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Magnetic-Field Diffusion Effects in Beam Position Monitors III: Application to DARHT-II Beam Data

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***Abstract*—Beam position monitors (BPMs) provide time-resolved measurements of the current and centroid position of high-current electron beams in linear induction accelerators (LIAs). One of the types of detectors used in BPMs is the B-dot loop, which generates a signal from the EMF due to the time varying magnetic flux through the loop. If some of the boundaries of the loop are composed of thick metal walls with finite conductivity, the resulting signal must be corrected for the magnetic field diffusion into the metal. The theoretically predicted flux due to diffusion is in remarkable agreement with experimental measurements. Although accurate BPM measurements of beam current require correction of magnetic field diffusion, accurate measurement of beam position requires no correction. In this note, we present experimental validation of current and position results from a prototype detector employing finite conductivity sensing areas, based on experiments on the DARHT-II LIA.**

***Index Terms*—Linear induction accelerators, electron-beam diagnostics, beam centroid position measurements, beam position monitors, magnetic diffusion**

I. INTRODUCTION

FLASH radiography is often used as a diagnostic of explosively-driven experiments. For the largest of these experiments, an intense relativistic electron beam (IREB) is focused onto a target of high-Z metal to create the source spot for point-projection radiography [1, 2]. Linear induction accelerators (LIA) are often used to create the IREB for this diagnostic technique. In the United States, three LIAs are presently used for this purpose [1, 2], and a fourth, called Scorpius, is under development [3, 4].

One of the most important IREB diagnostics for tuning these LIAs to produce radiographic quality beams are the beam position monitors (BPMs) that provide time-resolved measurements of the beam current and the position of the beam centroid. Both of these measurements are critical for tuning and reliable operation of the LIAs.

For our high-current LIAs, BPMs based on detection of the beam magnetic field have proven to be very effective and reliable [5, 6]. The magnetic field detectors for the Scorpius BPMs have a vacuum magnetic-flux detection area bounded on three sides by the metal BPM body. Therefore, diffusion of the magnetic field into the bounding metal contributes to the EMF generated by the time varying field. This effectively increases the detection area in time, resulting in a signal slightly greater than what would be expected based on the geometrical area of the loop. This is most noticeable if the metal is highly resistive, such as stainless steel used for the Scorpius prototype BPM, and field diffusion was evident in initial tests [7]. Therefore, accurate measurement of magnetic flux at the detector location requires correction for diffusion. However, because calculation of the beam centroid position uses the difference between detector signals divided by their sum, beam position measurements do not require correction.

In what follows, we summarize recent works on the theory underlying this important result in Section II, with experimental verification in Section III, followed by a short discussion, and conclusions.

II. THEORY

Four recent papers [8, 9, 10, 11] on this subject have presented in detail a description of the field diffusion process and its effect on BPM data taken using the prototype detector, which is also described in those discussions. In quick summary, the finite resistivity of the walls forming three sides of the rectangular sensing area allow for a diffusion of the field into the metal with a time constant in the ten to twenty microsecond range. For the one hundred nanosecond long pulses of interest to Scorpius, the maximum value of the diffused flux can be as much as twenty per cent of the total signal, as was observed in initial laboratory testing of the prototype [7, 9].

The evolution of the correction of the BPM flux measurements for this time dependent increase has been reported in detail [8, 9, 10]. The first [8] of those papers demonstrated that a first order theory provided a good correction for a known source input. The second [9] paper extended a multi-step approximation correction process to single pulse data without a known source, and the third [10] brought the correction to theoretical maturity using a Laplace Integral deconvolution formulation. The final step in the theoretical analysis was to show that it was possible to measure beam position without having to correct sensor data for diffusion [11]. At all stages of this development, the theoretical calculations were originally subject to verification using data from calibration measurements taken on a laboratory test fixture [9]. An early sample of LIA data to be presented more completely in this paper was included in [10] and [11] as verification of the validity of the theoretical discussion

III. EXPERIMENTAL VALIDATION

The success of early diffusion correction trials with approximations to the full theory provided strong encouragement for a trial of the prototype sensor on a full IREB. The authors extend their deepest gratitude to Howard Bender, J-6 Group Leader, and all the people in the DARHT operations team for their support in working the fielding of the Scorpius Type 1 prototype into the DARHT-II schedule in September, 2021.

The operational plan for the experiment is documented in a Scorpius Tec Note [12]. The Scorpius BPM prototype was installed on the DARHT-II beam line ahead of a standard DARHT-II beam position monitor, BPM29, in the post-kicker transport region, just before the final focus magnet. See Table 1. Comparison of results from the prototype, labeled as BPM77 for data archival purposes, with the proven detector BPM29 would serve to evaluate both the basic performance of the prototype, and the still evolving diffusion correction process. With that dual purpose in mind, the experimental plan optimistically called for data taking in a variety of hardware configurations, and using a variety of beam formats with differing pulse separations and widths. Because the Scorpius BPM test was an add-on to a previously designed target interaction experiment, it was recognized that it was possible that not all of the options could be completed. Hardware alternatives included with and without in-line resistors, with and without hardware integrators, and a selection of digitizer sampling rates. Key parameters for the experiment are listed in Table 1.

Table 1
Parameters for Scorpius BPM Testing on DARHT-II

Beam Energy	16.1 MeV
Beam Current	1.5 kilo-amps nominal; Pulse dependent
BPM77 Position	11.2 cm upstream of DARHT BPM29
BPM29 Position	6664 cm from Cathode
Beam Pulse Format	Variable; typically 4 pulses, 30 to 100 ns wide, separated by 200 to 500 ns

The prototype BPM77 was installed on the beam line 11.23 cm up-stream of BPM29. Outputs were carried from the weather enclosure to the patch panel in the recording hall using existing cabling for BPM28. A stand -alone DAAAC station was established using Keysight M9703B digitizers to record the BPM77 outputs. No common timing runs were made, but using known data for the BPM28 house cables and unique jumpers, timing could be established within 5ns relative to BPM29. The relative position of the two BPM spools was difficult to measure precisely in a crowded beam line environment. The nominal center of BPM77 relative to BPM29 was measured to be offset - .9mm in X and +.7mm in Y, with an error estimate of +/- .5mm. All beam position displays in this paper have been plotted relative to BPM77 center.

The data from BPM29 was processed using the IDL production code D2_Bdot that has been thoroughly tested and used for DARHT-II analysis for two decades. The data from the prototype BPM77 was processed using ASD_Bdot, a carefully modified version of D2_Bdot, that had been checked against individual record processing using the DAAAC software from Voss, Inc. As a second check on the ASD_Bdot modification of the D2_Bdot software, the diffusion correction option could be turned off and the code then duplicated the D2_Bdot results for BPM29. Calibrations for BPM77 were calculated using a similarly modified and verified version of the code used to determine calibrations for all of the DARHT-II BPM's. Examples of that calibration processing can be found in references [9] and [11]. While [11] established the fact that diffusion correction is not required for making valid position measurements, all of the data presented here used a single code run, with full diffusion correction, to compute both beam current and beam position.

Data comparisons which follow are broken into results from the three major hardware configurations: 1) No in-line resistors at the BPM and software integration; 2) In-line resistors at the BPM and software integration; 3) In-line resistors at the BPM and hardware integrators at the digitizer input. The configurations with the in-line termination of the sensor loops are preferred for recording data for times longer than the cable transit time from BPM to digitizer, and are considered the primary data from this experiment. The no-resistor configuration was included to provide further information on diffusion behavior differences observed in laboratory calibration with and without the in-line resistor.

Unfortunately, a fundamental property of the digitizers that was confirmed between the two experimental sessions on DARHT-II precluded straightforward processing of software integrated data later in time than the first kicked pulse. A discussion of this difficulty will be the subject of a separate report.

A. Single Pulse Data without In-Line Resistors, Software Integration

Based on calibration laboratory testing of the prototype BPM, this configuration was anticipated to provide the greatest diffusion effect, and therefore be the most serious test of the diffusion correction theory. As previously noted, this hardware configuration is not planned for Scorpius operation. However, it is included here as additional confirmation of the diffusion correction process, since independent determinations were made of the diffusion constants for the no-resistor and with-resistor hardware configurations. Figure 1 displays the beam current calculated from the Scorpius Type 1 data for shot 38347. It compares the same pulse with and without diffusion correction and illustrates the absolute need for diffusion correction for current measurements.

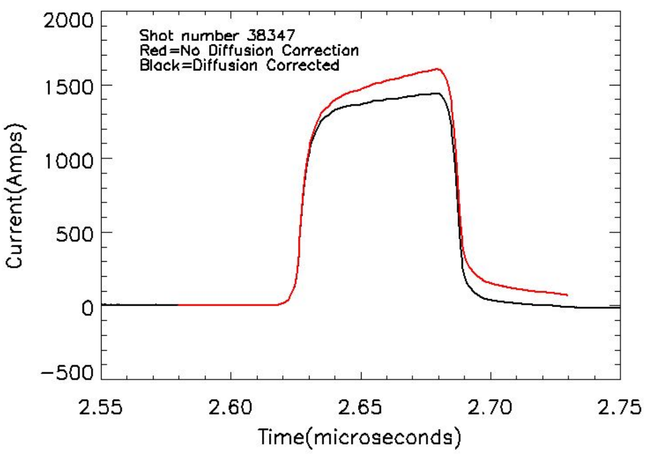

Fig. 1: DARHT-II Bean Current from Scorpius Detector data with and without diffusion correction. First pulse in four pulse sequence. No in-line resistors on BPM output.

Figure 2 compares the corrected beam current from BPM77 with that measured by BPM29.

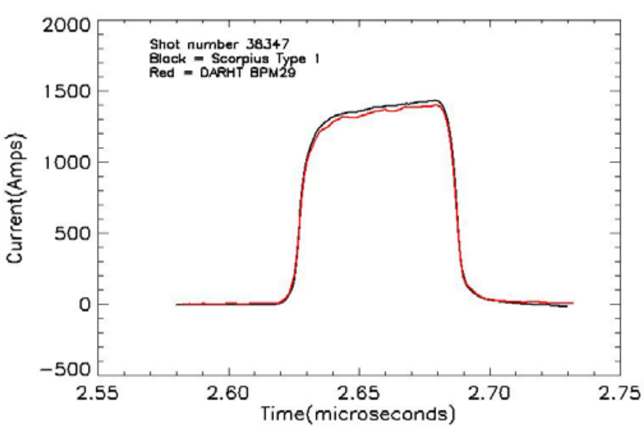

Fig. 2: DARHT-II Beam Current Pulse as Measured by Scorpius Prototype (Black Curve) and BPM29(Red Curve.) First pulse in four pulse sequence. No in-line resistors on BPM output.

Figures 3and 4 compare the beam position measurements from the two BPM's.

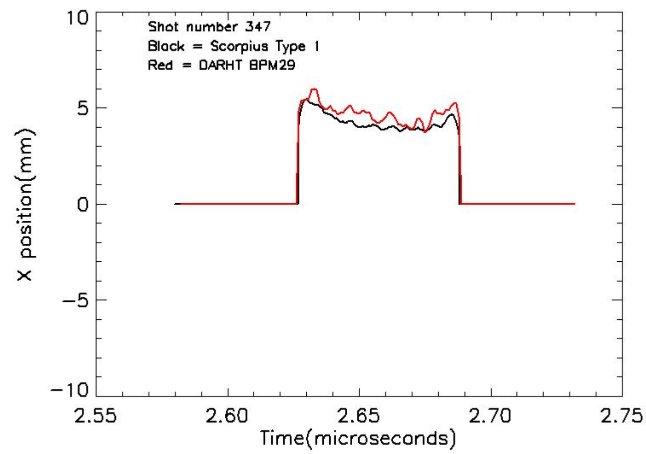

Fig.3: DARHT-II Beam Pulse X Position as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve). Values restricted to times with current greater than 500Amps.

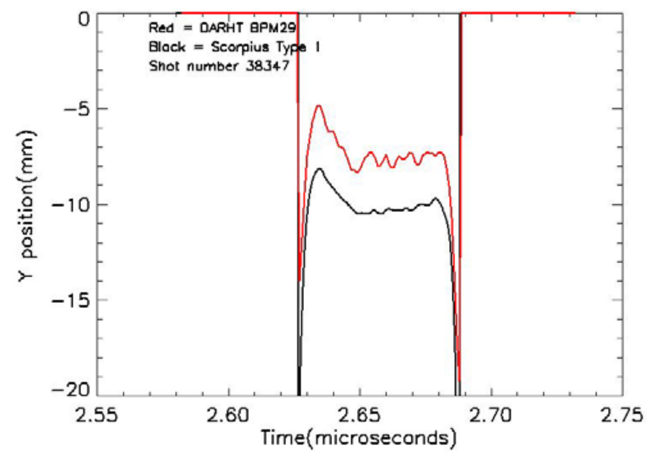

Fig.4: DARHT-II Beam Pulse Y Position as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve). Values restricted to times with current greater than 500Amps.

While only one shot is presented here, measurements were taken with a range of inter-pulse spacing and kicker timings that varied the current pulse shape and position. The agreement between the two BPMs for this shot is typical of what was observed in the other configurations , and indicates a possible 2% discrepancy in the current calibration for the Scorpius BPM, slightly outside the expected uncertainty in the calibration and preliminary diffusion correction process used to provide these numbers. Further refinement of that processing is anticipated once final Scorpius prototypes are delivered.

B. Single Pulse Data with In-Line Resistors and Software Integration

Because the pulse train configuration was determined by the primary experiment, to which the Scorpius BPM tests were a secondary priority, the beam parameters for tests with in-line resistors were not an exact match to the without-resistors configuration. Therefore, pulse-to-pulse direct comparisons cannot be made, since the pulse widths and spacing used for the first day of testing could not be replicated for the data taken with in-line resistors and software integration. However, it can be seen in Figure 5, the first pulse in the train for shot 38376, that the magnitude of the diffusion is less in this circumstance than what is visible in Figure 1 for the no-resistor case.

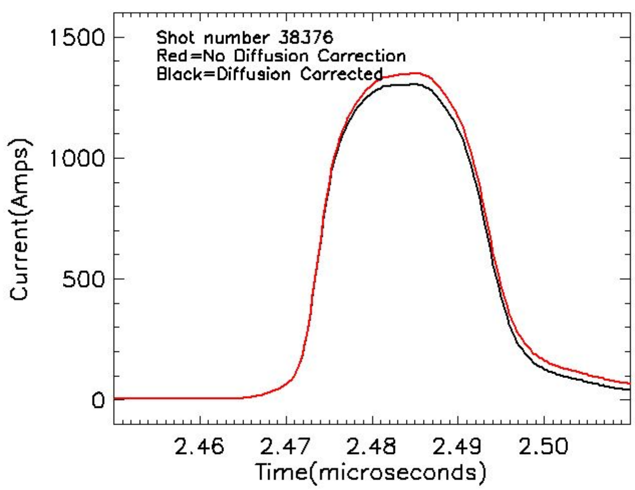

Fig. 5: DARHT-II Bean Current from Scorpius Detector data with and without diffusion correction. First pulse in four pulse sequence. In-line resistors at BPM output. Narrower Pulse width and earlier timing compared to Fig. 1 were dictated by primary DARHT experiment,

Figure 6 compares the beam current results from the Scorpius BPM with the DARHT-II BPM for shot 38376.

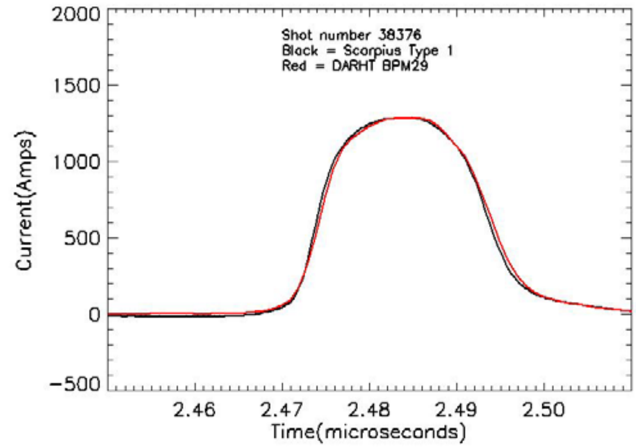

Fig. 6: DARHT-II Beam Current Pulse as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve.) First pulse in four pulse sequence. In-line resistors at BPM output.

Figures 7 and 8 compare the beam position as measured by the two BPMs for the with-in-line-resistor shot 38376.

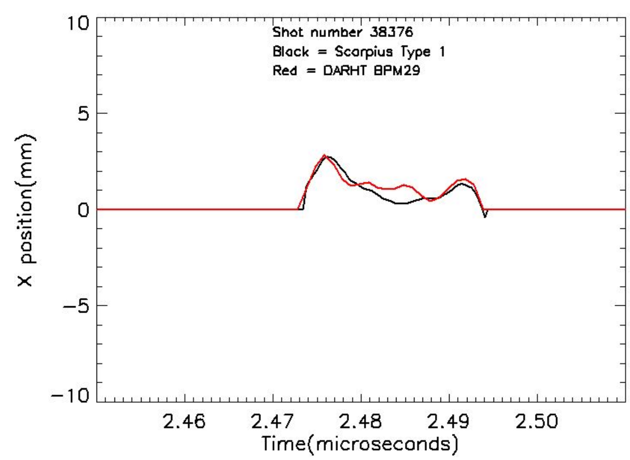

Fig. 7: DARHT-II Beam Pulse X Position as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve). Values restricted to times with current greater than 500Amps.

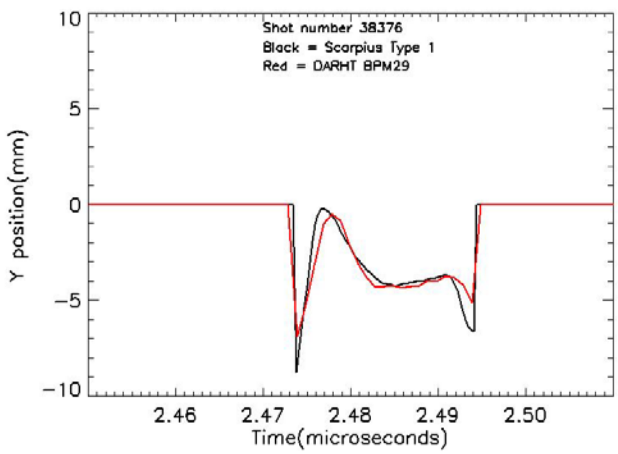

Fig. 8: DARHT-II Beam Pulse Y Position as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve). Values restricted to times with current greater than 500Amps.

Under some beam conditions, the beam position is not expected to be the same at the locations of BPM77 and BPM29. If the beam is incident at an angle, there would be a constant offset of position between the two BPMs. The 2 mm offset seen in Fig 4 is suggestive of such an effect. Moreover, beam corkscrew motion would cause a time-varying difference between the two BPMs. Nevertheless, the comparison is a useful check of the accuracy of Scorpius BPM beam position measurements in the operational environment.

C. Multi-Pulse Data with Hardware Integrators.

The digitizer difficulty which has delayed multi-pulse processing for the software integrated data was not a problem for the tests using hardware integrators. Fig. 9 compares the beam current from the Scorpius detector with that from BPM29 for the full four pulse train recorded on shot 38357.

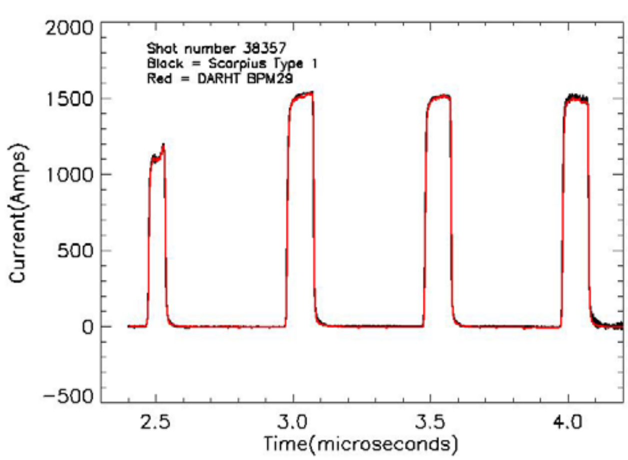

Fig. 9: DARHT-II Beam Current Pulses as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve.) Full four pulse sequence. In-line resistors at BPM output.

Fig. 10 and Fig. 11 compare the beam position for shot 38357as determined from the two BPMs.

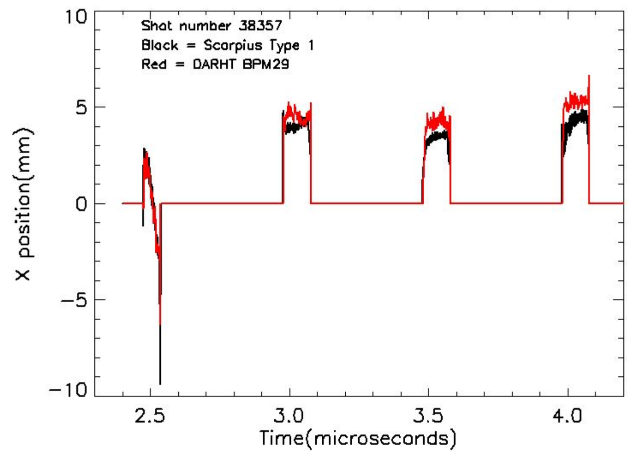

Fig. 10. DARHT-II Beam Pulses X Position as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve). Values restricted to times with current greater than 500Amps.

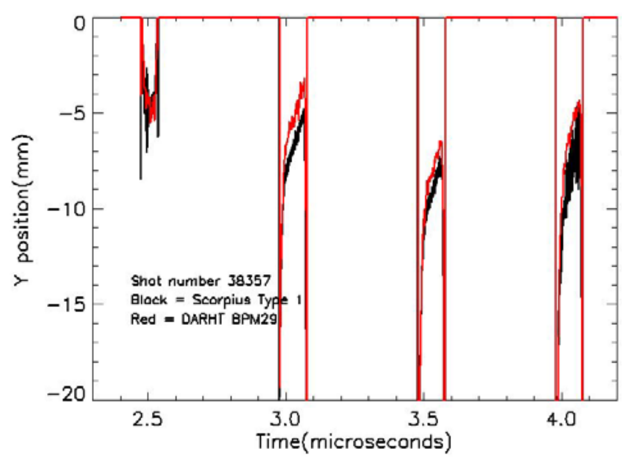

Fig. 11: DARHT-II Beam Pulses Y Position as Measured by Scorpius Prototype (Black Curve) and BPM29 (Red Curve). Values restricted to times with current greater than 500Amps.

The beam current comparison is very encouraging, although it must be noted that the calibration uncertainty noted earlier is operative for this data also. The beam position data suggest possible corkscrew movement of the beam during the last three pulses, though the 1mm displacement is barely outside the relative location accuracy of the BPM spools.

IV. DISCUSSION

The data presented here is a small sample of results from two days of recording that spanned a multitude of pulse train configurations in spacing and width. For all of the pulse shape variations attendant to that span, the correlation between the Scorpius prototype, BPM77, and DARHT_II BPM29 followed the behavior as displayed in the foregoing examples. The beam current time histories, after diffusion correction, as determined with the various hardware configurations tracked the reference BPM29 data to within the expected 1-2% uncertainty. As discussed in [11], the position calculations were independent of whether or not the signals were corrected for diffusion in the sensor.

The focus of this report has been the verification of the beam current and position accuracy of the Scorpius prototype. It must be noted that these data constitute the very first measurements of an LIA IREB with a diagnostic designed and built for Scorpius. Some additional observations can be made based on the experience with the DARHT beam. The new detector was quite capable of registering the very fast rise (< 2 ns) signals created by the combination of the rapid current switching and vertical motion of the leading and trailing edge of the pulse. The Scorpius detector was significantly more sensitive to the high frequency signals produced in the downstream environment. It provided a clear record of signals in excess of 1Ghz that were invisible in the BPM29 data, even with hardware integrators in place for the Scorpius BPM data. This result suggests that large bit depth may not be required for BBU studies, opening the way for lower cost recording.

V. CONCLUSION

The comparison of beam current and position data from the new prototype BPM with results from a known detector in a real-world accelerator environment has demonstrated that the sensor is capable of meeting its design goals for use in the Scorpius accelerator and down-stream transport applications. A critical part of that success involves the application of diffusion correction methods [8, 9, 10, 11] based on fundamental physical principles.

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