UCRL-JC-130426
Preprint

Improvements on the Accuracy of Beam Bugs

Y. J. Chen and T. J. Fessenden

This paper was prepared for submittal to
19th International Linear Accelerator Conference
Chicago, IL
August 23-28, 1998

August 17, 1998

Lawrence Livermore National Laboratory

IMPROVEMENTS ON THE ACCURACY OF BEAM BUGS

Yu (Judy) J. Chen and T.J. Fessenden

Abstract

At LLNL resistive wall monitors are used to measure the current and position of intense electron beams in electron induction linacs and beam transport lines. These, known locally as "beam bugs", have been used throughout linear induction accelerators as essential diagnostics of beam current and location. Recently, the development of a fast beam kicker has required improvement in the accuracy of measuring the position of beams. By picking off signals at more than the usual four positions around the monitor, beam position measurement error can be greatly reduced. A second significant source of error is the mechanical variation of the resistor around the bug. In addition, in-situ bugs used on ETA-II show a droop in signal due to a fast redistribution time constant of the signals. This paper presents the analysis and experimental test of the beam bugs used for beam current and position measurements in and after the fast kicker. It concludes with an outline of present and future changes that can be made to improve the accuracy of these beam bugs.

Description

Perhaps the most important diagnostic developed for electron induction accelerators is the device that monitors the beam current and position in the accelerator and associated beam transport lines. This type of monitor (1) was first developed for use on the LBL ERA accelerator (2) about 1970. It was rapidly adapted (3) for use on the Astron Accelerator (4) and has been used on all LLNL induction accelerators since. These instruments commonly called "beam bugs" are capable of measuring kiloampere beam currents and beam position with rise times of less than 0.2 ns and relative position resolutions less than 100 μm. Signals are generated by placing a resistor in series with the inner wall of the beam transport lines and detecting the currents induced in the wall by the passage of the beam. The resistors are made of 0.2 mil nichrome foil (5.4 μm) that is spot welded across an insulated break in the beam tube wall to form a band that encircles the inside of the beam pipe. The diameter of the band equals the inner diameter of the beam pipe so that the beam sees no abrupt steps or extraneous capacitance during its passage through the bug. A small overlap is formed as the band wraps around the inside diameter of the pipe.

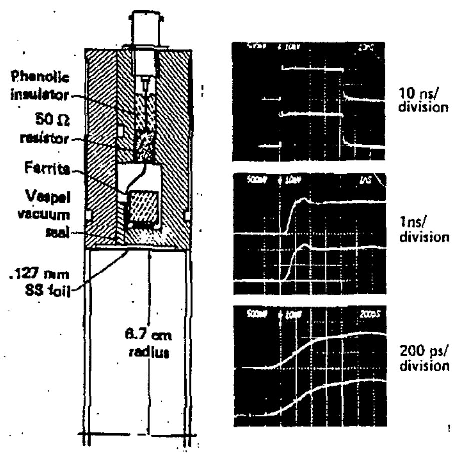

Fig. 1. Drawing of an ATA beam bug. ETA-II bugs use 5.4 μm nichrome foil and have no 50 Ohm resistor in series with the outputs. Each has 8 pickoffs around the bug circumference. Also shown is the response of the bug (lower trace) to a 10 Amp pulse (upper trace) along the bug axis from a mercury pulser.

Figure 1 shows the design (5) of the beam bug used with the ATA accelerator (6). The ETA-II bugs are only slightly different. The resistance of the resistor foil was approximately 20mΩ with a resulting sensitivity of the instrument of 1 kA/V. Also shown are measurements of the response of the bug to a 10 amp fast rising current pulse from a test pulser. A ferrite inductor is placed behind the resistor foil to prevent the beam current from flowing around the resistor. Because of the very low foil resistance, the *L/R* time for the current to decay is very much longer than the beam pulse. Eight pickoffs around the circumference of the bug are used to develop the current and position signals. Two of the pickups encircle the ferrite in a direction opposite to that of the other six thus producing a negative signal. The current signal is formed by adding four positive signals from cardinal points around the bug. The x and y position signals are formed adding positive and negative signals from opposite sides of the bug. Analysis and additional descriptions on beam bugs and other diagnostics for high current linacs can be found in [7] and [8].

Analysis

Consider a beam moving within a conducting pipe as sketched in Fig 2.

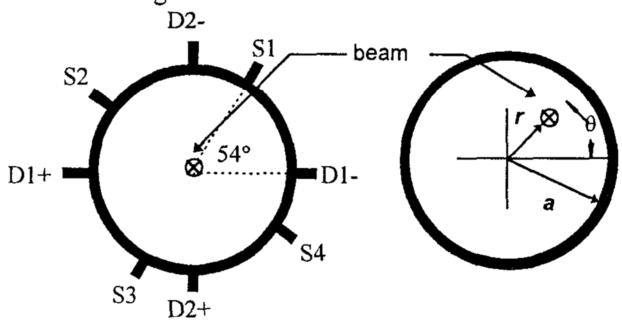

Fig. 2. (a) ETA-II's beam bug port configuration. (b) Sketch of a beam off-axis in a conducting pipe

It is possible to show (by the method of images for example) that a current I flowing within a pipe of radius a at a distance r off axis causes a surface current to flow on the inner pipe wall.

Consider interrupting the beam pipe with a resistive band or ring placed at the inner circumference of the pipe with total resistance R. The surface current passing through the resistor that initially or for a short time develops a voltage around the pipe V(θ) given by [8]

$$V(\theta) = K(\theta)\, 2\pi a\, R = RI \frac{\rho^2 - 1}{1 + \rho^2 - 2\rho\cos\theta}. \qquad (1)$$

where $\rho = r/a$ is the normalized beam displacement. The angle θ is defined by Fig. 2. For most of the ETA-II accelerator and transport the beam current signal comes from adding the voltages of the four S1-S4. It is fed through a resistive summing circuit in which care is taken to avoid reflections in the cabling. Therefore,

$$V_I = \left[V(54°) + V(144°) + (234°) + V(324°)\right] \qquad (2)$$

Similarly, the position signals are obtained with

$$V_x = V(0) - V(180°)$$
$$V_y = V(90°) - V(270°) \quad (3)$$

Combining (1)-(3) and taking the limit of small beam displacement ($\rho << 1$), we obtain

$$V_I = 4IR \quad (4)$$

and

$$V_\rho = 4\rho IR\cos\theta \quad (5)$$

or

$$\frac{x}{a} = \rho_x = \frac{V_x}{V_I}; \qquad \frac{y}{a} = \rho_y = \frac{V_y}{V_I} \quad (6)$$

Improved current and position functions

The determination of beam current and position can be improved by using all eight pickoffs to determine beam current and position which already exists on ETA-II's beam bugs (see Fig. 2a). Define the beam x and y-position relations as:

$$V_x = V(0) - V(180) + [V(54) - V(234)]\cos(54) - [V(144) - V(324)]\sin(54) \quad (7)$$

$$V_y = V(90) - V(270) + [V(54) - V(234)]\sin(54) + [V(144) - V(324)]\cos(54)$$

and the relation for the beam current is given by

$$V_I = V(0) + V(54) + V(90) + V(144) + V(180) + V(234) + V(270) + V(324) \quad (8)$$

The relationships for x and y are the same as (6).

Let us consider in detail the error in the position signal resulting from the assumption of small beam displacement ρ. Fig. 4 shows plots of the error in measured beam position by the bug as a function of the normalized beam displacement ρ for the case of two and six pickoffs as defined above. These curves were obtained from Eq. (3) and (7). Each pair of curves show the values to be expected for the case of the beam displacement angle toward a pickoff point and for the case of the beam displacement angle half-way between two pickoff points. For an arbitrary displacement these curves bound the measurements to be expected. At a normalized displacement of $\rho = 1/2$, the position ranges from -37% to 48% for the case of two pickoffs and -7% to 3% for six pickoffs.

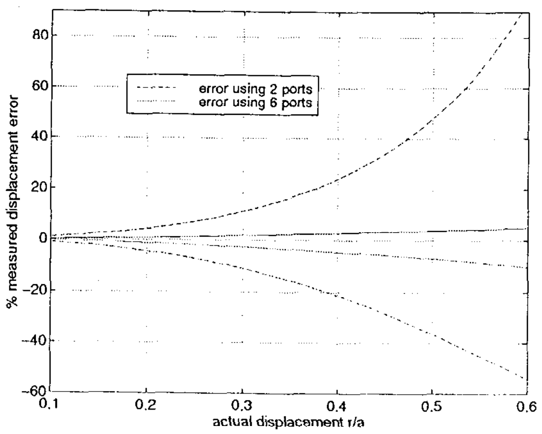

Fig. 4. Plots of the measured error as a function of the normalized beam displacement from axis for two and six pickoffs as defined above. For arbitrary angle, the point will be bounded by the two curves.

Limitations and Errors

Bug Testing and Calibration

Beam bugs are tested and calibrated using a mercury pulser and a test fixture. The fixture consists of two coaxial cylinders; the larger has an inside diameter equal to that of a beam bug that is attached in its center. The second simulates the beam and threads the assembly. It is smaller in diameter by a ratio of 2.3 to achieve a 50 Ohm impedance. The two cylinders are attached with tapers to a coax line that is driven by a mercury pulser. The pulser generates current pulses with a rise time of 0.2 ns that are typically 200 ns long. The oscillograms presented in Fig. 1 were obtained from such a fixture. The bugs are calibrated by recording the voltage signals generated by a known current from the pulser.

Measurements of the eight output signals from the beam bug show random amplitude variations of approximately ± 2%. For the ETA-II bugs this implies an uncertainty in beam position of ±1.4 mm. These errors result from variations in the resistance of the foil around the circumference of the bug. These variations arise principally from two causes. Measurements revealed that the thickness of the 5.4 μm foils randomly vary by about 2 percent, and variations in the spot welds that attach the foil also contribute to the error. This latter effect is evident in Fig. 3. The foil on Beam Bug 26 was re-welded with extreme care. This reduced the variation between pickoffs by about a factor of two.

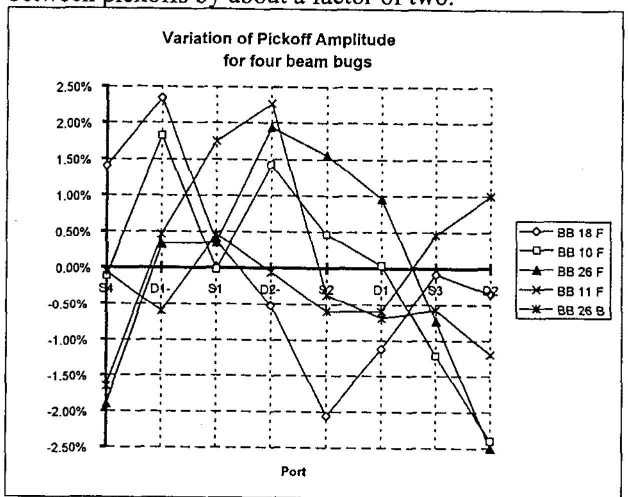

Fig. 5. Variations between electrical signals at the eight ports of four ETA-II beam bugs. The foil on Beam Bug 26 was re-attached with extreme care.

Signal Droop

The beam bugs are fabricated of metal and essentially shorted by the housing as shown in Fig. 1. The inductor provides time isolation for the monopole current signal for times long compared with the beam pulse. This time is determined by the *L/R* time constant developed by the ferrite inductor and foil resistor. For ETA-II parameters this time is typically hundreds of microseconds. Thus the current signal will droop by less than 0.1% in the time of the 70 ns ETA-II pulse. The position signal is generated by an off-axis beam which produces a dipole excitation of the bug. The dipole component of the excitation does not link the ferrite inductor. As a consequence the droop of the position signal is much faster.

The center cylinder of the calibration fixture can be moved with respect to the outer cylinder so as to simulate an off-axis beam. Fig. 6 shows bug signals developed at opposite sides of a one centimeter offset of this center cylinder. Adding these signals together produces a signal that is approximately proportional to the offset of the center conductor. For the parameters shown here the decay time constant is approximately 200 ns. Thus, in the 70 ns of the ETA-II pulse, the position signal droops by approximately 30%. For centering the beam this droop is of little consequence. However, for determining the position of an off-axis beam this droop must be compensated by either processing the position signal or partially integrating the signal.

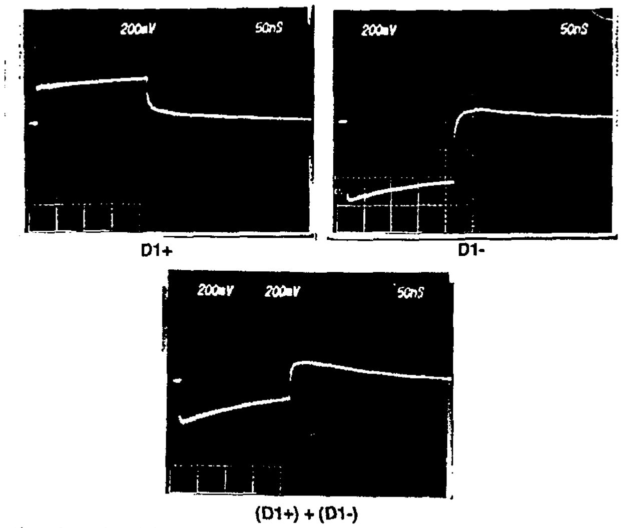

Fig 6. Oscillograms showing bug signals generated at opposite sides of a 10-mm offset of the center conductor of the test fixture. For the ETA-II parameters the position signals decay with a time constant ≈ 200 ns.

Analog compensation of the position signal droop is used for on-line viewing of the ETA-II beam during tuning using the circuit shown in Fig. 7.

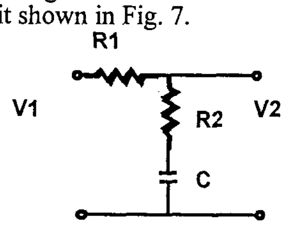

Fig 7. Simple compensation circuits for the beam bug position signals.

This circuit has the transfer function

$$V_1 / V_2 = \frac{R_2}{R_1 + R_2} \frac{\left(s + 1 / R_2 C\right)}{\left(s + 1 / \left(R_1 + R_2\right) C\right)} \qquad (9)$$

If R_2C is made equal to the droop time t, the effective droop time is increased by the ratio $(R_1 + R_2)/R_2$ whereas the rise time is unchanged. The signal level is, of course, reduced by the same factor.

The present droop compensation scheme on ETA-II is to correct it in software, thus preserving signal strength. A simple yet accurate approach is to calculate the amount of droop by finding the value the signal immediately reset to (and it is usually non-zero) and add a ramp to the signal with that amplitude.

Summary and Conclusions

A wealth of extremely detailed characterization on two generations of beam bugs (ATA and ETA-II) has pointed to a number of improvements that can be made on the accuracy of these diagnostics. It has been known that increasing the number of pick-off points increases off-axis accuracy. However, one must be careful about implementing this idea. The increased number of pick-offs also increases the inherent error in port to port variations as shown in Fig. 5. To combat this source of error, one should document port amplitude variation for each port on each beam bug. This can be stored in a look-up table and compensated in software. This necessitates individual measurement of each pick-off and summing and differencing is processed in software, not hardware as has been traditionally done. This also increases on-axis precision as long as bit noise is not a major source of error (if one goes to 16-bit data acquisition). The other more expensive option is to simply build better bugs.

The dipole *L/R* droop on ETA-II beam bugs has been corrected in software. In addition, a real-time display of processed I, X, and Y values has been implemented. In the long term, beam bugs around the fast kicker (which require a high level of precision) will have it's pick-offs individually routed to the control room.

Acknowledgments
We are grateful to C. Holms who fabricates, calibrates and maintains the ETA-II bugs and to J.C. Clark for his assistance in gathering experimental data and in the preparation of this manuscript. This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

References

[1] Avery, A. Faltens, and E.C. Hartwig, "Non-Intercepting Monitor of Beam Current and Position," UCRL-20166, LBL, (1971).

[2] Avery et. al., "The ERA 4 MeV Injector," Proc. of the 1971 PAC, Chicago, IL. (1971) also UCRL-20174, LBL (1971).

[3] Fessenden, B. W. Stallard, and G.G. Berg, "Beam Current and Position Monitor for the Astron Accelerator," Rev. of Sci. Instru., **43**, 1789, (1972).

[4] C. Christofolis, R.E. Hester, W.A.S. Lamb, D.D. Reagan, W.A. Sherwood, and R.E. Wright, Rev. Sci. Instrum. **35**, 886, (1964).

[5] K. Struve, "The ATA Beam Bug," informal communication, LLNL.

[6] Reginato, IEEE Trans. Nucl. Sci., **NS-30**, 2970, (1983).

[7] K Struve, "Electrical Measurement Techniques for Pulsed High Current Electron Beams", submitted to the Measurement of Electrical Quantities in Pulse Power Systems-II, National Bureau of Standards, Gaithersburg, Maryland (1986), also UCRL-93261, LLNL, (1986).

[8] Fessenden, "Diagnostics for Induction Accelerators", Conference Proceedings No. 252: Beam Instrumentation Workshop, p. 225, AIP (1992).

[9] Fessenden, "Beam Bugs--Asymptotic Response,"

Beam Research Program Memo RM 88-8, (1988), informal LLNL communication.
[10] Chambers et. al., "Diagnostics and Data Analysis for the ETA-II Linear Induction Accelerator," Proc. of the 1991 PAC, San Fransisco, CA., 3085, (1971).