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Unsupervised spatial-resolution enhancement of electron beam measurement using deconvolution

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ABSTRACT

This paper presents an unsupervised de-blurring technique that enhances the spatial resolution of electron beam (EB) diagnostic instruments. The inherent degradation in EB diagnosis waveforms is modeled using the convolution between the EB current distribution and the sensor characteristic function. Due to the use of various sensors, the diagnosis results are device dependent. Sensor inaccuracy has a detrimental effect on the deconvolution-based restoration of the ground truth signal. In this research this adverse effect is mitigated by an accurate sensor's Point Spread Function (PSF) derivation, which allows the successful restoration of waveforms. As approximate size of the sensor is known, a probability distribution is assigned to the expected interval of PSF features in the frequency domain, which increases the accuracy of the PSF analysis. By deploying this method, sensor inaccuracies are considered in the dynamic PSF formation, hence providing a promising consistency to the restoration. Restoration is performed with Wiener inverse filter and blind-deconvolution and results are compared with the ground truth pulses, obtained using a sensitive sensor (18um diameter). Experimental results confirm that the purposed method delivers a universal device independent measurement, facilitates instrument production, and EB characterization.

1. Introduction

High power electron guns have various applications including Electron Beam Melting (EBM), 3D printing, Electron Beam (EB) Surfi-Sculpt™ [1], welding, heat treatment and metal coating. Reproducibility of process with identical quality in different EB machines is of great importance. The quality of the EBM process is influenced by EB properties [2]. EB is influenced by other variables, which depend on the machine setup, and it changes from one machine to another [3]. As a result, beam measurement and optimization, within the quantified tolerances before the process, becomes very important. Quantification of EB characteristics, facilitates the replication of the EB accurately on different machines, therefore, providing reproducibility, predictability and reliability for EB process [4]. The main beam properties are: *Full Width at Half Maximum* (FWHM), peak power intensity, brightness, power intensity distribution, and angular distribution. For the EB characterization there exist various diagnostics equipment, also known as EB probe, such as: Modified Faraday Cup (MFC), Enhanced Modified Faraday Cup (EMFC), high power EMFC, Annular Sensor, slit probe, rotary wire probe, wire probe and pinhole probe. These devices are all working based on a similar principle that of a Faraday Cup (FC). A further study has been done about the EB probing equipment in Ref. [5]. Since the electron guns that are used for melting applications have high power, a fast sweep is necessary to avoid damaging and melting the probe [6].

Ideally, using any of the devices above for probing, quantifying and characterizing the electron beam should yield a similar result, although without appropriate corrections, results are probe dependent. Various slit widths (Δx), wire diameters (Ø), or pinhole diameters that are used in the EB probes, influence the EB measurements and make them probe specific. Wire/slit or pinhole, all impose breadth and filter the true EB power distribution. This smears and blurs the signal and conceals the sharp detailed features of the inspected EB power distribution and results in an inaccurate characterization.

To address this problem Hichken et al. [7] stated that, a narrow opening is better for inspection, however, the signal to noise ratio must be at an acceptable level for measurement. It was assumed that the slit width is small compared to the diameter of the beam, and therefore the error was neglected. Authors suggested that the

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slit width should be 10% of the full beam width (95% of the beam power, 2σ of Gaussian distribution). The experimental data was fitted with a Gaussian distribution, in which the 2σ of the fitted curve was measured as 400 μm (beam full width). However, for purpose of practicality, the experiment was performed with a 100 μm slit width, which is 25% of the full beam width. In fact, a Gaussian distribution with 2σ~375 μm, convolved with a 100 μm opening, results in a semi-Gaussian distribution of 400 μm, causing an error of 25 μm. For 3D printing applications EB is in order of 50–100 μm this requires an opening of 5–10 μm, which reduces the SNR and makes the measurement inaccurate.

Elmer et al. [8], arranged a table with slit width and beam FWHM, to estimate the error of FWHM measurement. The measurements are carried out in various machines for a range of accelerating voltages, using different slit widths and beam focus settings. By measuring the relative error of measurements and fitting the data with a second order polynomial, the error of the FWHM measurement was predicted. For instance 22.5% error, for $R = 0.943$. (R is the slit width divided by the beam FWHM). Although this approach does not restore the true signal, it modifies the FWHM calculation.

Koleva et al. [9] assumed that beam has an axi-symmetrical distribution, and cumulative beam current distribution is the result of the Volterra integral. The inverse transformation to achieve the EB current distribution, requires: a) An estimation of beam radius. b) An approximation of the axi-symmetrical beam or axi-symmetrical cumulative beam. Authors concluded that parameters of this problem are poorly defined and its solution can be unstable for small changes in the parameters. There are multiple problems with this approach. Section V shows that the EB is not completely symmetrical. Furthermore, the aim is to measure the beam, and find its radius. Guessing the right radius cannot be an accurate solution, and requires trial and error. Differentiation of the practical data, which is collected in the presence of noise, reduces the solution stability.

A computerized tomography (CT) method was used to compute the two dimensional distribution of the EB [10–12]. Whereas, without restoring each measurement, utilization of the CT does not correct the measurements, resulting in an inaccurate two dimensional distribution.

Since the total beam current measurement was not possible from the degraded signal, a different type of probe is used by Rempe et al. [13]. This device is a slit probe and a FC. The FC is added only for total beam measurement. A rotary wire probe was also used for inspection, which had a different wire diameter than that of the slit width. Beam was characterized without considering the effect of this difference. FC and wire probes are known for their inaccurate measurements, due to the significant amount of electron backscattering [11]. Furthermore, a FC could be avoided, by restoring the pulses collected by the slit.

Currently, making the slit width, wire diameter and pinhole size smaller in comparison to the EB dimensions, is recognized as the most common solution to reduce the inaccuracy of the measurement, for instance the pinhole diameter is reduced to 20 μm in Ref. [14]. Whereas, other solutions only reduce the FWHM measurement error and do not change or provide an accurate beam distribution. Theoretically, reduction of the slit/wire or pinhole size, reduces the measurement inaccuracy but, at the same time it effects the SNR and makes the signal detection and measurement impractical and inaccurate [7,11].

A deconvolution based restoration methodology is proposed in this paper that corrects the probe measurements. The deconvolution eliminates the unwanted effect of the probing device which is imposed on the collected waveform, and extracts the true power distribution of the electron beam. We estimated the length of the PSF for each measurement and adjusted the PSF function length dynamically and compensated the thermal expansion of the sensor. This deconvolution technique achieves significantly more accurate measurements than the explained methods. Successful execution of this technique includes: noise extraction, *Point Spread Function* (PSF) estimation and probe size inaccuracy compensation, unsupervised signal restoration, and derivation of an electron absorption coefficient for wire probes, which are explained as follows.

This paper is arranged as follows. In section 2 the degradation is modeled with a linear motion blur. Section 3 presents the proposed beam restoration technique. Section 4, presents the practical test results and their analysis which confirms the accuracy and functionality of the model, restoration techniques, and the practical electron absorption coefficients and Section 5 includes the conclusion of the research.

2. Proposed EB probing model based on convolution

One common problem of EB probes is that they broaden and smoothen the measurements. Using fine slit/wire or pinhole, requires precise manufacturing which increases the cost, complexity and production time of the probes. Furthermore, such instruments require cautious handling, which prevents the probe from being used for full power measurement. As beam parameters change with changing the EB power, it is important to assess the beam at the desired process power. A narrow opening obstructs a significant portion of the deflected EB from entering the FC. Therefore, to measure the deflected beam, tapered or beveled blocks of tungsten are used to form the slit [15]. Reduction of the slit width, requires a higher taper angle and a thinner thickness of the slit material, which makes it vulnerable to heat [16]. Slit width and wire diameter are likely to change due to thermal expansion, and corrosion [11]. This change needs to be taken into account during measurement. Wire type probes suffer from electron backscattering which further increases the complexity of using these probes as the total beam current measurement is inaccurate.

Despite the difficulties outlined above, by studying the probing process in Fig. 1, and interpreting the signal collected from the probe we can clarify the process and model it accurately. At a specific distance from the electron source, EB is considered by a two dimensional power distribution function $p(x,y)$ on the surface of the probe ($z = 0$ plane). Electron absorption of the probing device is denoted as $q(x,y)$. For wire type probes, $q(x,y)$ depends on the wire

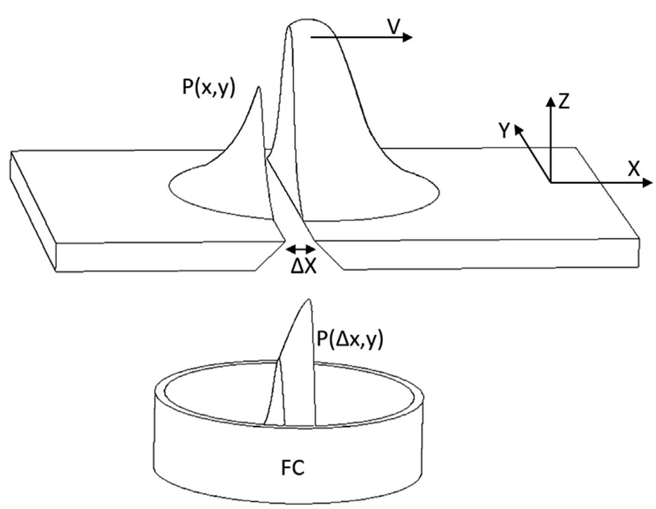

Fig. 1. EB sweeps over a slit (opening), with relatively a narrow width and long length. Part of the beam is passed through and collected by the FC.