tank-out and tank-in BPMs, respectively. These numbers have been confirmed with beam measurements.

BPMs have been installed at each tank end from the output of Tank 5 to the end of our nine-tank Linac. BPMs for the rest of the Linac, except Tank 1, are under construction, as are BPMs for the 200 MeV line. Installation of BPMs between Tanks 1 and 2 (a mere 220 mm drift) and at the input to Tank 1 (also a logistics problem) is under consideration.

Electronic Readout

Signals from the BPM pickups are carried to RF position decoding modules in the equipment gallery on 3/8 inch foam dielectric copper jacketed coaxial cables. In the RF Modules, the signals are processed by heterodyned AM-PM position circuitry to provide normalized position outputs with 2 MHz bandwidth. This circuitry, with 28 MHz IF processing, is similar to that used in the Fermilab Booster BPM system.[1] It has been modified in the frequency conversion stage to receive the 201 MHz component of the Linac beam signal. The position output is linear over more than half of the pickup aperture and is scaled to 4mm/volt. Accuracy is better than 0.3mm and resolution is approximately 25 microns over an input signal range of >40db. In addition to the position output, a sum signal output is available.

The analog position and sum signals are read into the computer through standard Linac control system sample/hold and digitizer electronics. Sample time is user variable allowing measurements of position vs. time to be made from the control console.

Beam Measurements

Five types of beam measurements have been made with the BPMs, each providing new information on the Linac beam. Items 3 and 4 below are discussed in detail in the following sections.

1. Beam Steering. In principle, BPMs make it possible to steer the beam down the center of the Linac. However, the compounding of uncertainties of the various measured offsets in the system makes the absolute mechanical center of the BPM with respect to "0.0 volts" on the readout difficult to ascertain. Furthermore, there are currently more BPMs (nine) than there are dipole correction elements (five) in the Linac, making it impossible to systematically correct for both position and angle offsets between tanks at this time.

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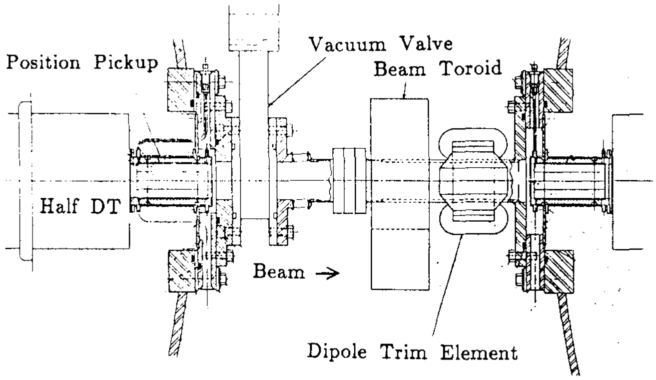

Figure 1. FNAL Linac BPM assembly drawing.

2. Betatron Amplitude I. One can accurately measure the position of the beam in a BPM as a function of the gradient in a quadrupole. From this measurement, one obtains the displacement of the beam in that quad, after accounting for the effect of the intervening quads. Misaligned quads are easily identified by this procedure. Also, one can *ad hoc* correct for a missteered beam by reducing the oscillations obtained by this measurement.

3. Transverse Instabilities. Fast beam steering changes within a beam pulse have been observed. Interesting phenomena, alluded to in the Introduction, have been observed and will be discussed in detail below.

4. Betatron Amplitude II. Measuring the amplitude of the transverse instability allows one to infer the actual betatron amplitude of the beam at the BPM. If these amplitudes are grossly different from BPM to BPM, then improvements in the lattice of the Linac can be made.

5. Other Sources of Instabilities. The spectra of the beam signals from the BPMs have been taken for various different running conditions. It was hoped that evidence for other sources of transverse instabilities would be seen, for example, a sharp line in the spectrum corresponding to a dipole RF mode in Tank 1. No beam-induced spectrum line has been observed. The features in all the spectra are consistent with either noise, the injection line beam-plasma instability or 201 MHz leakage into the measurement equipment. The source of the noise is under investigation; our inclination is to blame non-uniformities in the beam at the ion source.

Transverse Instabilities

Observations: Under the conditions described below, oscillations in the transverse position of the beam with amplitudes as large as 4 mm have been observed within the 30 μs Linac beam pulse. The oscillation takes about ten microseconds to develop. Identical oscillations, except for an overall amplitude factor, are observed at all the BPMs currently installed in the Linac. The size of the oscillation at a BPM may be affected by making small changes in the lattice upstream of the BPM, thus moving the point of high betatron amplitude into or away from the BPM.

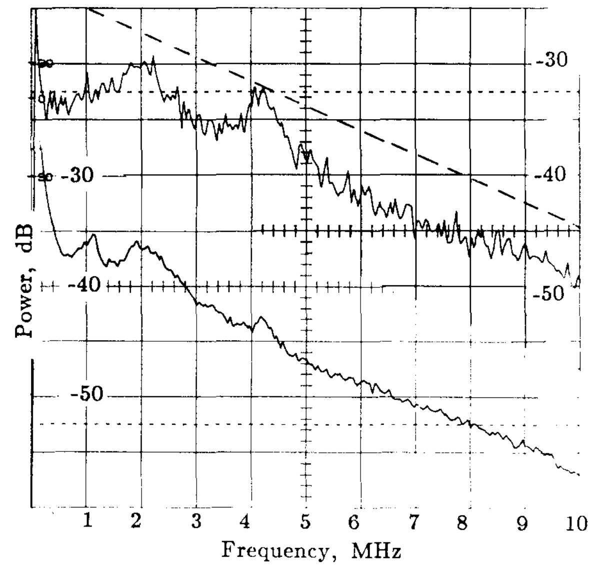

Figure 2. Spectra from the BPM at the output of Tank 7 for high (top) and for low (bottom) pressure in the 750 keV injection line; the dashed line is the response of the RF detector, -20 dB/octave.

These observations are made while the pressure in the ten-meter 750 keV injection line is 7 x 10^{-6} torr.[2] The pressure had been raised two years earlier, from 1.3 x 10^{-6} torr, to reduce the effects of space charge on the beam and thereby reduce the effective emittance entering the Linac.[3] When the minimum pressure for the line is reinstated, the oscillations are reduced by a factor of 10. Adjusting the lattice in the Linac as before has no appreciable effect on the oscillations at the BPM at low pressure.

Typical spectra from the Tank 7 output BPM are shown in Figure 2. (We have traded the intensity insensitivity of the RF modules for a broader and more uniform frequency response by using a Texscan CD-50 RF detector to obtain the spectra presented here.) Note the presence of a large enhancement at 4 MHz at high pressure; the enhancement is suppressed at low pressure.

The oscillation has been observed only in beam originating in our "H^-" source and its accompanying ten-meter injection line; the oscillation is not observed in beam from our "I^-" source and its four-meter injection line.

Interpretation: A beam-plasma instability in the injection line is a major source of the observed oscillation. The passage of the beam through the background gas in the 750 keV injection line generates the plasma by ionization. The plasma frequency of this system is[4]

$$\omega^2 = \frac{4 \pi n e^2}{m_p/2}$$

where: n is the density of the H^- beam, 3 x 10^8/cc for typical 58 mA beam at 750 keV

$m_p/2$ represents the reduced mass of the H^- beam and the hydrogen gas background, m_p=proton mass

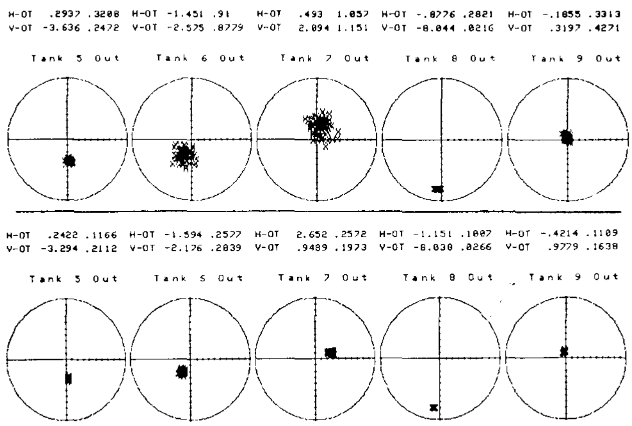

Figure 3. "Bull's eye" plots of beam positions through the Linac, high pressure in injection line, before (top) and after (bottom) *Parmila*-directed quad tuning.

This gives a plasma frequency of 3.6 MHz. The wavelength of this oscillation at β=0.04 is four meters.

We have previously observed that the 750 keV emittance at the entrance to Tank 1 take about ten microseconds to stabilize because of the time it take to develop a neutralizing plasma in the line. Our recent observations of the development time of the transverse instability show the same ten microsecond development time.

Betatron Amplitude II

The large oscillations generated by the injection line instability have been used to determine the amplitude of the betatron oscillations throughout the Linac. With the "H$^-$" 750 keV line pressure set to 8 x 10^{-6} torr and the Linac tuned in the standard fashion for maximum transmission (ratio of the output current to the input current here is 64%, a typical value for our Linac), large changes in the pulse-to-pulse beam centroid at the BPMs are seen. A typical view of the beam is shown in the set of "bull's eye" plots in Figure 3.[5] Assuming an offset at the beginning of Tank 1 which is random from pulse-to-pulse and no other pulse-to-pulse variations, the spread of the offsets measured at a BPM is directly proportional to the betatron amplitude at that BPM.

In order to connect these observations with theoretical predictions, the popular Linac simulation code *Parmila* has been modified to simulate our Linac. The actual quad gradients at the time of the measurement are used; surveying data exist, but the results are not yet self-consistent[6].

Due to the discontinuities in the Linac lattice, a small offset at the beginning of Tank 1 is predicted to be amplified down the Linac and produce the large offsets observed at the BPMs, Figure 4. (The choice of initial offsets of x'=y=0, x=.75 mm, y'=1 mr, produces a fairly good qualitative match to the data on the bull's eye plots above.)

The effect of changing specific quad gradients is explored with *Parmila* and a set of small changes to some of the quad gradients in Tank 1[7] and at tank boundaries has been implemented. After installing the

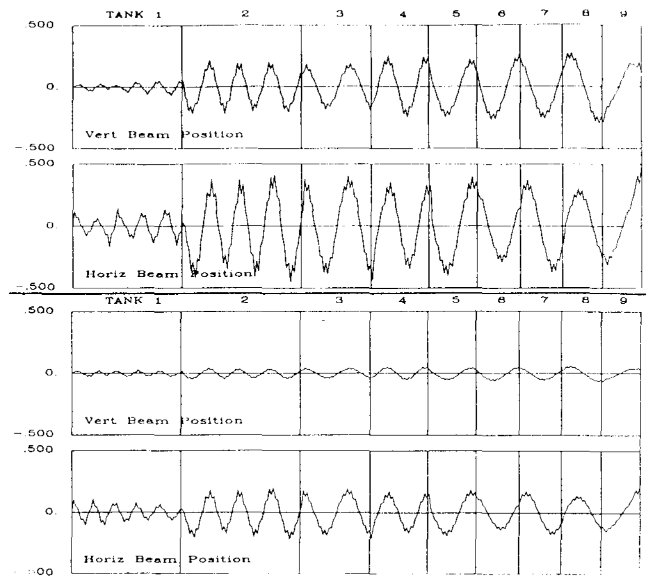

Figure 4. *Parmila* predictions of beam positions down the Linac resulting from slight 750 keV offset.

improved gradients as predicted by *Parmila* and then, *ad hoc*, tuning to minimize the loss of beam after Tank 1, the second set of bull's eye plots of Figure 3 are obtained. *Parmila* predicts these changes to have the effect shown in Figure 4 (with the same initial offsets of the previous run). The transmission through the Linac in this case is 68%. No emittance changes at 200 MeV are observed.

Summary

The installation of a few Beam Position Monitors has greatly improved the diagnostic capabilities of the Fermilab Linac. Upon installation of the BPMs we immediately discovered that high pressure in the 750 keV injection line produced severe transverse oscillations. Using the BPMs to read the betatron amplitude of the beam, the effect of this transverse instability was reduced by improving the Linac's quadrupole tune.

References

[1] R. Webber et al., "A Beam Position Monitoring System for the Fermilab Booster," Proceedings of the 1987 IEEE Particle Accelerator Conference, IEEE Catalog 87CH2387-9, pp 541-543.
[2] The pressures quoted in this paper are the uncorrected gauge readings; our major source of contamination is hydrogen gas.
[3] C. D. Curtis, C. W. Owen and C. W. Schmidt, "Factors Affecting H$^-$ Beam Performance in the Fermilab Linac," 1986 Linear Accelerator Conference Proceedings, SLAC-report-303, September, 1986, pp 138-140.
[4] N. A. Krall and A. W. Trivelpiece, Principles of Plasma Physics, 1973, McGraw-Hill, Inc, p 9.
[5] These data have passed through the Linac and Fermilab control systems, so some bandwidth is lost and only one datum per BPM per beam pulse is obtained. The connection to the bottom plate in the Tank-8 out BPM is broken for this run. Note also that the absolute positions of the BPMs has not been firmly established.
[6] Preliminary results from *Parmila* including surveying data and inter-tank dipole correction elements show that the quad misalignments have a large effect (up to 10 mm offsets) on the beam positions.
[7] The quads in drift tube 19 through 32 have been changed from around 72 T/m to about 53 T/m.