We would like to express our sincere gratitude to Reviewer for their detailed examination of our manuscript and for their positive, constructive recommendations. Addressing the reviewer's thoughtful remarks has allowed us to fix key mistakes from our first draft and substantially refine the overall narrative. We have carefully responded to each point below, with our replies in blue and Reviewer's questions in Bold.

The manuscript presents a useful technical study on improving the temporal resolution and sensitivity of beta attenuation monitors (BAMs) for real-time particulate matter monitoring. The authors investigate two main strategies: reducing the particle deposition area to increase mass loading per unit area, and using multi-sensor ensemble averaging to reduce stochastic beta-intensity variability. The results show that reducing the deposition area improves signal sensitivity, while ensemble averaging substantially improves measurement stability. The integrated configuration, using a 0.4 cm^2 deposition area, six-sample ensemble averaging, and a 30-minute smoothing window, reduced response time from 60 to 22 minutes while maintaining acceptable measurement precision and detection limits. Overall, the study is technically relevant and contributes to the development of higher-resolution PM monitoring systems.

1. **The manuscript should more clearly explain the practical novelty of the proposed approach compared with existing commercial BAM designs and previous optimization studies. The authors should clarify whether the main contribution is the reduced deposition area, the multi-unit ensemble concept, or the combined optimization framework.**

   The primary contribution and core novelty of this study lie in the unified, synergistic hardware-statistical optimization framework, rather than any of the individual components in isolation.

   1. Signal Amplification via Area Reductio:
      Reducing the particle deposition area to 0.4 cm^2 increases the areal mass loading by a factor of 5 under identical flow condition. This significantly amplifies the log-attenuated beta signal per unit time ($\ln(I_0/I)$), enhancing measurement sensitivity for short intervals.
   2. Variance Reduction via Multi-Sensor Ensemble (Statistical Optimization): A known limitation of reduction sampling area is that shielding decreases incident count rates (I_0), which elevates statistical counting noise (CV). We employ a multi-unit ensemble array to reduce the variance.

      Neither modification alone achieves high temporal resolution. Only their combined application enables the system to shorten responses times from 60 minutes to 22 minutes while maintaining an LOD (8.28 μg m^{-3})

To make this novel framework clear to readers, we have revised the Abstract (**Lines 20-23**), Results and Discussion (**Lines 350-354**) and Conclusion (**Lines 380-384**) to explicitly highlight the complementary interplay between deposition area reduction and multi-sensor ensemble averaging, contrasting our framework against standard single-detector commercial BAM designs.

2. **The experimental design is generally clear, but the simulation of a multi-sensor array using repeated measurements from a single BAM requires further justification. The authors should discuss how well repeated measurements represent truly simultaneous operation of multiple independent BAM units, especially under variable ambient conditions.**

   Simulating a multi-sensor array using repeated measurements from a single BAM was to isolate the stochastic fluctuations inherent in radioactive decay from inter-instrument systematic errors. This allowed us to rigorously quantify how ensemble averaging specifically reduces the coefficient of variation (CV) of the beta intensity.

   We agree that in a field deployment, "system bias"—such as differences in detector sensitivity or flow control among multiple units—could introduce additional variance. However, we contend that these systematic biases can be significantly mitigated through rigorous pre-test calibration of each individual BAM unit.

   While this simulation might provide an "idealized" LOD by focusing on source stability, it establishes the theoretical performance ceiling for the multi-sensor ensemble strategy. In real-world ambient conditions, the system bias would indeed be present, but as the reviewer suggests, it is a manageable engineering factor rather than a fundamental limitation of the beta attenuation principle itself.

   We have revised our running text in Materials and Methods (Lines 141 - 151) clarifying this methodological justification and detailing how field-deployed arrays would address inter-instrument bias.

3. **The results show a trade-off between reduced particle deposition area, increased signal sensitivity, higher pressure drop, and increased relative statistical noise. This trade-off should be discussed more explicitly in terms of practical field deployment, filter lifetime, maintenance frequency, and instrument reliability.**

   We agree that reducing the deposition area increases the concentrated mass loading rate by a factor of 5 under identical volumetric flow rates. This introduces specific operational considerations that can be elegantly managed through automated instrument control:

1. Filter Lifetime: Higher particle loading accelerates pressure drop accumulation across the filter spot, which could lead to filter tape deformation or flow rate decay if left unaddressed. In practical field deployments, this is managed by shortening the automated filter tape advance cycle. Instead of traditional time-based advances (e.g., every 1 hour), the system can implement a dynamic pressure drop triggered advance mechanism that moves to a clean filter spot before flow attenuation or tape deformation occurs.

2. Maintenance Frequency: Because dynamic tape advances consume the filter tape roll at a faster rate, the maintenance interval for replacing the physical filter tape reel will decrease. However, because the tape advance is fully automated, daily field operations remain unattended.

3. Instrument Reliability: As particle loading on the filter increases, measurement variance grows alongside the loading mass. To maintain high measurement reliability, continuously monitoring the variance or detection limit over time provides an automated quality control check, signaling a tape advance if signal noise or pressure drop exceeds predefined operational limits due to heavy filter loading.

   We have added a paragraph in Methods and Discussion (Lines 184–192) detailing these practical field deployment considerations, dynamic tape advance mechanisms, and instrument maintenance trade-offs.

4. **Several figures are important for supporting the conclusions, particularly Figures 4, 8, 10, and 11. The authors should improve figure readability by increasing font sizes, clarifying legends, and ensuring that all units and symbols are consistently formatted.**

   We have thoroughly revised and re-rendered Figures 4, 8, 10, and 11 (as well as all other figures in the manuscript) to improve visual clarity and formatting consistency:

   Font Size and Readability: The font size for all axis labels, tick marks, titles, and legend text in all figures has been increased (from 12 pt to 14 pt bold/semi-bold) to ensure full legibility when embedded at final publication width.

   Symbolic and Unit Consistency: We have systematically updated all figure labels, unit expressions, and variable symbols to match the exact mathematical formatting in the main text.

5. **The manuscript would benefit from a clearer explanation of the detection-limit calculation. Since the authors compare empirical LOD values with theoretical estimates, the assumptions behind the LOD definition, blank measurements, smoothing window, and ensemble averaging should be stated more explicitly.**

   We have expanded the "Materials and Methods" section (Lines 136-139, 158-162) to explicitly state the assumptions, equations, and protocols used in our LOD framework::

   LOD Definition: We define the LOD as two times the standard deviation (2σ) of the mass concentration measured under particle-free (blank) conditions. This 2σ benchmark provides a conservative 95% confidence interval for the instrumental noise floor.

   Blank Measurements: Empirical blank concentrations were acquired by sampling HEPA-filtered dilution air within the controlled aerosol chamber. To ensure statistical significance, we recorded the 1-Hz beta intensity for one hour per test run, using unused glass fiber filters to establish the baseline I_0 stability.

   Smoothing Algorithm: We utilized a simple Moving Average (MA) method to mitigate stochastic variance. In this approach, a uniform weight is assigned to each 1-second data point within the specified window (e.g., 5 to 75 minutes), and the values are summed and averaged to produce the smoothed output.

Ensemble Averaging Assumptions: For the multi-sensor simulations, we assumed that the stochastic fluctuations of the beta source across independent runs are uncorrelated and calibrated. By aggregating N independent blank datasets, the standard deviation of the ensemble average is reduced, which we then used to calculate the improved LOD for array-type configurations.

6. **The language is generally understandable, but some sentences are long or repetitive. Careful language editing is recommended to improve grammar, flow, and conciseness, especially in the Results and Discussion section.**

We thank the reviewer for this constructive suggestion regarding language and readability. We have performed a comprehensive language revision throughout the manuscript, with that are over 30–40 words long and contain complex nested clauses.

7. **The authors are strongly recommended to cite recent work on high-spatiotemporal-resolution particle monitoring in complex urban environments. In particular, Yeganeh, B., Shakerdonyavi, A., Zafarmomen, N., and Taheri, A.: *Comprehensive spatiotemporal analysis of long-term mobile monitoring for traffic-related particles in a complex urban environment*, Atmospheric Pollution Research, 102870, 2025, is highly relevant. That study used a year-long mobile monitoring campaign to measure $PM_{2.5}$ and black carbon at high spatial and temporal resolution in Tehran, demonstrating the importance of dense, high-resolution monitoring strategies for traffic-related particulate exposure assessment. Citing this work would strengthen the manuscript's discussion of real-world applications and the need for improved high-resolution PM monitoring technologies.**

   We thank the reviewer for recommending this highly relevant study (Yeganeh et al., 2026). This work clearly demonstrates that standard monitoring networks reporting hourly average $PM_{2.5}$ concentrations are insufficient for capturing rapid concentration dynamics and providing accurate assessments of personal human exposure.

   We have updated Section 1 (**Introduction, Lines 37–39**) by integrating the suggested reference alongside existing literature: "In addition, high-sensitivity monitoring with rapid response capabilities is essential for capturing rapid spatiotemporal variations in urban particle concentrations (Yeganeh et al., 2026) as well as supporting effective policy development, emergency response, and exposure assessment (Schweizer et al., 2016)."