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Re-Analysis of DARHT Axis 2 S4 Magnet Sweep Measurements

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Introduction

The Dual-Axis Radiographic Hydrodynamic Test (DARHT) facility provides flash radiography capabilities using two electron Linear Induction Accelerators (LIA's). Understanding fundamental properties of the electron beams is essential to optimizing spot size and dose for radiography. This work describes distribution measurements of a single-kicked electron beam (16.5MeV, 1.7kA, 60ns) at a location downstream at imaging station C on DARHT Axis 2. The beam at station C is focused by the S4 solenoid located upstream. The beam distribution is measured by imaging optical transition radiation (OTR) from electrons striking a 51-µm thick titanium foil. This data and analysis were originally published by Ekdahl[1]. The results here are a re-analysis of the asymmetric halo emittance contribution as compared to the emittance resulting from the FWHM of the distribution. This is accomplished using xtr[2] fits to the data which include non-linear magnetic field effects in S4. Also examined are the calculated S4 spherical aberration contributions to the emittance using xtr.

Experiment Set-up

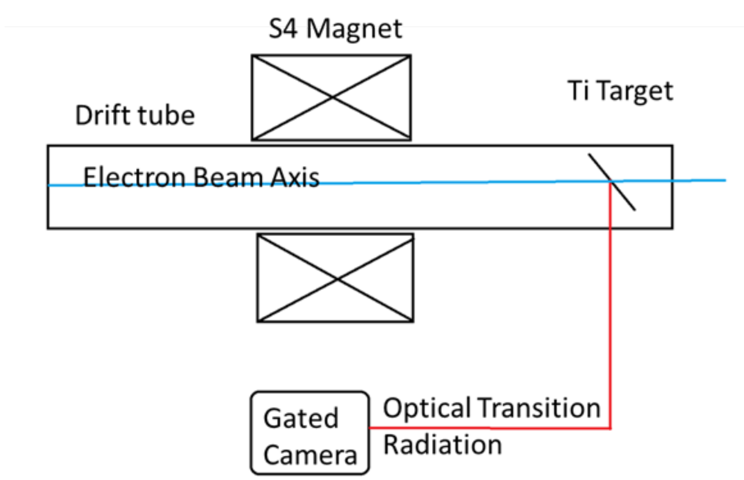

Figure1. Schematic of the experimental set-up for gated camera images of the beam distribution as a function of magnet current (TOP VIEW).

The experimental arrangement is shown in Figure 1. The S4 solenoid is used to focus the electron beam on a titanium target. The electron beam produces optical transition radiation (OTR) when it strikes the foil[3]. The spatial OTR is imaged on the photo cathode of a PIMAX 3 gated camera. The distance from the midpoint of S4 to the titanium OTR screen is 108.6cm. The titanium foil was 51um thick.

[1]*Ekdahl, C, "Emittance Growth in the DARHT-II Linear Induction Accelerator", IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 45, NO. 11, NOVEMBER 2017*

[2]*Allison, P. W., "xtr, A New Beam Dynamics Code for DARHT", DARHT Technical Note No. 50*

[3]Vermare, C and Moir, D, "Angular Distribution Measurement of an Intense Pulsed Electron Beam using the Optical Transition Radiation (OTR)", LA-UR-01-1171

In order to maximize OTR light, the foil was rotated along the vertical axis approximately 2° (1/gamma) from the 45° angle so that the camera was focused on one of the OTR lobe peaks. Current in the S4 magnet was varied between 10 and 140A. Near minimum focus (~100A), the titanium target was damaged. The beam was steered to obtain a clear spot for the subsequent pulse but the camera field of view was unchanged. This limited the available image background for some of the data with small distribution diameters. The camera images were 1002x1003 pixels. The magnification was obtained from a static image of the Ti foil and was 0.1337mm/pixel. The correction for the foil at an angle of 43 degrees was 0.932 in the horizontal direction. Background radiation put speckles on the camera image. The speckles were single pixels which had a large number of counts due to radiation directly striking an element of the CCD array. The effect of the speckles was reduced, without biasing the beam distribution, by using a de-speckling program[4].

[4]McCuistian, B T, private communication.

Analysis

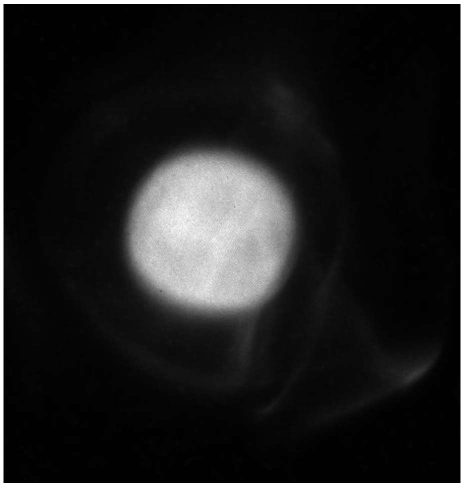

Figure 2. Raw Uncorrected Image of Axis 2 Shot 23901 with 50A on S4 magnet.

Figure 2 is a raw image taken by the PIMAX 3 gated camera. The image size is 1002x1003 pixels. The dynamic range is 16-bit (max count 65,536). The camera gate was 10ns and was centered on a 60ns single pulse timed away from the Axis 2 kicker rise and fall.

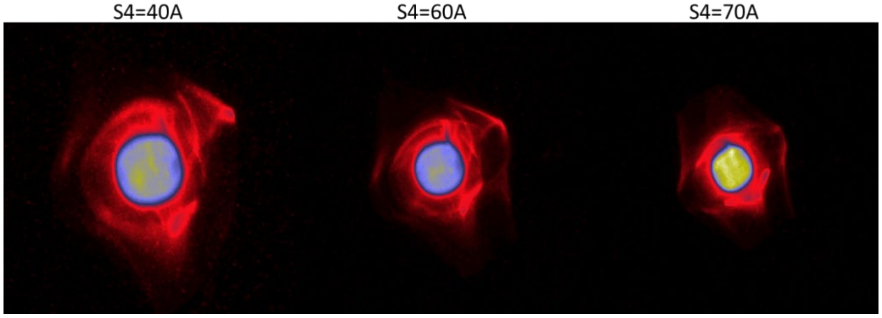

Figure 3. Image of Axis 2 Shots 23908, 23907, 23906 with 40A, 60A, 70A on S4 magnet. Images have been corrected for OTR angle, speckles and background.

The halo around the beam was thought to be off energy but in fact is at the same energy as the core. It focuses as the magnetic field is increased as shown in Figure 3. The original images were cropped before analysis. In this work, cuts were made to assure that the amount of data in the image were maximized and the beam halo was included. Some of the images with small spot sizes were cropped to 512x512. The larger spots were cropped to 768x768. Cropping minimized the contribution of the radiation background on the camera to the tails of the spot size distributions.

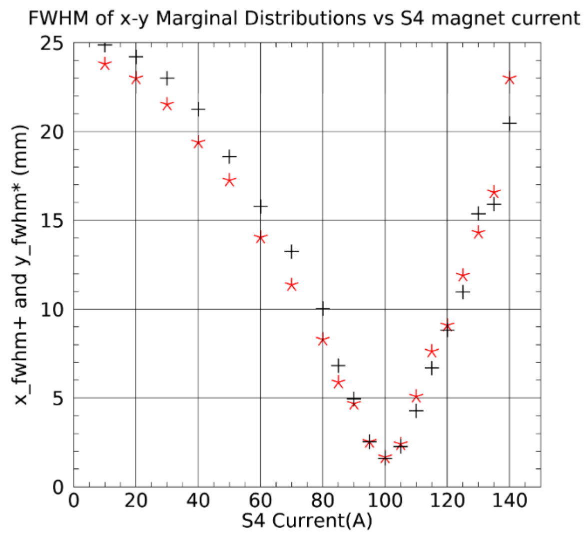

Figure 4. FWHM of the x (black) and y(red) marginal densities versus S4 magnet current

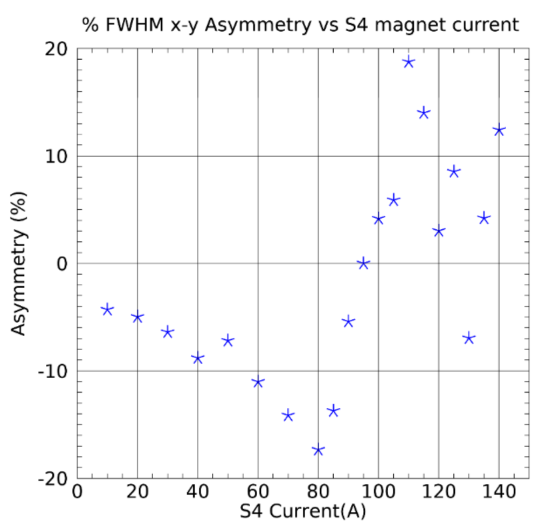

Figure 5. Asymmetry of x and y planes as a function of magnet current.

The initial analysis focused on x-y symmetry of the image data, I(x,y) (bivariate distribution). Shown in Figure 4 is a plot of the FWHM of the x and y marginal densities, D(x) and D(y) versus S4 magnet current where

$$D(x) = \int I(x,y)dy \text{ and } D(y) = \int I(x,y)dx$$

Figure 5 is a plot of the asymmetry of x and y planes as a function of magnet current. This plot suggests that the beam itself is elliptical even with the OTR foil angle correction. The ratio of x to y FWHM is changing with the phase advance produced by the solenoid focusing. A round beam would have a constant ratio of x to y. This data indicates an elliptical beam.

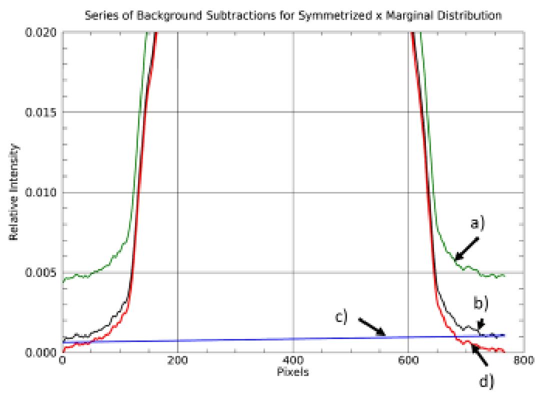

Figure 6. Background subtractions for a symmetrized marginal distribution with S4 magnet at 40A. a) Raw de-speckled image, b) distribution with the minimum of the raw distribution subtracted, c) linear fit to the end points of b) and d) the resulting marginal distribution used in the analysis.

The average marginal distribution of the OTR angle and speckle corrected data were obtained by rotating the image 15° in clockwise increments and obtaining each marginal distribution for 360°. These distributions were averaged together to obtain a single symmetrized distribution that was used to calculate the 2RMS and FWHM value of x (or y) for input into xtr. To remove the background, the following technique was followed for the analysis of each image. First, the symmetrized marginal distribution of the raw image, where S4 magnet was set to 40A, was calculated shown in Figure 6a). Next, the minimum value of this distribution was subtracted to produce Figure 6b). A linear fit to the endpoints of this distribution were are shown in Figure 6c). It is subtracted to produce the final distribution in Figure 6d).

Table 1. Summary of beam distribution analysis.

S4 Magnet Current(A)	2RMS from Distributions (cm)	2RMS from FWHM (cm)	Weight for XTR Fitting
10	2.09	2.03	1.00
20	2.02	1.98	1.00
30	1.91	1.86	1.00
40	1.78	1.70	1.00
50	1.62	1.50	1.00
60	1.37	1.26	1.00
70	1.04	1.06	1.00
80	0.77	0.77	1.00
85	0.57	0.55	1.00
90	0.44	0.40	1.00
95	0.29	0.23	1.00
100	0.29	0.15	1.00
105	0.35	0.20	1.00
110	0.54	0.40	1.00
115	0.73	0.64	1.00
120	0.93	0.76	1.00
125	1.11	0.99	1.00
130	1.33	1.29	1.00
135	1.51	1.42	1.00
140	1.80	1.85	0.01

Table 1 is a summary of the analysis for all S4 magnet current settings. Column 1 is the S4 magnet current. Column 2 is the calculated 2rms of the background subtracted average marginal distribution for 360^o. See Figure 4d). Column 3 is the 2rms of the same distribution taken from the full width half maximum (FWHM). In order to extract the 2rms, a Gaussian distribution must be invoked. This analysis excludes the effect of the beam halo. Column 4 is the weighting factor used in the xtr analysis and will be discussed later.

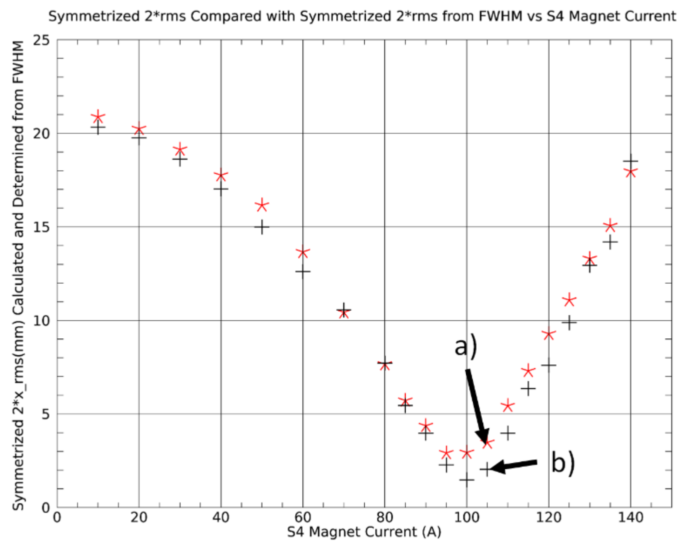

Figure 7. Plot of a) symmetrized 2RMS calculated from the marginal distribution compared to b) 2RMS extracted from FWHM for the same data as a function of magnet current. The data is from Table 1.

Results shown in Table 1 are plotted in Figure 7. The symmetrized 2RMS in Figure 7a includes the beam halo in the marginal distribution and clearly produces a larger diameter beam than the simple FWHM in Figure 7b. Using the FWHM to generate an RMS, implicitly assumes a Gaussian distribution which deceptively ignores the beam halo contribution.

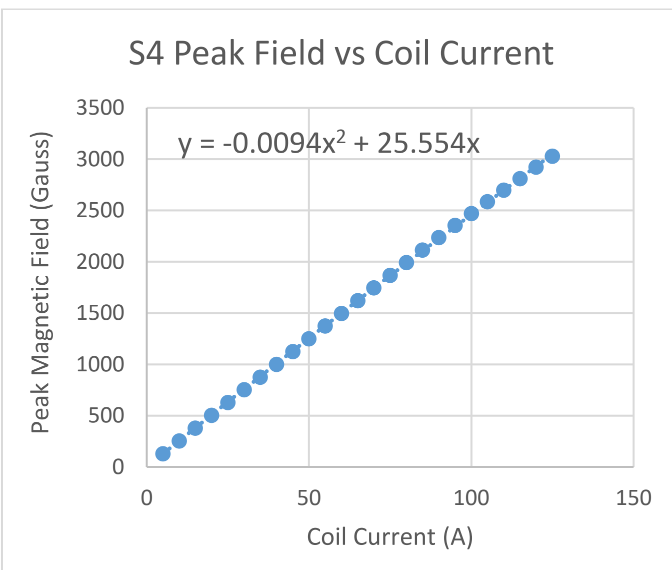

Figure 8. S4 magnet peak field as a function of coil current. The equation is the fit to the data showing the non-linear component due to iron saturation.

Results

The beam envelope code xtr[2] is used to analyze the magnet sweep data[4]. The 2RMS data, extracted from the marginal distributions as a function of the S4 magnetic field, can be fit to extract the 2RMS beam envelope radius (r0) and divergence (r0p) along with the 4RMS normalized emittance (en) at a point 50cm upstream of the center of the S4 magnet (Figure 1). The magnetic fields in xtr are linear with current. Since S4 is not linear with current, a field algorithm was added to xtr specifically for the S4 magnet. See Figure 8. The result of adding the non-linear field was a 25% improvement in the figures of merit for data fits.

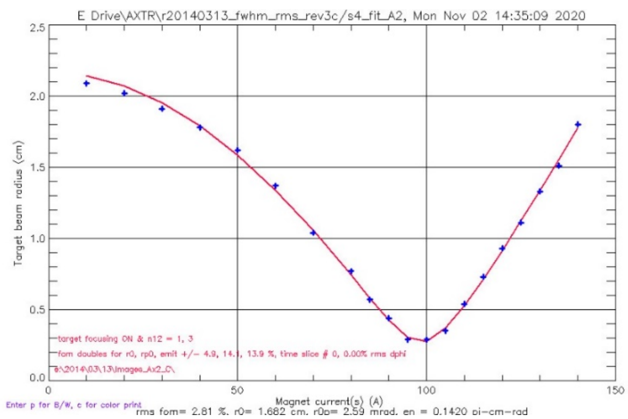

Figure 9. xtr fit to the symmetrized 2RMS beam radii which includes the beam halo.

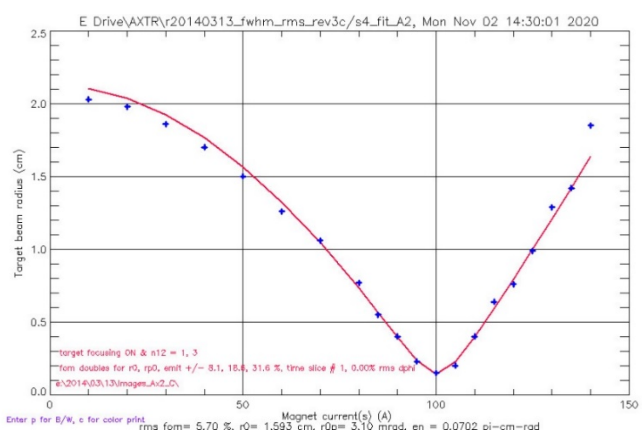

Figure 10. xtr fit to 2RMS data extracted from the FWHM of the symmetrized marginal distributions.

[4]*Paul, A. C., Chong, Y. P, Kallman, J. S. and Neil, V. K. "Probing the Electron Distribution Inside the ATA Beam Pulse", NIM A300 (1991) 137-150*

Figures 9 and 10 are plots of the fits to the 2RMS marginal distribution data. The weight of all of the data for the fit is 1.0 except for the 140A S4 current which is 0.1. The detector field of view is clearly smaller than the beam image for this data point.

Table 2. Summary of beam parameters extracted from xtr data fits extrapolated back to 50cm upstream of the S4 magnet.

	2RMS Envelope Radius, r0 (cm)	2RMS Envelope Divergence,r0p (mrad)	4RMS Normalized Emittance, en (cm-rad)	RMS Figure of merit (%)
2RMS data	1.68+/-0.08	2.59+/-0.36	0.142+/-0.020	2.81
FWHM 2RMS data	1.59+/-0.13	3.10+/-0.56	0.070+/-0.022	5.70

Table 2 is a summary of the fit results shown in Figures 9 and 10. The values of r0, r0p and en are determined at 50cm upstream of the S4 magnet. The values of r0 and r0p are the same within the error associated with the fit (change in value required to double the figure of merit). The resulting emittance, en, is quite different. Inclusion of the beam halo doubles the value of the calculated emittance. How these results effect the spot size is not clear because the spot size measurement is made after the electron beam is converted to x-rays. This technique has limited dynamic range of approximately 1000, which depends on the attenuation of the pinhole tungsten. As a consequence, the halo effect may not be observed.

Spherical aberration contribution of the S4 magnet to the 4RMS emittance was also calculated using xtr. The largest contribution occurred at 140A and was a 2% increase for the 2RMS data and a 3% for the FWHM 2RMS data. Both are much smaller than the error from the data fits. xtr uses the formulation from Scherzer[5] to calculate the change in emittance.

[5] *Scherzer, Zeitschrift fur Physik, Vol. 101, 1936, p.138*