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DML and Foil Measurements of ETA Beam Radius

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W.E. Nexsen and John Weir

Abstract: Simultaneous measurements of the ETA beam radius have been made with a quartz foil and a diamagnetic loop (DML). While the measurements agreed at some settings they diverged at others. While the DML measures the rms radius of the total beam, the foil measures mainly the core and the divergence can be explained by the presence of a low density halo. Evidence of such a halo from other measurements is presented.

Introduction: While the DML has been declared operational on FXR and ETA by one of the authors (WEN), until now no valid comparison has been made between its measurement of beam rms radius and that of the normal radius diagnostic, the quartz foil. On 2/17/05 we took simultaneous measurements of the ETA beam radius with a DML located in the drift region just downstream of solenoid EF1 at Z=4.514 m and a quartz foil in the cross at Z=4.920 m. The magnetic field at the DML is set only by the current in EF1 and for these series of measurements was at a constant value of 139 Gauss (EF1=7A) while the beam radius was varied by adjusting the current in the next upstream solenoid, EF0, centered at Z=2.045m. At the beginning of the run the ETA energy analyzer measured the beam total energy at 5.39 MeV at the time of peak current. (Peak current was slightly less than 2kA.) Since it was not physically possible to make the two radius measurements at the same location, the foil data was treated with the FITS code to determine the entrance conditions at Z=0 of Rrms= 7.9 mm, R'=3.5 mr, emittance=5.1 (cm-mr), current =1800 A and kinetic energy= 5.25 MeV. These values were then used to

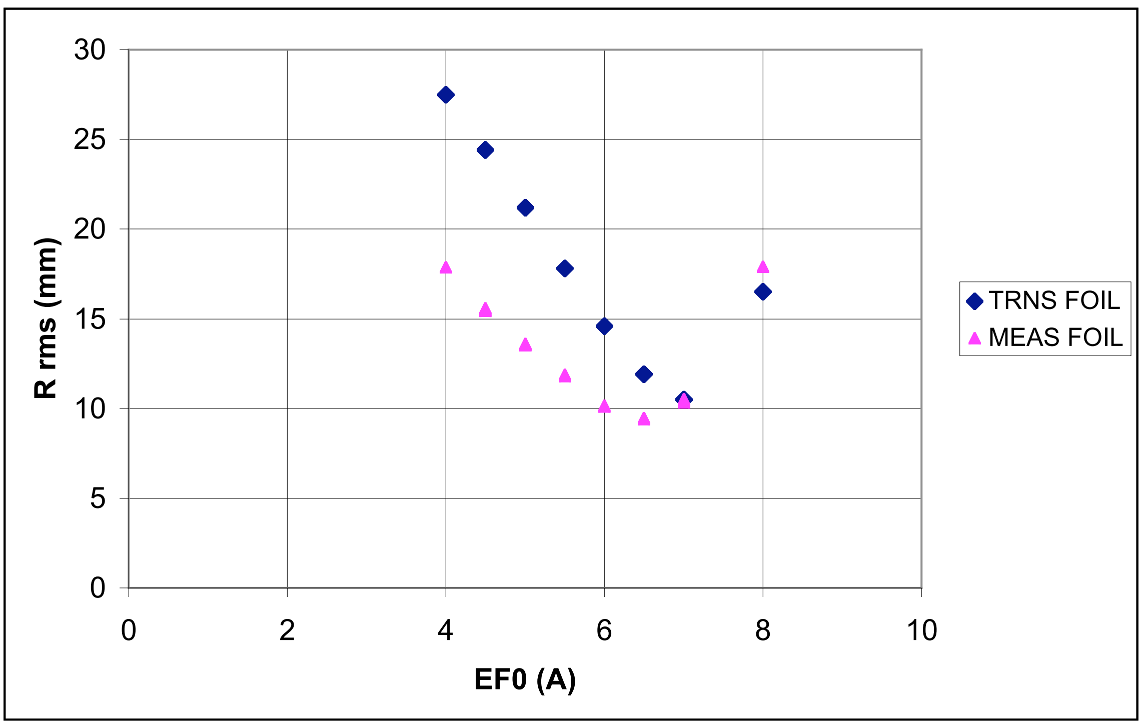

Figure 1 Foil measurements of rms beam radius and implied values at DML.

determine a consistent set of "foil" radii at the DML position. The beam radii as measured at the foil and the implied values at the DML as determined from the FITS code are plotted in Figure 1 as functions of current in EF0.

The DML signal is produced by changes in the flux linking the loop due to the passage of the beam. The DML has been calibrated using a small diameter, long pulse coil of known magnetic moment, and using this calibration, the signal can be processed to obtain the beam magnetic moment as a function of time. The beam magnetic moment can consist of four components, M= M_r +$M_{\square}$+M_u- M_c, of which M_r is the component of interest for obtaining the beam radius and is proportional to the magnetic field at the DML. M_c is zero if the average flux linking the cathode is zero while the remaining two components arise because of the breaking of symmetry by field errors. Setting the field at theDML to zero allows us to determine the contributions of the other components which usually can be minimized by steering the beam centroid within a few millimeters of the axis at the DML and adjusting the field at the beam cathode. The conditions of this scan had been repeated twice previously at which times only the M_r component was found to be important but for this days data it was found, after the fact, that the moment measured with zero DML field, M_0, was large enough that it was necessary to correct the moment measured with field on, M_B. We set $M_r = M_B - M_0$ where M_0 was taken as the average value over 10 ns at peak current of four shots, two at the beginning and two at the end of the run. The rms radius is then given by

$$R_{rms} = 6.81E4(\square\square/B(G))\sqrt{M_r/I}\ \text{(mm)} \qquad (1)$$

In Figure 2 we plot the uncorrected and corrected DML radius measurements. The

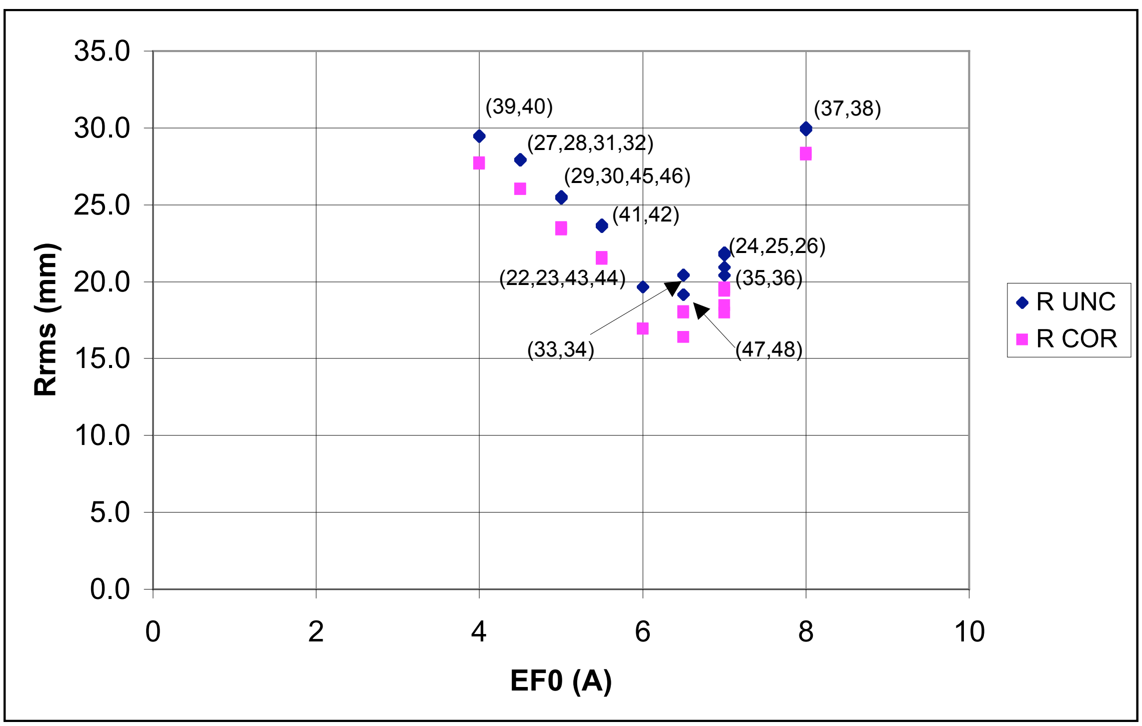

Figure 2 Uncorrected and corrected DML rms beam radius measurements.

numbers by the uncorrected points are the shot numbers and illustrate the reproducibility of the measurements. In the case of theEF0= 6.5 and 7 A data adjacent shots overlay but diverge from values from later in the run indicating some change has occurred in the operation. Finally in Figure 3 we plot the implied beam radius at the DML from the FIT treatment of the foil data and the corrected DML measurement. The two measurements agree at EF0=4A but diverge at higher values. Especially noticeable is that the EF0=8A

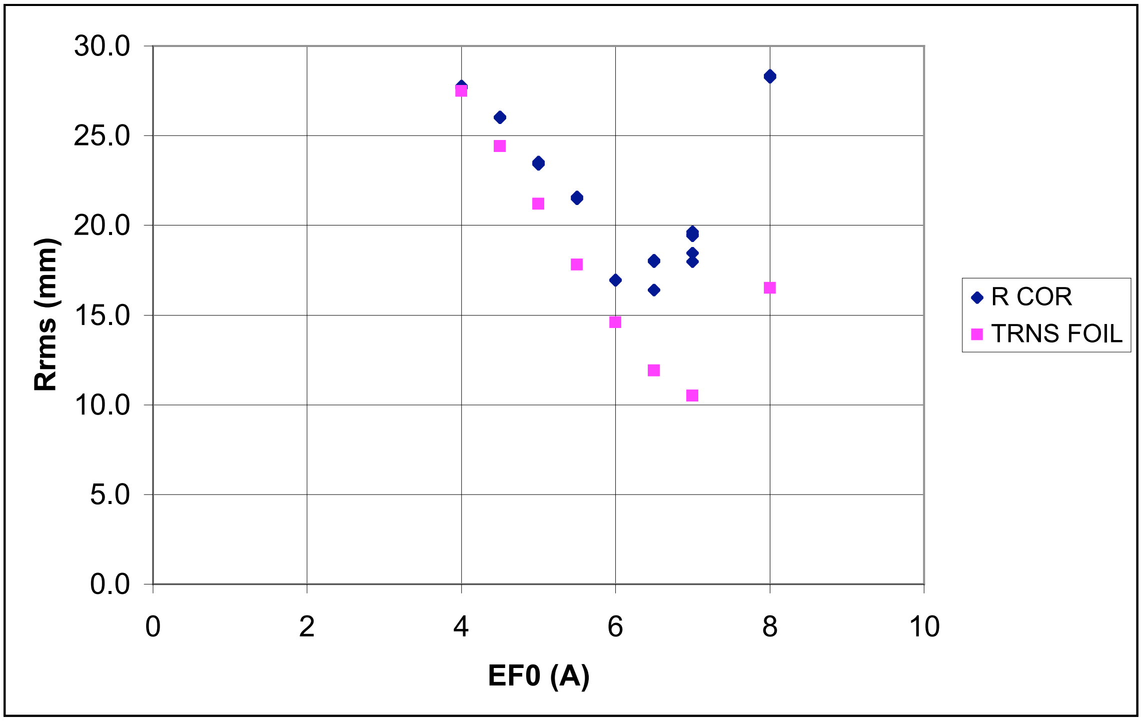

Figure 3 Overlay of DML and foil measurements of beam rms radius.

DML value obtained from the next two shots after the EF0=4A measurements is almost the same as the latter value and is certainly as good as that measurement. This may indicate some error in the FIT values used to generate the implied foil values as does the fact that the minimum radius for the two sets of measurements occur at different values of EF0 current.

Discussion: We argue that both of these sets of measurements are valid and diverge because they are measuring two different parameters. The DML yields a rms radius for the total beam passing through the loop and is independent of any assumptions about the radial profile of the beam. The foil measurement concentrates on the core of the beam and through the choice of a baseline before reduction ignores the contribution of any very low level halo that might be present. We illustrate this difference by invoking a crude model current distribution. Assume a radial distribution given by

$$\begin{aligned} f(r) &= 1 \qquad 0 < r < r_0 \\ &= \alpha (r_0 / r) \qquad r_0 \le r \le R \end{aligned} \tag{2}$$

where α is some small fraction of the peak density at r_0 and R is the radius of the beam tube wall. This distribution has a rms radius given by

$$R_{rms} = \left[\frac{(r_0 R^3/3)\delta + (1/4 - \delta/3) r_0^4}{r_0 R \delta + (1/2 - \delta) r_0^2} \right]^{1/2} \tag{3}$$

The DML would be expected to yield this radius; the foil measurement, if δ is so small as to be ignored, will give $r_0/\sqrt{2}$ and the ratio of the two measurements is

$$\text{Ratio} = \frac{\sqrt{2}}{r_0} \left[\frac{(r_0 R^3/3)\delta + (1/4 - \delta/3) r_0^4}{r_0 R \delta + (1/2 - \delta) r_0^2} \right]^{1/2} \tag{4}$$

In Figure 4 we plot the ratio of the corrected DML rms beam radius measurement to the implied foil rms radius, i.e., the data plotted in Figure 3. Also shown are the ratio values

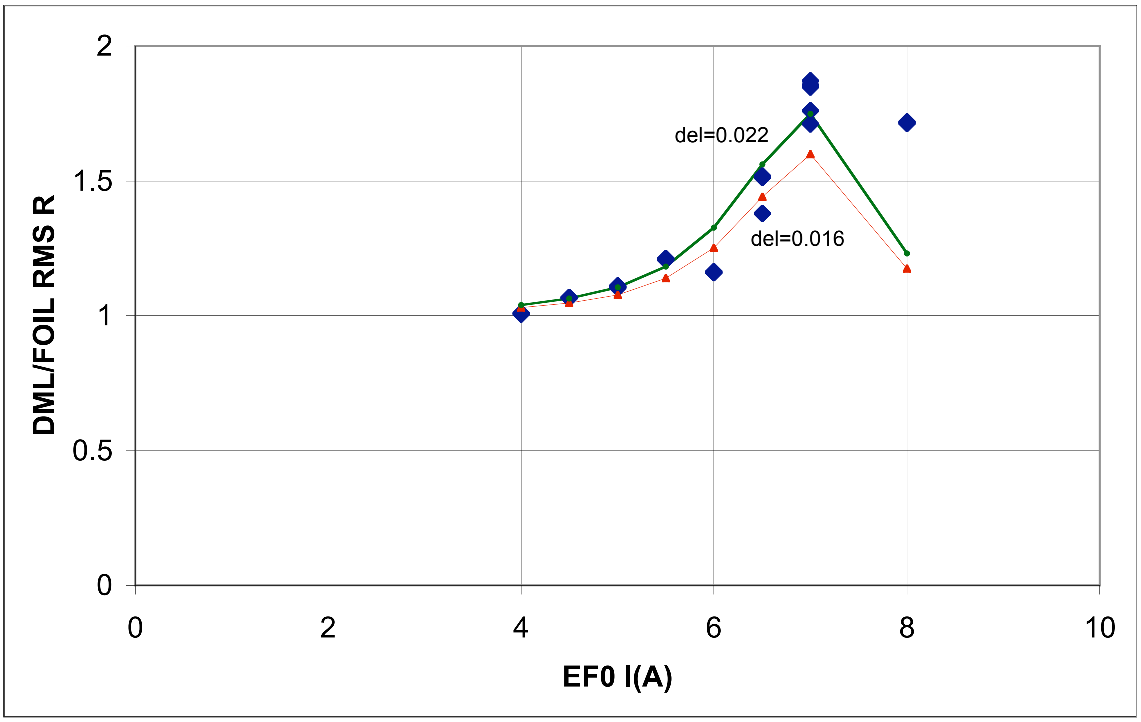

Figure 4 The ratio of the two data sets overlaid with Equation 4 values.

from Equation 4 for two values of δ. for the beam tube radius, R=66 mm and $r_0 = \sqrt{2}$ times the implied foil rms radius at the DML, Although this model is crude it illustrates that a halo with current density at the edge of the main distribution of the order of 2% of the peak density can explain the divergence of the two sets of measurements.

Several other sources provide evidence of the existence of a halo. The DML can act as a probe that detects beam electrons hitting the walls, and current loss between the DML and the BBT05, the next downstream beam bug can be documented. The signals from the two DML terminals, designated A and B, have been recorded separately. Their difference, B-A, is the voltage induced by changing flux linkages while, if the loop is floating, any resultant B+A signal indicates a net charge entering the loop. The ETA measurements have shown the presence of such a signal, negative in polarity signifying a net influx of electrons into the loop. Whether these are secondary electrons produced by direct bombardment of the DML surroundings by energetic beam electrons or whether there is an intermediate stage involving x-rays is not known at present. The data of 2/17/05 was taken with a loop whose center point had been grounded, allowing any charge to be bled off but similar runs had been made earlier with an ungrounded loop and the A+B data from one such run is shown in Figure 5. This data from 9/3/04 was taken under the same conditions of EF1=7A and EF0 varied and shows a signal occurring

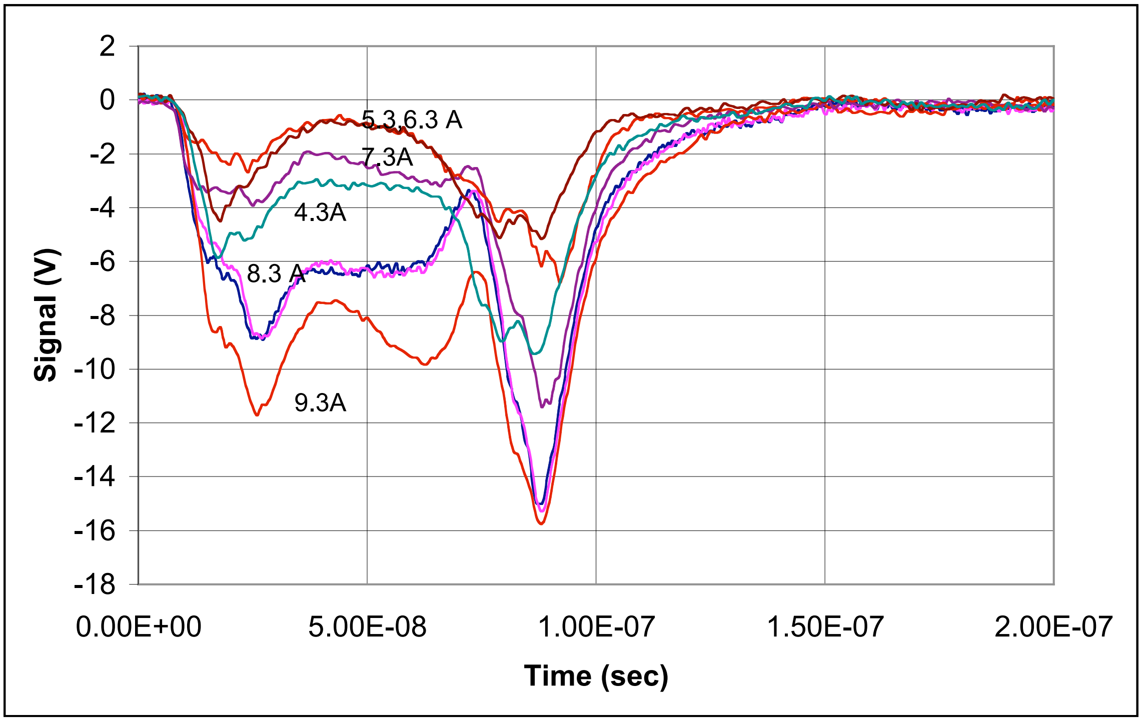

Figure 5 A+B data from 9/3/04. EF1=7A. Labels are EF0 current values.

when beam is present whose shape and magnitude depend on the value of current in EF0 and thus on the size of the beam at the DML. Observe that the signals have a minimum for values of EF0 in the same neighborhood as the minimum in radius. We interpret these signals as evidence that there is a beam component in contact with the wall at or near the DML.

If the beam-bug calibrations could be believed there would appear to be on the order of a minimum 70 A loss of beam current between the DML and BBT05, located 0.221 m downstream. We know from experience, however, that such a loss is suspect, probably because the beam-bugs are not calibrated with the summing chassis they use on ETA. Also from experience we know that when current is lost, it usually is lost over only a portion of the signal profile, consequently if by scaling one of the beam-bug calibration constants we get a good overlay of the two signals we can rather safely assume that there is little current loss between them and choose the scaled value as the correct calibration relative to the first beam-bug calibration. Subsequently if we no longer get a good overlay under a different running condition we can interpret this as being due to current loss between the two beam-bug position. We illustrate this in the next several figures.

In Figure 6 we plot a condition for which we get our best overlay. This is for EF0 set to 5.5 A and with the BBT05 calibration increased from 212A/V to 218A/V or about 3% while the DML calibration was kept constant at 198 A/V. While this seems to be the best eyeball fit, the current, when averaged over a 10 ns period around the peak current, decreases about 11 A between the DML and BBT05. If we further increase the BBT05

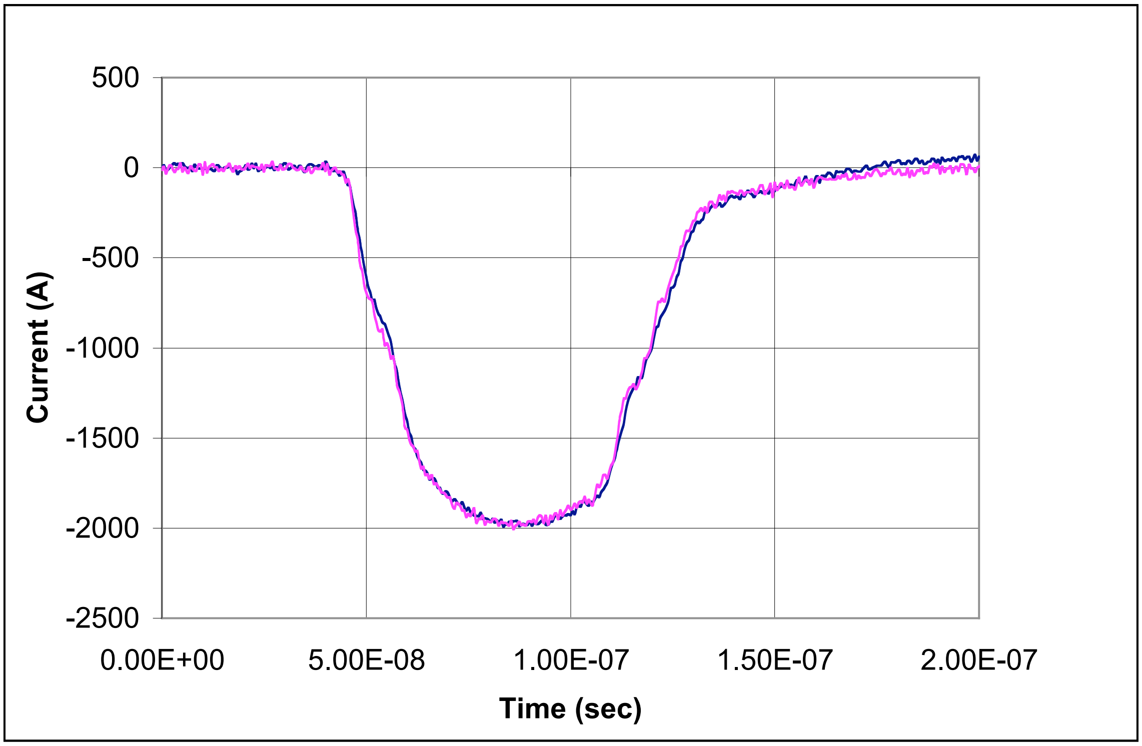

Figure 6 Overlay of DML and BBT05 current for EF0=5.5A.

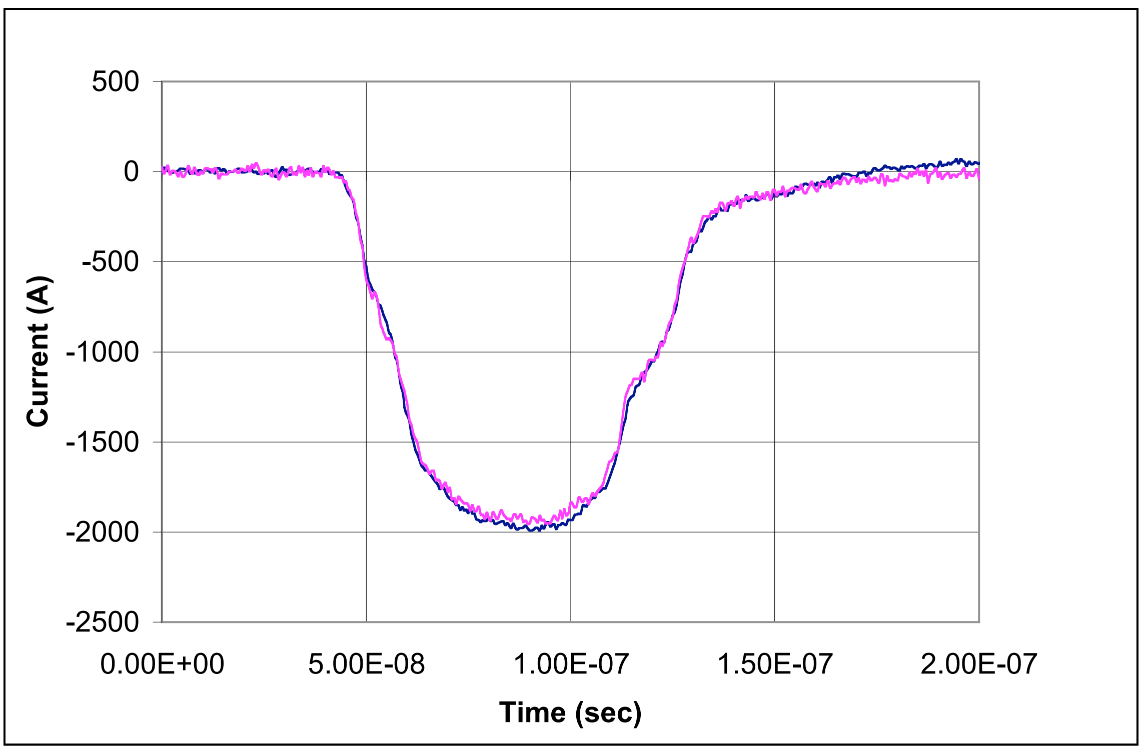

Figure 7 Overlay of DML and BBT05 current for EF0=4.5A.

calibration to the point where this difference disappears, the eyeball fit is not as good. This is probably the limit on our measurement accuracy but the current difference between the two beam bugs is quite a bit larger than this for other settings of EF0. One such case is shown in Figure 7 where with the same calibration as for Figure 6 we now see a loss of over 50 A between the two beam bugs. In Figure 8 we plot the 10 ns average around peak current at the two beam bugs as a function of the EF0 setting. This shows that there is some current loss between the two beam bugs over the whole range of settings and at the extreme EF0 settings there is additional loss upstream of the two.

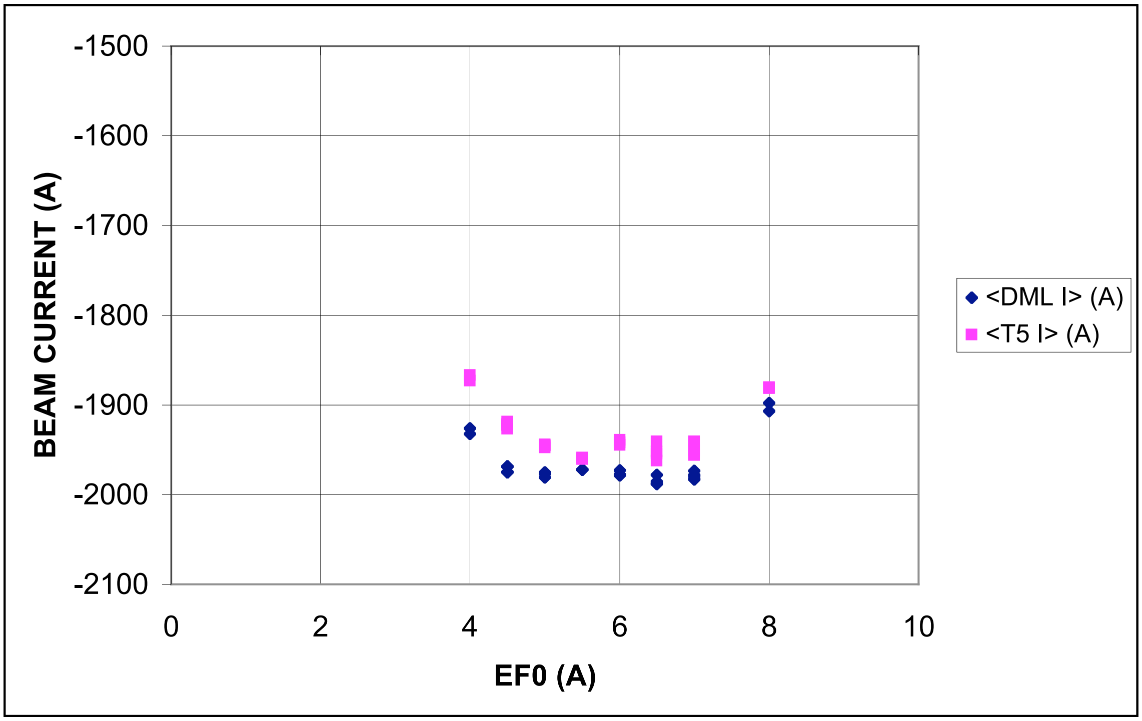

Figure 8 Peak beam current at the two beam bugs.

For the distribution of Equation 2 the current density for $r < r_0$ is

$$j_{z0} = \frac{I}{\pi\left(r_0^2 + 2r_0\alpha(R - r_0)\right)} \qquad 0 < r < r_0$$

while at the wall the current density is

$$j_z(R) = \alpha(r_0/R)\, j_{z0} \,.$$

The average current density lost to the wall between the two beam bugs is

$$j_r(R) = \frac{\Delta I}{2\pi RL}$$

where L is the axial separation of the two beam bugs (=22cm). For the model to be consistent with the observed losses it is necessary that the average angle of the beam particles hitting the wall to be

$$< r\theta(R) >= j_r(R)/j_z(R) = \frac{r_0(1 - 2\alpha) + 2R\alpha}{2L\alpha}\frac{\Delta I}{I}$$

In Figure 9 we plot the implied values of the average angle for the measured current loss and foil measurement of r_0, assuming $\alpha = 0.022$. These values do not seem unreasonable;

a straight line path from the center of the DML to the wall at BBT05 makes an angle with the axis of about 300 mr.

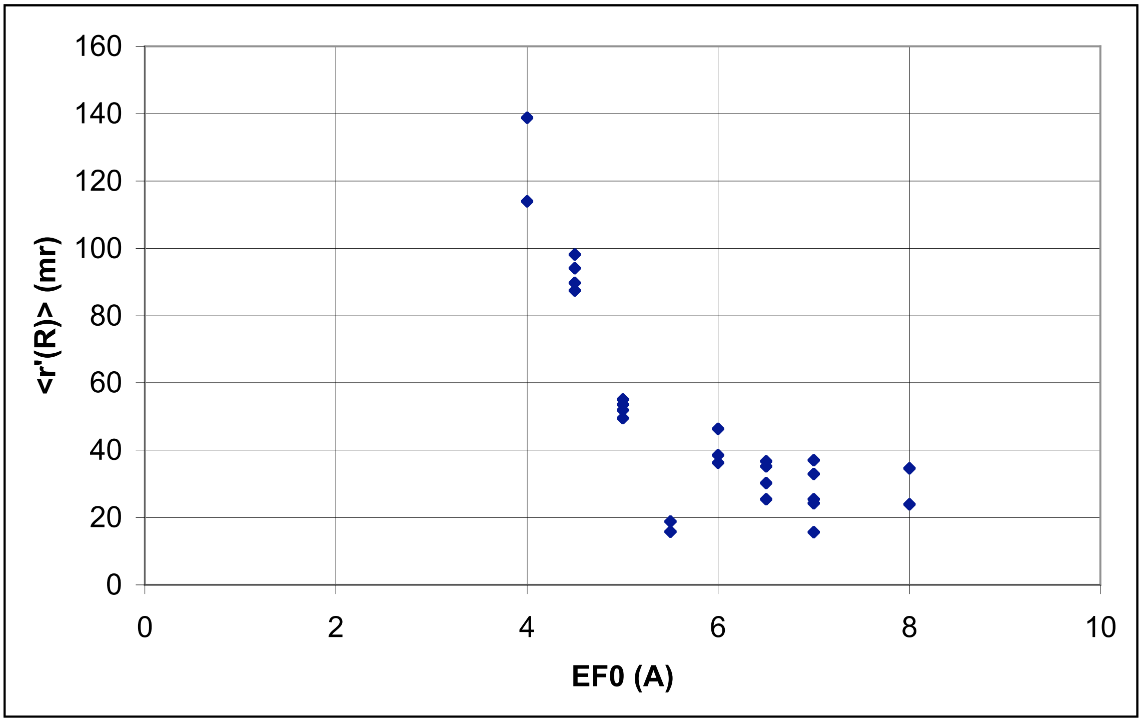

Figure 9 Average angle of particles hitting wall implied by current loss and halo model for del=0.022.

Conclusion: We conclude that both the DML and foil measurements are correct but diverge at smaller beam radii because they measure two different parameters, the DML the rms radius of the entire beam and the foil the rms radius of the beam core. We have presented a simple model of the radial beam current distribution and have shown that a rather low-density halo can explain the discrepancy between the two measurements. Signals due to wall bombardment and current loss to the walls are consistent with our model. Both DML and foil measurements may be necessary when working with beams with halos.

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