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Author(s): Pierce, Stanley W.
Burgardt, Paul

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EVALUATION OF TWO DEVICES
FOR
ELECTRON BEAM PROFILING

S.W. Pierce, MET-1

P. Burgardt, MST-6

Los Alamos National Laboratory

Los Alamos, NM 87545

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INTRODUCTION

Electron beam profiling is the process of measuring the size and shape of the electron density in the electron beam produced by an electron beam welding machine. The basic concept behind beam profiling is to cause the beam to move across a small aperture and to then measure the electron flow through that aperture. The apertures used here are small openings in a tungsten plate, which we will call the aperture plate. If the aperture is sufficiently small, the number of electrons flowing through that aperture is a direct measure of the electron density in the beam. By measuring current flow versus time (and knowing the velocity with which the beam is made to traverse the aperture) a map of the current density in the beam versus position is determined. Using that data, the beam diameter and other useful beam properties are determined. This paper discusses and compares the beam profiling results obtained using two different profiling devices available at this time.

DESCRIPTION OF THE TWO BEAM PROFILERS

Both devices evaluated here have in common that the electron detector is a Faraday cup. A Faraday cup is simply a hollow metallic collector (conceptually a hollow cylinder) with a small entrance aperture (the entrance aperture of the Faraday cup designed to be consistent with the aperture in the plate above; the details of this will be discussed subsequently). As long as the entrance aperture is small, thereby minimizing flow of scattered electrons back out of the Faraday cup, the Faraday cup collects essentially all of the electrons entering the cup. The current flow into the cup is measured by passing the electrons off to ground through a ground path resistor (GPR). The voltage across the GPR is a direct measure of the electron current flow into the Faraday cup. The basic difference between the two profilers studied here is the design of the aperture plate above the detector and the details of how the beam is made to travel across the aperture.

The basic notion of measuring beam power density using a small detector has been around since at least the mid-1960's. Some of these measurements were made with a "flying wire" where a small diameter tungsten wire was moved through the beam. Also, the concept of passing the beam across a small circular hole in a tungsten aperture plate had been explored at that time. These profiling techniques suffered from the drawback that they involved physically moving the detector under a stationary beam, which resulted in melting (or at least degradation) of the aperture or current collecting device. This happened basically because physical motion of the detector results in a practical limit to the speed with which the detector can be moved through the beam and melting of profiler components inevitably results.

One basic improvement in beam measurements was made by noting that the beam could be moved across a stationary detector using the beam deflection capability of the electron beam machine. Machines of that era had the capability of circle deflection as well as linear sinusoidal deflection in the X and Y directions. An appropriate combination of deflection frequency and amplitude will easily result in the beam moving across the aperture at an effective speed of $> 2\text{m/sec}$. Basic development work on a prototype device using beam deflection started circa 1985 and was largely accomplished by P. Burgardt, who worked at Rocky Flats at that time. The essential concept was to use the linear deflection capability of the EB welder to sweep the

beam across an aperture plate that consisted of a single long slit about 0.05mm in width. Linear deflection was used to move the beam perpendicular to the slit. This device was dubbed the “modified Faraday cup” (MFC). By knowing the frequency of oscillation and its amplitude, the dimensions of the beam could be calculated. The slit style of aperture integrates the beam current along the slit direction and yields a derivative of the beam current density in the direction perpendicular to the slit (ie. It yields beam size and shape information in the beam deflection direction). The data from the single slit MFC was shown to be useful for machine characterization and process transfer between machines. The obvious drawback of the single slit profiler is that it only yields beam current density information in one direction for any one orientation of the device.

Enhanced Modified Faraday Cup (EMFC)

The drawback of having only a single slit on the beam diagnostic device was solved by J.W. Elmer and his colleagues at LLNL circa 1995. They developed a Faraday cup with a multiple slit aperture plate. They settled on 17 slits arranged like the spokes on a wheel so that beam data was collected for every 20° of azimuthal angle. The slits in the aperture plate were each about 0.12 mm wide and were EDM cut into the tungsten plate. A picture of the aperture plate is shown in Figure 1. Circle beam deflection is used to sweep the beam across the 17 slits.

Figure 1: Picture of the EMFC 17 slit tungsten aperture disk. The burn track around the disk is a one inch diameter heptadecagon.

The resulting data consists of 17 cross-sections of the beam at the 17 orientations for each time the beam moves around the circle. Additionally, improvements to the Faraday cup were made to minimize scattering of electrons out of the cup, thereby improving electron collection efficiency. On Figure 1 you will also notice a central hole. This allows electrons to pass unimpeded into the Faraday cup and allows the device to be used to confirm overall beam current. The final multiple slit beam diagnostic device is known as the “enhanced modified Faraday cup” (EMFC). The device is described in some detail in: “An Enhanced Faraday Cup for Rapid Determination of Power Density Distribution in Electron Beams”, J.W. Elmer and A.T. Teruya, *Welding Journal*, pp. 288s-296s, 2001.

A critical part of the EMFC is the accompanying software. The software was mostly developed by A.T. Teruya. It is a LabView based data acquisition and data analysis package. The software collects the 17 voltage pulses resulting from circle deflection around the aperture plate. Using the input values of circle diameter and circle frequency the voltage versus time signals are converted into beam current versus position data. The resulting 17 current density versus position data packets are then passed through a tomographic reconstruction routine to yield a map of beam current density versus position in the beam. The resulting raw data map of beam current density versus X and Y is saved in an Xcel spreadsheet format (Reconstruction file) for later analysis if desired. Since it is known that the electron beam is reasonably Gaussian in shape, the software automatically performs an analysis of the data assuming a Gaussian distribution description of the electron density (ie. a least squares fit to a function of the form: $E = C \exp(-r^2 / \sigma^2)$, where E is electron current density, r is radial distance from the beam axis, and σ is the standard deviation of the distribution). The software actually assumes that the beam could be best described by an ellipse with an arbitrary orientation. Therefore, the least squares fit returns values for σ along the major and minor axes of the best fit ellipse as well as the angular orientation of the ellipse. For the purposes of this paper the most important output of the analysis is the diameter of the beam where its current density falls to $1/e^2$ of its peak value. This value is called FWe-2 throughout this paper.

Pro-Beam Diagnostic Device (PBD)

The Pro-Beam diagnostic uses the same essential concept as the EMFC to measure the beam power density distribution. However, the details of the measurement are a bit different because the Pro-Beam machine has unusual beam deflection capabilities. The Pro-Beam electron beam welding machine is in many ways designed like a scanning electron microscope (SEM). It has the usual beam alignment deflection coils but also has a set of “high speed” deflection coils. These deflections coils provide the capability to deflect the beam to different positions very rapidly. The current flow to the coils is CNC controlled so that very complex deflection patterns can be generated by defining an appropriate path. One of the standard deflection patterns used by Pro-Beam is a square raster pattern. This pattern moves the beam left-to-right while stepping in the front-to-back direction, thereby creating the raster pattern. This deflection pattern is used by Pro-Beam for secondary electron imaging (ELO) wherein a relatively low power beam is scanned across the part and secondary electrons are detected in order to generate an image of the work area. ELO is used for a number of standard operations during welding including: auto-focusing, auto-astigmatizing, and beam centering. Since this deflection pattern and the accompanying image analysis software is already an integral part of the Pro-Beam operating system, they use that scheme for their beam diagnostic device. An additional advantage of the Pro-Beam control system being fully integrated with operation of the PBD is that an automated program can easily be devised that collects the image data while incrementing the machine parameters, such as focus coil current.

The PBD aperture plate consists of a single small round hole (pinhole) that the beam is swept across using the raster deflection pattern. Figure 2 is a schematic of the PBD and a picture of one of the pinhole apertures. Direct measurements showed that the actual pinhole diameter is about 0.14 mm. (An interesting side note – looking at a pinhole under a microscope, the hole diameter right at the surface is actually about 0.25 mm, which is clearly too large to work

properly. This caused us considerable concern until we measured the hole diameter with a pin gauge and found its diameter to be closer to the desired 0.1 mm. The hole diameter clearly tapers rapidly inward such that the minimum hole diameter is in fact about 0.14 mm.) A typical

Figure 2: Schematic cross-section of the PBD device and a picture of one of the pinhole apertures. The arrow indicates the location of the pinhole aperture above the Faraday cup. Note that the round aperture plate actually has a number of these pinholes that can be rotated into place if one is damaged. Also notice that the pinhole diameter is about 0.14mm.

Faraday cup detector is positioned below the aperture plate and is used in place of the usual secondary electron detector during use of the PBD. It should be noted that the 0.14 mm diameter pinhole used in the PBD is actually a bit large for proper beam current density determination at sharp focus. The significance of that will be discussed later.

There is a potential problem with the PBD related to the details of the raster deflection pattern used with that device. The deflection pattern is a 13.2 X 13.2 mm square, which the image analysis software uses to generate an image that is a 376 X 376 pixel array. This corresponds to a pixel size of 0.035 X 0.035 mm/pixel. ISO 11146-1 suggests that the pixel resolution should be 0.05 of the beam diameter (ie. about 0.015mm). Near to sharp focus, the pixel size is too coarse by roughly a factor of two for good beam resolution. This is apparently not a fatal flaw relative to the PBD data but should be considered as the data analysis is performed. It is interesting to note that the EMFC for typical conditions (50Hz circle of 25.4mm diameter) has an equivalent pixel size of 0.016mm, which is consistent with the ISO specification recommendation relative to detector resolution.

The details of the Pro-Beam software analysis of the beam current density data is proprietary information and, therefore, is not known to us. However, it is clear that the image analysis software has been modified to include calculation of beam diameter values consistent with the international standard: ISO 11146-1, “Lasers and laser-related equipment – Test methods for laser beam widths, divergence angles and beam propagation ratios – Part1: Stigmatic and simple astigmatic beams”. The ISO standard specifies that beam diameter is computed from the second moment of the distribution and the PBD software does that. The significance of the second moment calculation will be discussed subsequently. The PBD software also computes second moment in the X and Y directions, beam eccentricity and an orientation angle of the eccentricity (methodology proscribed by the ISO standard). For our purposes here the important result is the overall beam diameter (overall distribution second moment), which we will call D86 throughout this paper. The PBD software also yields beam image data which, after processing with a MathCad program, gives 3-D images of the beam that can be compared with EMFC generated beam images.

Definitions of Beam Diameter

The primary purpose of this study was to compare the beam diameter data from the two diagnostic tools. Therefore, it is important to discuss the beam diameter definitions used by the two software packages since they are a bit different.

First, consider the analysis used by the EMFC. The software accompanying the EMFC assumes that the data is described by a Gaussian distribution. That software then performs a least-squares fit of the raw data to a Gaussian distribution to determine the standard deviation, σ , of that distribution. The diameter value then returned by the software is FWe-2 defined as: $\text{FWe-2} = 2\sqrt{2} \sigma$. The relationship between σ and FWe-2 is illustrated in Figure 3.

Figure 3: Illustration of a Gaussian electron density distribution showing the significance of the standard deviation of the distribution, σ , and its relation to FWe-2.

The significance of FWe-2 is that about 86.5% of the beam current is within this diameter and considerable welding experience has shown that this is consistent with the “useful” diameter of the beam (ie. FWe-2 corresponds reasonably well to the width of the keyhole produced by that beam). It should be noted that the EMFC software does actually assume an elliptical Gaussian, ie. it actually computes σ_{maj} and σ_{min} the standard deviations of the distribution along the major and minor axes. In that case, the beam diameter value is: $FWe-2 = 2\sqrt{2} (\sigma_{maj}^2 + \sigma_{min}^2)^{1/2}$.

The validity of the EMFC diameter values has been thoroughly validated and we have considerable confidence in those numbers. For example: circa 2000, P. Burgardt performed a series of comparison tests of the EMFC versus the prototype single slit MFC. The single slit MFC results were obtained and the data from the MFC were analyzed manually, assuming the usual Gaussian distribution. In all cases, the beam diameter values from the manual analysis of MFC data and those returned by the EMFC software agreed within a few percent.

PBD data analysis is performed in accordance with ISO 11146-1, wherein beam diameter is defined by a computation of the first and second moments of the electron density distribution. The ISO specification assumes that the beam current density is basically in a pixel form, ie: the beam current density is known as a function of x and y position, $E(x,y)$. The first moment is computed to find the centroid of the distribution (ie. the intensity weighted average values of x and y) and returns those centroid values X and Y. This process is specified as:

$$\text{First moment: } X = \frac{\sum E(x,y)x}{\sum E(x,y)} \text{ and } Y = \frac{\sum E(x,y)y}{\sum E(x,y)}$$

Once the distribution center is known, the intensity weighted standard deviation of the distribution is computed (ie. its second moment). This process is specified as:

$$\text{Second moment: } \sigma_x^2 = \frac{\sum E(x,y)(x-X)^2}{\sum E(x,y)} \text{ and } \sigma_y^2 = \frac{\sum E(x,y)(y-Y)^2}{\sum E(x,y)}$$

The overall electron current standard deviation is then: $\sigma^2 = \sigma_x^2 + \sigma_y^2$

And finally the overall diameter of the distribution is: $D86 = 2\sqrt{2} \sigma$.

One of the primary goals of this study was to demonstrate whether or not the Pro-Beam software was actually performing the calculations correctly. As you will see subsequently our efforts in that regard were only partially successful. We can only trust that Pro-Beam has properly incorporated the ISO specified calculations into their software properly. The data do show that their software is undoubtedly working properly.

An important point about the relation between D86 and FWe-2 should be made. If one follows the mathematics, it turns out that D86 and FWe-2 are identical for a circularly symmetric Gaussian beam. If the beam is elliptical in shape (but still overall Gaussian in nature) the two diameter values are also the same. It is the case that, if the beam is highly eccentric with arbitrary orientation angle, the two diameter values could be a bit different. However in general, the beam is sufficiently circularly symmetric that this shouldn't be an issue. Therefore, we expect that the PBD and EMFC devices should yield the same results for beam diameter.

EXPERIMENTAL PROCEDURES

The basic experimental plan was to generate an electron beam under a number of combinations of beam accelerating voltage (high voltage, HV), beam current and beam focus. The two diagnostic devices, EMFC and PBD, were then used to measure the beam current density and the results were compared. All beams used here were generated by a Pro-Beam (PB) manufactured low voltage electron beam machine installed at LANL in building SM-39. Essentially all of the data was generated with HV = 60kV and beam current of 10 mA.

The basic experimental goal was to compare beam shape and diameter determined by the two diagnostic devices versus beam focus (from sharp focus to about ± 50 mA focus coil current). The result of the study was intended to be a consistency/validity check of the two diagnostic devices. CNC generated circle beam deflection with a pattern diameter of 25.4mm was used with the EMFC. This led to an interesting problem that will be discussed subsequently. The standard 13.2 X 13.2mm square raster deflection was used with the PBD.

RESULTS AND DISCUSSION

An Interesting Problem with PB Circle Deflection

The first beam measurements with the EMFC on the Pro-Beam machine were actually made as a part of the acceptance testing of the Pro-Beam machine at the factory in Germany. It was noted at that time that the data was basically reasonable but seemed to have some internal inconsistencies. This work was eventually repeated here at LANL with basically the same result but here it was realized that the original data had been filtered as it was recorded (to help block random noise) and this had masked a real problem with the quality of the raw data. The problem is illustrated in Figure 4. Figure 4 shows the 17 voltage versus time signals generated

Figure 4: Raw beam shape data (17 voltage versus time traces) from the EMFC software for one pass of the beam around the slit plate. Notice the unusual “jagged” appearance of the data.

as the beam is swept around the aperture plate. What one expects to see in Figure 4 is 17 Gaussian shaped voltage versus time signals. Instead the raw data has an unexpected “stair stepped” appearance. This problem was eventually traced to the way in which the Pro-Beam

generates circle deflection. The PB machines make a circle by using a CNC computed path to feed the appropriate deflection current to the fast deflection coils. Basically this means that the beam starts at a point on the circle, and then after an appropriate dwell time quickly moves to the next point on the circle, dwells there and so on. The standard circle does this process using 1,000 points on the circular path. Note: the dwell time at any point is basically: $\Delta t = 1 / (f N)$, where f is the frequency of the figure and N is the number of points making up that figure. The beam moves between points are limited in speed only by the slew rate of the deflection amplifiers (very high slew rate of $10\text{V}/\mu\text{s}$) and the inductance of the deflection coils, which is small. Thus, the time to move between points is small (perhaps $\approx 10 \mu\text{s}$) and those moves can be considered to be essentially instantaneous. This method of circle deflection generation is problematic for the EMFC because, as the beam crosses a slit on the aperture plate the beam will actually dwell on the aperture several times at different beam positions. If we consider the standard 25.4mm diameter circle at 50Hz generated with 1,000 points, the beam at sharp focus would dwell while passing over the slits about 6 times. The resulting beam motion yields the “stair stepped” data seen in Figure 4. The standard “point figures” possible with the Pro Beam system include 1000 and 10,000 point figures. Good quality EMFC results require that the point density on the circular path be increased to $> 50,000$ (the resulting deflection pattern is effectively a continuous circular path). Note: the CNC programming of beam deflection can be modified to include up to 1,000,000 intermediate points in the final generated pattern.

An interesting solution to the limitation of the standard circle point figure was the 17 sided polygon (heptadecagon) “vector figure” developed by Stan Pierce. The vector type program allows the creation of figures composed of many more points than the point type program. The heptadecagon is composed of 1,000,000 points and is generated in the CNC programming by specifying linear beam travel between 17 end points with roughly 59,000 intermediate points in each line segment. Figure 5 shows a schematic of how the programming is accomplished as

Figure 5: Schematic of the CNC programming and the resulting beam path for the heptadecagon deflection pattern used with the EMFC.

well as the resulting burn track on a tungsten plate. Assuming that the heptadecagon is properly oriented relative to the EMFC slits, it results in linear travel across each slit. The

heptadecagon was used to generate the EMFC data discussed in this paper. Figure 6 shows data from the EMFC with heptadecagon deflection showing the expected Gaussian-like beam current density (contrast Figure 6 with Figure 4).

Figure 6: EMFC data when using heptadecagon beam deflection. The data has the expected Gaussian-like behavior for each voltage versus time pulse.

Initial Beam Shape Data

The first data considered in this study were simply the overall shape of the beam at various focus values. Images of the beam were generated (for the EMFC these are contour plots from the Xcel spreadsheet of data values - for the PBD these were generated in MathCad from the image file data) and are shown in Figure 7. It is immediately apparent that the two beam diagnostic devices are returning data that are qualitatively identical. This gives us considerable confidence that both devices are operating properly and that their data are equivalent.

Figure 7: Images of the beam shape resulting from EMFC and PBD data. These data were obtained from the LVEBW at 60kV and 10mA and for three beam focus conditions,

Even though the two image sets are qualitatively similar, there are a few apparent differences in the images and some discussion of the differences is warranted. First, there are differences in the apparent diameter of the images. This is unimportant because, while we did try to scale the images to be similar in size, the horizontal dimensions of the images in Figure 6 are actually completely arbitrary. A second interesting observation (especially apparent for the 50mA over focus images) is that the EMFC and PBD images do seem to be rotated 180° relative to each other. After detailed discussions with Pro-Beam it was established that the PBD images are in fact rotated by 180° away from their correct orientation. That happened because, in our version of the PBD software, the PB programmers failed to properly reference the data to the beam coordinates and instead referenced to the aperture plate coordinate system, which effectively flips the data in the X and Y dimensions – equivalent to a 180° rotation (PB will fix that problem in future software updates). A third point is that the data at sharp focus show considerable eccentricity with the EMFC and PBD images rotated roughly 45° relative to each other. Figure 8 shows some additional data obtained near to sharp focus that shows the qualitative difference in the data seen in that focus regime. This rotation is common to the data obtained near to sharp focus and is not understood. As was noted previously, the PBD software processes the image using inadequate resolution to properly characterize a sharp focus beam. At least part of the apparent 45° rotation may result from inadequate resolution (presumably the EMFC data are more accurate for the beam near to sharp focus and are more trustworthy).

Figure 8: PBD and EMFC beam shape data near to sharp focus showing the bit of difference in the beam eccentricity and beam orientations observed in that focus regime.

Beam Diameter Values

The primary goal of this work was to compare the beam diameter data from the two diagnostic devices and to check them for consistency. Therefore, a number of measurements of beam diameter were made near to sharp focus and for HV = 60kV and BC = 10mA and for a fixed work height. The summary data are shown in Figure 9. For the purposes of this paper, the

Lens [mA]	Centre X [px]	Centre Y [px]	Dimension X [mm]	Dimension Y [mm]	Ellipticity	Angle [degree]	Beam diameter [mm]
1939.51	187.53	188.53	0.35	0.34	0.97	-10.09	0.34
1939.51	187.04	188.71	0.36	0.36	0.98	23.96	0.36
1940.49	187.54	188.51	0.35	0.33	0.94	-9.24	0.34
1941.47	187.54	188.59	0.38	0.31	0.83	-0.66	0.35
1942.44	187.54	188.59	0.35	0.30	0.87	-4.10	0.33
1943.54	187.49	188.49	0.38	0.30	0.78	-3.53	0.34
1944.52	187.57	188.67	0.42	0.29	0.70	-3.64	0.36
1945.49	187.69	188.57	0.44	0.30	0.68	-3.25	0.37

a. PBD data near to sharp focus

Focus	FWHM	FWe2	Measured PPD	Theoretical PPD at FWHM	Theoretical PPD at FWe2	Angle3	Major Width	Minor Width
1937	0.15	0.26	19500	21975	23209	-71	0.287	0.207
1938	0.14	0.25	21000	25812	24539	-69.8	0.287	0.192
1939	0.14	0.24	21300	27103	25467	-66.9	0.271	0.223
1940	0.14	0.24	22100	28530	26030	-56.5	0.271	0.192
1941	0.14	0.24	21700	28530	25746	-46.8	0.239	0.223
1942	0.14	0.25	21100	27103	24797	-24.9	0.223	0.223
1943	0.14	0.25	21000	27562	24667	-12	0.239	0.207
1944	0.14	0.25	19700	28038	23795	-4.3	0.239	0.239
1945	0.14	0.26	19000	26229	22871	0.3	0.271	0.223

b. EMFC data near to sharp focus

Figure 9: Summary data from the PBD and EMFC for HV = 60kV; BC = 10mA; fixed working distance. The yellow accented values are judged to be sharp focus in each case.

primary interesting feature of these data is the considerable difference between the sharp focus FWe-2 versus D86 values. This measurement was repeated a number of times with all results being essentially the same (on the average the results yielded FWe-2 = 0.24mm and D86 = 0.34mm at sharp focus). The difference in diameters is clearly outside of experimental error. Since, the two diameters were expected to be the same (or at most different by a few percent) this result requires further analysis.

One potential cause of the diameter discrepancy is the rather large pinhole used in the PBD aperture plate. If the aperture is too large relative to the beam, the raw data of voltage versus time will be too wide depending on the ratio of beam size to hole size. Results of Elmer and Teruya (op. cit.) showed that, for a slit, the measured beam diameter will be too large by about 30% when the slit width is comparable to the beam FWe-2. In support of this paper, numerical calculations of the beam diameter error for a round hole aperture were made. The results are shown in Figure 10. In agreement with the Elmer and Teruya results, these calculations showed that the measured beam size for a FWe-2 = 0.24mm beam would increase to about

Figure 10: Numerical simulation of the PBD output for a circularly symmetric beam with $\text{FWe-2} = 0.24\text{mm}$ for various pinhole diameters.

0.28 mm when a pinhole diameter of 0.14 mm is used for the measurement. That seems to account for at least some of the beam size discrepancy shown in Figure 9. However, there are two important details that argue against that explanation.

The first important point is that the PBD and EMFC apertures are actually similar in size and errors induced by aperture size would be about the same for both devices. Interestingly, this means that the sharp focus diameter given by both devices is actually roughly 10% larger than the actual beam diameter. The second point is that if one considers the results shown in Figure 10 and asks how the hole size affects a defocus beam, it is clear that the aperture size is actually unimportant. The considerable error in beam diameter only occurs when the pinhole size is comparable to the beam size. If the beam were twice as large as the pinhole, any aperture size effects are $< 5\%$. However, beam diameter data obtained over a fairly large range of defocus show that the beam diameter difference persists to large beam diameter. Example data illustrating this point are shown in Figure 11. Over the entire range of values ($\text{FWe-2} = 0.24 - 1.5\text{mm}$), $D_{86} \approx 1.35 \text{ FWe-2}$. This suggests that there is some basic difference between the PBD and EMFC software analyses and that further study of the problem is warranted in order to understand this difference.

Figure 11: EMFC (FWe-2) and PBD (D86) beam diameters versus focus coil current over a range of defocus values. Note that the beam diameter difference persists to large defocus as an approximately constant multiplier with $D86 \approx 1.35$ FWe-2.

Manual Analysis of PBD Data

Our initial assumption was that there is a mistake in the PBD software analysis. Therefore, we endeavored to manually analyze the PBD data using the second moment calculation and hopefully identify the problem. Unfortunately, raw data from the PBD device is not presently available from the software package. What we can access is the image files used to generate the pictures shown in Figures 7 and 8. Based on our understanding of the analysis, the image files should be a pixel map of the beam with a pixel size of 0.035×0.035 mm. Figure 12 is the pixel map manually extracted from the PBD sharp focus beam data and the accompanying beam image. Figure 13 shows two slices through the data (along the yellow highlighted directions in Figure 12) along with Gaussian fits to those data. This analysis yielded: $FWe-2 \approx 0.6$ mm and a computation of distribution second moment yielded $D86 = 0.62$ mm.

The diameter values resulting from this analysis are considerably larger by at least a factor of X2 than those given by the PBD or EMFC analysis software. This discrepancy obviously means that we do not understand the actual size of a pixel in the PBD image. In any case, it was clear that further analysis of the PBD data was a waste of time. Although, this does reinforce the point that we really don't know how the PBD software analyzes the data and what effect this may have on the results.

Figure 12: PBD image file data and accompanying beam image for the sharp focus beam.

Figure 13: PBD sharp focus beam data in the X and Y directions along with best-fit Gaussian curves for those data.

Figure 14: Contour plots of the PBD and EMFC data at sharp focus (scaled to be the same dimension scales). This shows that the raw beam data from the PBD appears to be much larger in size than those given by the EMFC.

Manual Analysis of EMFC Data

Since it was impossible to reproduce the PBD software analysis of that data, we endeavored to perform manual analysis of the EMFC data, where the raw data values (Reconstruction files) are available as an Xcel spreadsheet. The goal was to discover if the difference between D86 and FWe-2 is a result of a software error or if it is a real property of the beam.

Our initial work in this regard was to confirm that the FWe-2 values yielded by the EMFC were correct. An error in this value seemed possible since the beam shape, especially for the underfocus, beam is substantially different than has been seen in the past. It seemed possible that this could “confuse” the calculation of FWe-2. Therefore, a detailed analysis of the sharp focus beam size was undertaken. Figure 15 shows contour plots of the EMFC data at sharp focus and illustrates the “square” shape of the beam that could potentially confuse the analysis. Data from several directions in the beam were extracted from the raw data and fit to the usual Gaussian distribution. Those results are shown in Figure 16. As expected the overall beam diameter value of 0.24mm given by the EMFC software is consistent with the data and appears to be correct.

Figure 15: Contour plots of the EMFC data at sharp focus (60kV; 10mA; F=1940) showing the somewhat unusual “square shaped” aspect of the beam.

Figure 16: EMFC data from several directions in the sharp focus beam showing the quality of the Gaussian fit to the data and the accompanying FWe-2 values.

Since the values of FWe-2 seem correct, the obvious next question is whether or not D86 and FWe-2 are simply different for this beam shape. Therefore, a template Xcel spreadsheet was developed that computes the first and second moments of the beam current density distribution. One simply pastes the EMFC data from the Reconstruction files into that spreadsheet and the value of D86 is automatically determined. This was done for the sharp focus EMFC data and the result was $D86 = 0.35$ mm. Notice that this is in excellent agreement with the PBD value of 0.34 mm. Once it was realized that D86 and FWe-2 are simply different for this beam shape, D86 calculations were similarly performed for a number of the defocus beam values and those results are shown in Figure 17 and are compared against the values of D86 given by the PBD.

Figure 17: Beam diameters as given by the EMFC and PBD as well as D86 values computed from the EMFC data (triangle symbols). Notice that the D86 values yielded by the EMFC and PBD are in good agreement.

There is a bit of scatter in the diameter values but one can see that there is overall excellent agreement between the D86 values determined by the PBD and by manual analysis of the EMFC data. Thus, we can conclude that the diameter values given by the PBD are correct (even though we aren't entirely clear how they are determined). The basic conclusion from this analysis is: the FWe-2 and the D86 diameters of this beam actually are different by roughly 35%. Since we expect those diameters to be the same, the critical question becomes: why are the two diameter definitions yielding different results for this beam?

Why Are D86 and FWe-2 Not The Same?

The basic answer to why D86 and FWe-2 are not the same is that the beam produced by the Pro-Beam LVEWB is not really Gaussian in nature (and in fact, over the range studied is often distinctly non-Gaussian). Referring to Figure 7 it is obvious that the underfocus beam simply cannot be described by any simple Gaussian distribution. From sharp focus to considerable overfocus the beam is clearly more Gaussian in nature and it would seem that the two diameter values would be more nearly equal. However even for those beams, at least some level of the complex beam shape is present and will render the Gaussian assumption at least somewhat invalid. At sharp focus, Reference Figure 8, it appears that the beam is Gaussian and it would appear that the two diameters should be equal. Nevertheless, if one examines the sharp focus beam contour plots shown in Figure 15 in detail, it is apparent that no single circular or elliptical Gaussian distribution can adequately describe the “square” shape of the beam.

The data presented in Figure 16, and labeled as the -45° slice, further illustrate how the non-Gaussian nature of the beam can produce a difference between D86 and FWe-2. As you can see, the data are reasonably well-represented by a Gaussian distribution with a width of 0.20 mm. However, in that direction in the beam there are a fairly large number of low density electrons outside of the Gaussian distribution. This deviation from ideal behavior would seem to be insignificant. However, an area integral of the total number of electrons in that direction shows that actually roughly 15% of the electrons are not inside of the Gaussian distribution. The second moment value computed for that direction yields $D86 = 0.32$ mm. This point is reinforced in Figure 18. The large difference between FWe-2 and D86 illustrated in Figure 18 seems counter-intuitive until one remembers that D86 is computed by multiplying the electron density by distance from the beam core squared, r^2 . That means that a relatively small number of electrons at a large distance from the Gaussian-like beam core will substantially increase the value of D86; that is often the case for any EBW machine and is most definitely the case for the Pro-Beam LVEB machine. Another way to say this is: FWe-2 mostly describes the high current density Gaussian core of the beam while D86 more heavily weights the low current density electrons outside the beam core.

In order to further illustrate the origin of the difference between FWe-2 and D86, values of $E(x,y) r^2$ computed for a circularly symmetric Gaussian simulation of the beam and the actual sharp focus data yielded by the EMFC are presented in Figure 19. Once again we see that there are a significant number of electrons in the actual electron beam outside of the ideal Gaussian distribution, which are there because of the complex beam shape produced at the electron gun. This makes the D86 values larger than expected by some 35% for the beam shape produced by this EBW over the entire focus range and even at sharp focus.

In any case, we now know two important things relative to D86 and FWe-2 : first, the PBD and EMFC devices and the accompany software are performing properly; second, the difference between the two diameter values is a difference in the basic definition of “diameter” used to characterize the data. We do not at this time know which diameter definition is the best overall description of the beam and its performance relative to EB welding.

Figure 18: Beam current density versus position data from the EMFC for the beam at sharp focus in the -45° direction with FWe-2 and the D86 computed for this direction in the beam.

Gaussian simulation – FWe-2 = 0.25 Sharp focus beam data (EMFC)

EMFC Image of beam
at 50 incr underfocus

Figure 19: Images of electron density multiplied by radius squared $[E(x,y) r^2]$ used in the calculation of D86 for a circularly symmetric Gaussian distribution (FWe-2 = 0.25) and actual data from the EMFC for the sharp focus beam. An image of the defocus beam is shown to qualitatively illustrate the origin of the structure in the data as being from the electron gun.

An Additional Interesting Observation – Difference in Sharp Focus Value

While making the beam size measurements previously discussed, it was noted that the two diagnostic devices yielded a bit different values for the location of sharp focus. For example: at a work height of 99.4 mm (the top of the PBD and EMFC aperture plates both placed at that height above the bottom of the chamber) PBD minimum beam size occurred at 1937 mA focus coil current while the EMFC minimum occurred at 1940 mA. This measurement was repeated several times and the details varied slightly but the PBD minimum was consistently at a bit lower focus coil current than that of the EMFC. Referencing the difference in sharp focus values to data for sharp focus versus work height, as determined by the PBD, the difference in sharp focus coil current means that the PBD (D86) sharp focus occurs about 3 mm closer to the gun than the sharp focus given by the EMFC (FWe-2). The sharp focus versus work height data are shown in Figure 20. This difference is not large but it is an interesting observation that does introduce another question about the basic validity of the data coming from the diagnostic tools.

Figure 20: Focus coil current for sharp focus versus work height as determined by the PBD. The triangle symbol is the sharp focus location determined by the EMFC. Note that work height is referenced from the bottom of the chamber so that greater work height is moving closer to the electron gun.

The first thing considered in this regard is the geometry of the aperture plate. We have always assumed that the proper reference point for beam profiling is the top surface of the aperture plate. That has always produced reasonable data that yield sharp focus values that agree with the usual methods of determining sharp focus. However, a ray tracing analysis of the interaction of the beam with an aperture shows that there is a bit of difference between the way the aperture blocks the beam for a converging and diverging beam especially if the aperture

plate is relatively thick. Thus one could imagine that an aperture in a thin plate could produce a different result than an equivalent aperture in a thick plate (basically the difference between the PBD and EMFC). A ray trace analysis showed that the PBD would indicate that the beam minimum dimension occurs a bit above that given by the EMFC. However, this analysis shows that the difference in sharp focus height should be < 1 mm, which is too small to account for the sharp focus data we have observed. We have not definitively shown that the difference in apertures is unimportant, but, it does seem most likely that the vertical offset in sharp focus originates elsewhere.

The likely cause for the sharp focus offset was first brought to our attention by: T. Löwer of Pro-Beam and J.W. Elmer of LLNL. In order to understand this we need to say a word about the electron gun design. In a triode gun design we have a hot filament (the electron source) in close proximity to a grid plate (or bias cup). The filament is generally made sufficiently hot that it is an efficient electron source (through thermionic emission) producing an excess of electrons for the required beam current. Beam current is controlled by creating an electric field (by control of bias voltage) between the filament and the grid plate that suppresses electron emission from the filament to yield the required beam current. Ideally, the bias voltage would limit the electron emission to a small circular region on the top surface of the ribbon filament. These are the electrons thought would be brought to a focus by the focus coils to produce the weld. However in actuality, at least some electrons escape from the cathode region coming from the edges of the filament. Therefore, the beam at the gun will consist of a high electron density core (mostly Gaussian in shape coming from the center of the filament) surrounded by a lower electron density “halo” (coming from the edges of the filament). The two collections of electrons leave the electron gun with different divergence angles and will, therefore, approach sharp focus (after passing through the electron lens) with different convergence angles. The net result is that, depending on the details of electron peaking, accelerating voltage and etc., the minimum waist dimension for the core and halo electrons could occur at substantially different vertical locations. It should be noted that this phenomenon seems more pronounced on the Pro-Beam machine than has been seen in the past on more conventional EB machines. We believe that is a result of the Pro-Beam gun design; that will be discussed in a future report.

A picture illustrating the point about the two sets of electrons was provided to us courtesy of: T. Löwer of Pro-Beam and is shown in Figure 21. That is a picture of an electron beam showing that there is a beam core with low convergence angle and a diffuse halo with higher convergence angle. (It should be noted that we do not know how the picture was made nor do we know what beam parameters were used. However, it does illustrate the basic concept being presented here quite well.) The blue and red lines on the picture in Figure 21 were drawn to help guide the eye of the reader and represent our best guess relative to the behavior of the core and halo electrons. As you can see, the outer (halo) electrons pass through their minimum dimension closer to the electron gun than do the inner (core) electrons. Also on Figure 21 is a schematic representation of what the picture is showing and illustrating how this could lead to a substantial difference in location of the minimum in D86 and the minimum in FWe-2. This latter point should perhaps be elaborated a bit. The calculation of FWe-2 assumes a Gaussian distribution and, therefore, is dominated by the high electron density portion of the beam (ie. the

[Photo courtesy of:T. Löwer of Pro-Beam]

Figure 21: Picture of an electron beam showing the presence of core and halo electrons with different convergence angles and different positions of their minima. Also shown in a schematic of the beam illustrating how the minima in D86 and FWe-2 could occur at different vertical heights.

core electrons). D86 more heavily weights outlying electrons and therefore is strongly influenced by the low electron density portion of the beam (ie. the halo). Therefore, the minimum in FWe-2 occurs near the waist of the core electrons while the minimum in D86 occurs nearer to the waist of the halo electrons. That is the situation being illustrated in Figure 21 and is most likely the origin of the difference in sharp focus values returned by the PBD relative to the EMFC. Recall that the actual focus data show that the D86 minimum occurs about 3mm above the FWe-2 minimum and that is consistent with the situation illustrated in Figure 21.

It is now apparent that D86 and FWe-2 measurements could yield different values for sharp focus but the question remains: does that apply to our particular machine? Figure 22 shows EMFC data for this machine with considerable underfocus illustrating that there is a Gaussian-like core to the beam surrounded by a sharply defined and almost circular halo of electrons, which is qualitatively exactly what the picture in Figure 21 led us to expect. For this value of underfocus the core diameter is about 0.65mm and the halo diameter is about 1.4mm. This basic beam shape persists and is clearly identifiable until near to sharp focus. The core (determined by a Gaussian fit) and halo (fit to a circle surrounding the core) diameters were measured over the focus range and the resulting data are presented in Figure 23.

Figure 22: EMFC beam profile for the Pro-Beam at 60kV; 10mA and 99.4mm work height and 50mA underfocus showing the core and halo electrons discussed in this paper.

Figure 23: Diameters of the core (Gaussian fit) and halo (circle diameter) electron distributions versus focus coil current as produced by our machine at 60kV; 10mA and fixed work height.

It should be noted that Figure 23 shows two data points for the halo electrons diverging after passing through their minimum size. These data points are at least somewhat questionable since the sharply defined halo is quite diffused after those electrons pass through minimum radius. This happens because strong space charge interactions between the electrons occur as they approach minimum radius and this tends to randomize their motions. Figure 24 illustrates that point. Nevertheless, enough remnants of the halo did exist in the $F = 1940$ and 1945 data that, with a little imagination, one could still estimate their diameter. In any case, the halo electrons clearly have a larger convergence angle than do the core electrons as they approach their minimums in diameter. It appears that the core electrons pass through their minimum waist at $F = 1940$ and the halo electrons pass through their minimum waist at $F \approx 1930$. Thus, it is entirely reasonable that the minimum in D86 would occur at a focus value perhaps 5 increments of focus lower than is the case for FWe-2 (this corresponds to a height difference of about 4 mm). In conclusion: it appears that the observed difference in sharp focus values between D86 and FWe-2 is probably a result of the different convergence behaviors of the core and halo electrons. Once again we see that the EMFC and PBD are undoubtedly operating properly and returning equally valid data. This is another case where the basic definition of beam diameter used in the analysis (second moment calculation versus Gaussian representation of the beam) led to the difference between the PBD and EMFC data.

Figure 24: Contour plots of the electron distribution in the beam for defocus values equidistant from overall sharp focus. This shows the randomization of the beam that occurs when it passes through sharp focus.

Which Sharp Focus Value Best?

For now we really don't know which determination of sharp focus is most representative of the actual minimum beam size (presumably yielding maximum weld penetration). The two values are sufficiently similar that either would generally be adequate for process characterization (3 – 5 mA of focus coil current is small and would most likely have little effect on actual welds). Certainly, either sharp focus value would be more repeatable than could be achieved by manual means. However, there should still be a best value of sharp focus and it is highly desirable to know which is best.

Some additional information in this regard can be garnered by considering data from manual sharp focus determination and its automated equivalent as used by Pro-Beam (the auto-focus procedure they use). Sharp focus in this case is determined by determining the sharpest image in what Pro-Beam calls the ELO procedure. ELO uses the square raster pattern at moderate beam current to generate an image of the work area using backscattered electrons. The basic idea is to find the sharpest image of a textured target. ELO can be done automatically by the machine (auto-focus), where the image analysis software finds the sharpest image, or can be done manually. Figure 25 shows images of a target generated during manual ELO for defocused and sharp focused beams. One can see that image quality degrades substantially for defocus > 10 mA of focus coil current. During those tests it was found that the human eye returned values of sharp focus in the range of 1943 – 1946 mA. The auto-focus ELO consistently returned a sharp focus value of 1946 mA. ELO sharp should occur where the majority of the electrons are at their minimum beam size.

At that point an experiment was performed to compare ELO sharp to that determined by the two diagnostic devices. The basic experiment was to set up the PBD, EMFC and ELO target all at the same work height (and with constant beam parameters) and to see what values of sharp focus were obtained for the three different sharp focus determinations. A summary of the results is presented as a bar graph in Figure 26.

Figure 25: Images from ELO focus determination showing where optimal visual focus of the beam occurs as well as the degree of image degradation for a defocus beam.

Figure 26: ELO, PBD and EMFC sharp focus values for the same work height and beam parameters.

The results of the sharp focus experiment (shown in Figure 26) are summarized as: PBD = 1943; EMFC = 1947; ELO-auto = 1946. Notice that these results once again confirm the difference in minimum values between D86 and FWe-2 (4 mA of focus coil current in this case). These data suggest that the “useful” minimum beam size is probably at the minimum in FWe-2. That is reasonable since the minimum in FWe-2 occurs when the majority of the electrons (the core electrons being $\approx 85\%$ of the total electrons) pass through their minimum waist size. Presumably, maximum weld penetration would occur at the minimum beam size given by the FWe-2 data. This latter point is presently a matter of conjecture and would have to be confirmed by welding experiments.

Ease-of-use Issues: PBD versus EMFC

While performing these tests we did learn a few things about the relative ease-of-use of these diagnostic devices that are worth mentioning. The PBD is fully integrated into the operating system of the Pro-Beam welder and is obviously the correct choice for beam measurements on that machine. The EMFC would have to be used on the older “conventional” EB machines because the raster beam deflection pattern is not available on those machines. Process transfer between the older “conventional” EB machines and the Pro-Beam may eventually become necessary and, in that case, at least some data from the EMFC would be needed.

As was stated above, the basic ingredients for operating the PBD were built into the Pro-Beam machine from its inception and are used for auto-focus of the beam. The PBD measurements simply replace the usual backscattered electrons detector with the PBD. A typical focus run consisting of 20 measurements at 5mA increments of focus (typically 10 values on either side of sharp) represents a total of about 5 seconds of beam time and takes about 2 minutes for processing of the data and its output as a data sheet. All of this is done automatically by the machine and requires no operator intervention and the potential for operator error in making the measurements is eliminated. The rather short beam-on time limits heat input to the PBD and the potential of damage to the aperture. Further, since all of the necessary parameter changes are CNC controlled, with a bit of CNC programming acumen it would be possible to arrange for the PBD program to automatically collect data over a range of beam currents, high voltage settings and etc. The only obvious shortcoming of the PBD is that it does not presently compute beam diameter given as FWe-2. If we eventually decide that FWe-2 is a better description of the beam relative to welding behavior, it would clearly be simply for Pro-Beam to modify the software to output that number also.

The EMFC is significantly less easy to use. In fairness, it should be noted that the EMFC is basically a research tool, which by design, requires a fair amount of operator intervention to use. The operator must manually input certain values into the software such as circle size, high voltage, beam current and etc. Further, each data point collected requires the operator to manually adjust focus, turn the beam on, wait for the beam to stabilize, and then trigger the software to collect the data. An equivalent data run collecting 20 data points would probably consume 30 minutes of elapsed time with perhaps a total of 2 minutes of beam-on time. The somewhat lengthy beam time does deposit considerable heat into the EMF and does limit its practical use to modest beam power levels (1000 W being comfortable and perhaps 2000 W as

the maximum practical power level). Obviously, the potential for operator error in all of this is significant. Another potential problem with the EMFC is that its operation is based on typical LabView controls. It is useful for its user to be familiar with LabView software. Successful use of the EMFC is clearly beyond the usual aptitude of a typical production weldor. We do not mean to say that a weldor could not be taught to use the EMFC, but, that would necessitate at least some hours of training time. Similar to what was said above, the EMFC does not presently compute D86. If we eventually decide that D86 is a better description of the beam, the software would have to be modified to output that number. In the present circumstances relative to EMFC availability, it may not be possible to obtain an updated version of the software that computes D86. That calculation can be performed by manual analysis of the data (as was done for this paper), but that would clearly be beyond our expectations of usual production personnel and would probably require additional support from others.

CONCLUSIONS

Extensive tests of two electron beam diagnostic tools were performed. The two beam profiling devices are: the Pro-Beam device (PBD, which Pro-Beam can supply as an adjunct to their welder) and the Enhanced Modified Faraday Cup (EMFC, a device that has been used for a number of years throughout the DOE complex). The results show that the two devices and the accompanying analysis software are working properly and are returning equivalent results. It should be noted that we do not know exactly how the PBD software works but it does seem to yield valid results.

The PBD software yields a beam diameter, D86, that is computed compliant with ISO 11146-1. The EMFC software assumes a Gaussian beam distribution and yields a beam diameter given as FWe-2. For an ideal beam the two diameters are equal. However, significant differences in the beam diagnostic diameter data were noted. These differences were traced to the fact that D86 and FWe-2 are not equal for a beam that is significantly non-Gaussian in shape. This Pro-Beam welding machine produces a beam that deviates significantly from a simple Gaussian shape such that D86 is always about 35% larger than the equivalent value of FWe-2. The difference in definition of diameter between D86 and FWe-2 also produces a small difference in the apparent location of beam sharp focus.

It is not presently known whether D86 or FWe-2 is a better description of the welding performance of the beam. Preliminary sharp focus data does suggest that FWe-2 may be a better description of beam performance for welding. However, additional welding data must be obtained before the relative usefulness of D86 and FWe-2 can be understood.