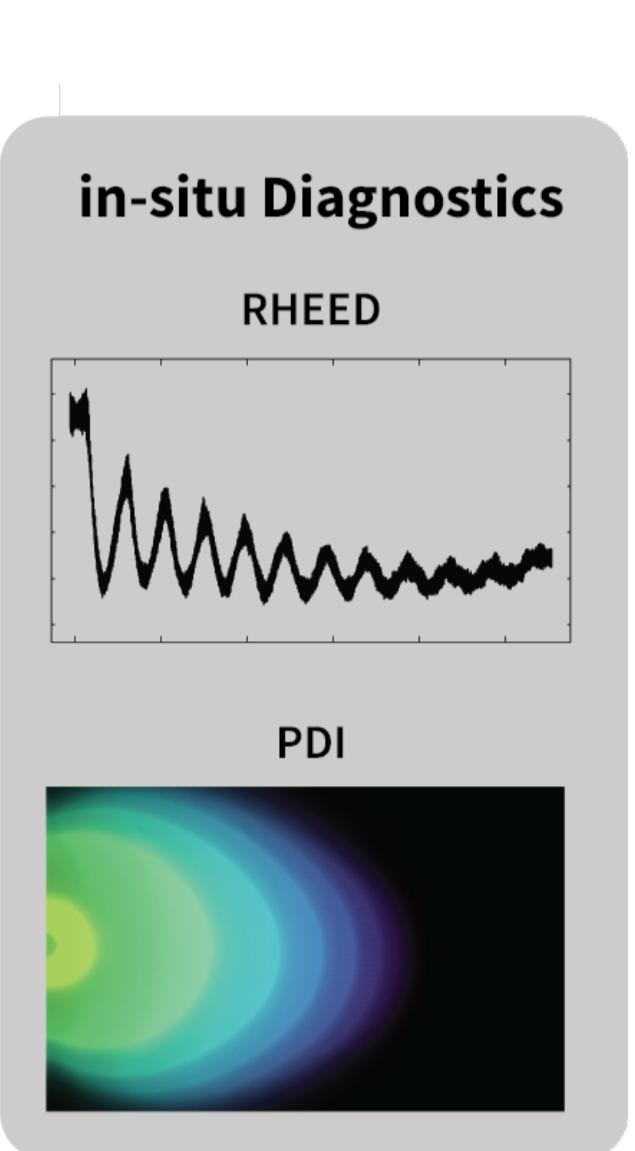
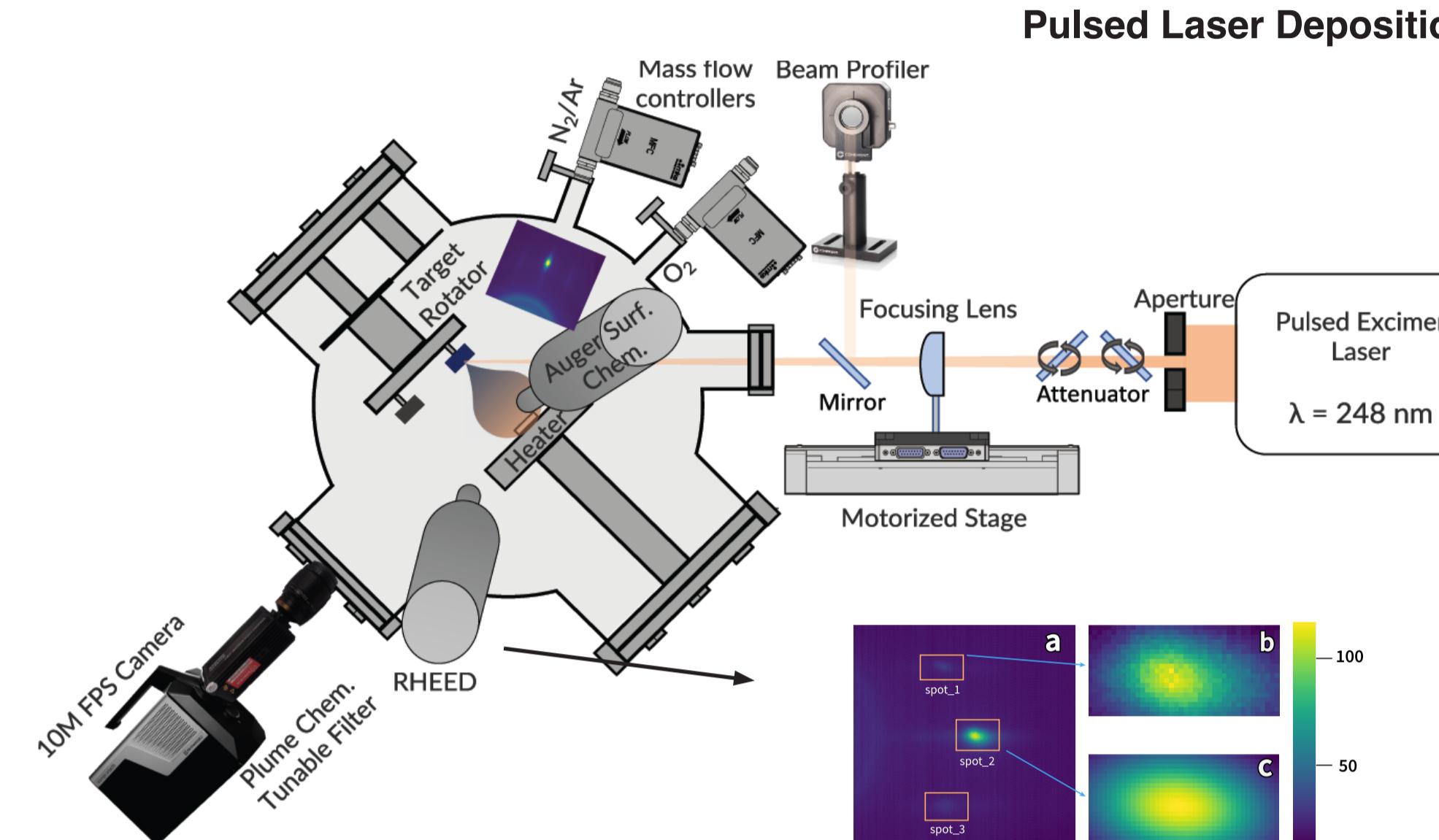


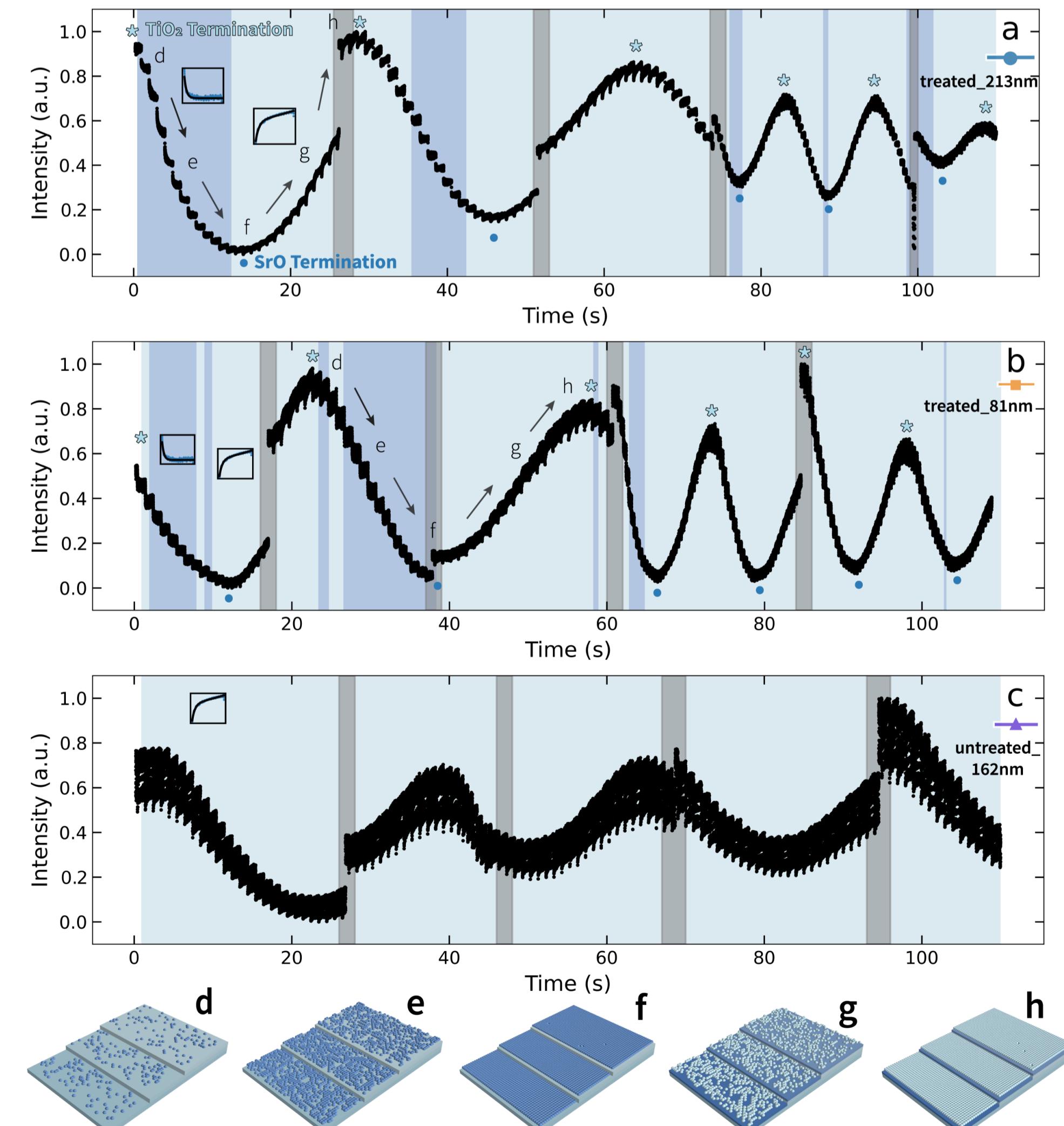
# High-Speed In-Situ Characterization for Pulsed-Laser Deposition: Insights into Growth Dynamics with RHEED and Plume Dynamic Imaging

Yichen Guo (yg446@drexel.edu), Liyan Wu, Peter Meisenheimer, Shuyu Qin, Xinqiao Zhang, Julian Goddy, Ramamoorthy Ramesh, Lane W. Martin, Jonathan Spanier, Joshua C. Agar (jca92@drexel.edu)

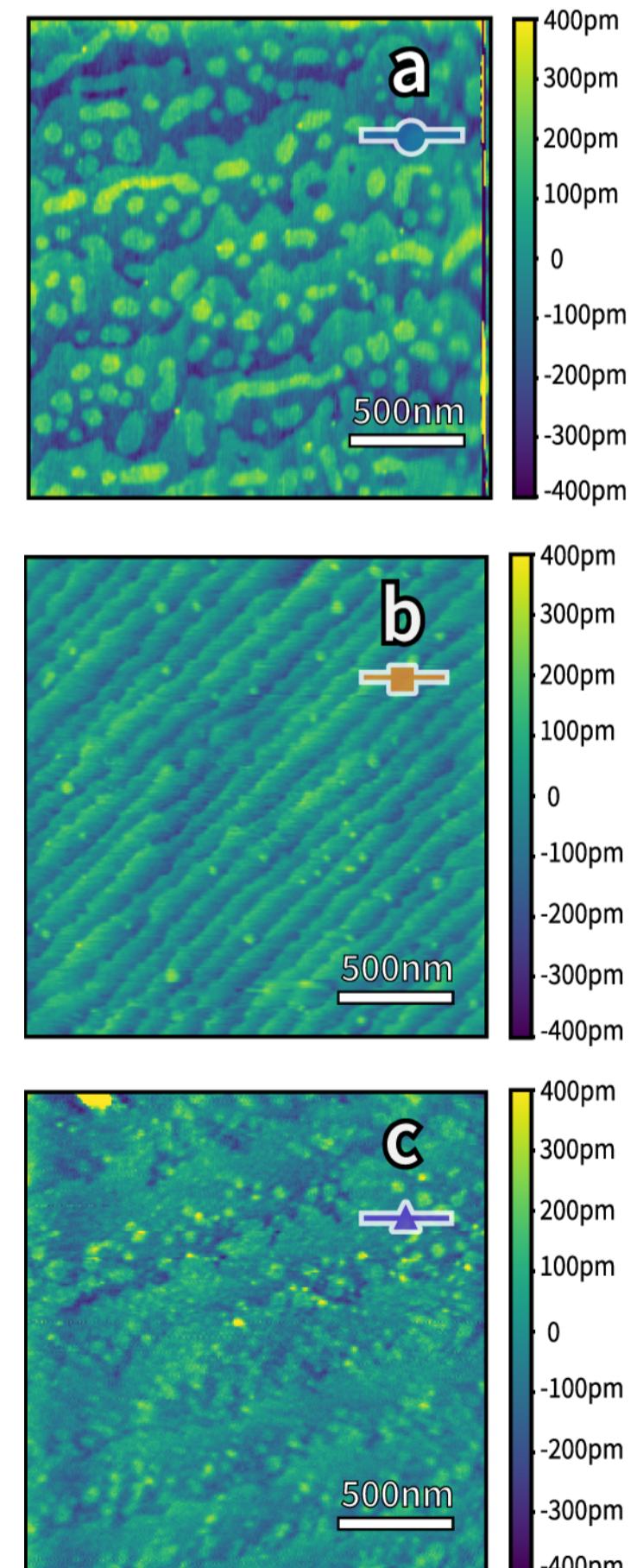
Pulsed-laser deposition (PLD) is a powerful technique for synthesizing complex oxide thin films with precise stoichiometric control, yet its high sensitivity to growth conditions necessitates advanced in-situ characterization techniques to monitor and optimize deposition processes. Reflection high-energy electron diffraction (RHEED) is commonly used to study surface crystallinity and growth dynamics during deposition. However, conventional video-rate systems (60–120 Hz) lack the temporal resolution needed to capture fast dynamics at practical deposition frequencies. Here, we implement a high-speed RHEED platform capable of recording dynamics at >500 Hz, paired with an open-source analysis package to extract single-pulse surface kinetics via 2D Gaussian fits of diffraction spots. Using homoepitaxially deposited (001)-oriented  $\text{SrTiO}_3$  as a model system, we demonstrate the ability of high-speed RHEED to uncover insights obscured by slower systems. Analysis reveals substrate-dependent effects, with diffraction intensity decays and adatom deposition kinetics varying with surface termination and step width, providing real-time insights into growth mechanisms. Complementing RHEED, we introduce Plume Dynamic Imaging (PDI), an in-situ technique capturing sequential frames of plume evolution with ultra-fast cameras. PDI enables the real-time visualization and analysis of plume dynamics, including metrics such as velocity, area, and intensity. Using  $\text{SrRuO}_3$  thin films on  $\text{SrTiO}_3$  substrates as a model system, we establish robust correlations between plume behavior, growth conditions, and film quality. PDI enhances reproducibility in thin-film synthesis and demonstrates potential for integration with advanced machine learning tools for real-time feedback and autonomous control. Together, these high-speed in-situ platforms—RHEED for surface crystallinity and PDI for plume dynamics—offer unprecedented temporal resolution and real-time data acquisition. This work not only advances our understanding of growth dynamics in PLD but also paves the way for data-driven machine learning analysis and autonomous control systems, enabling precise and scalable deposition of next-generation materials.



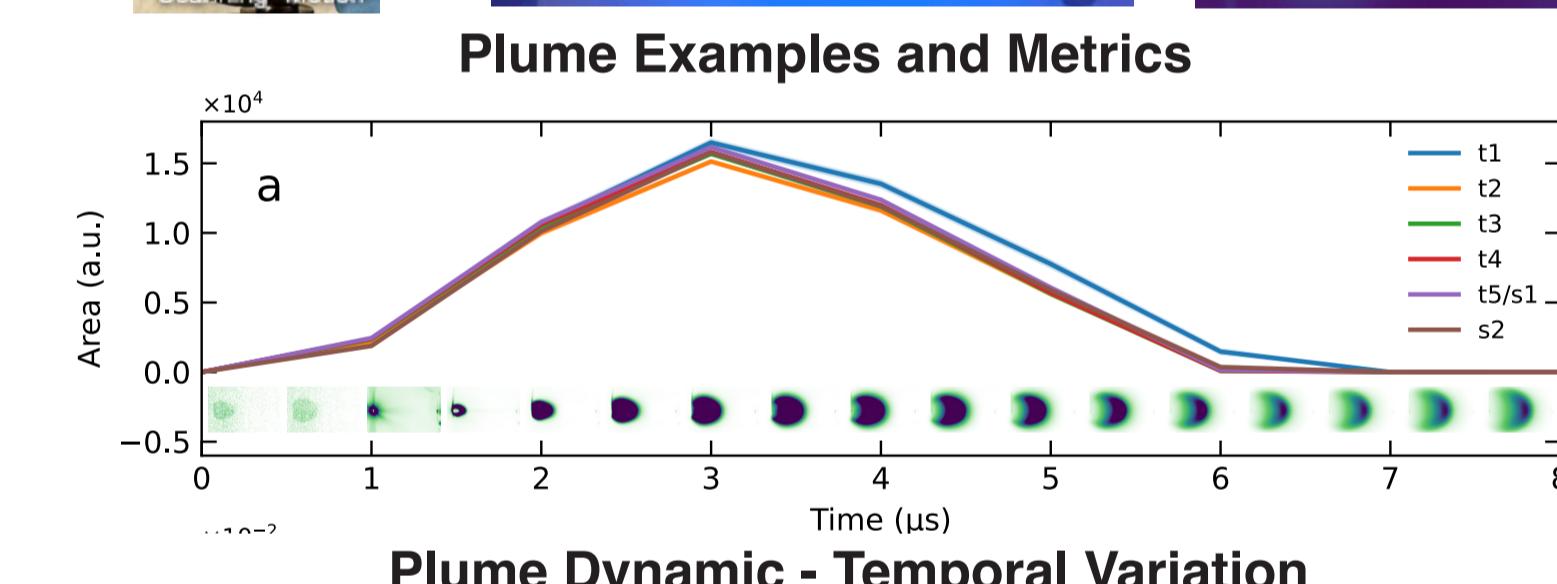
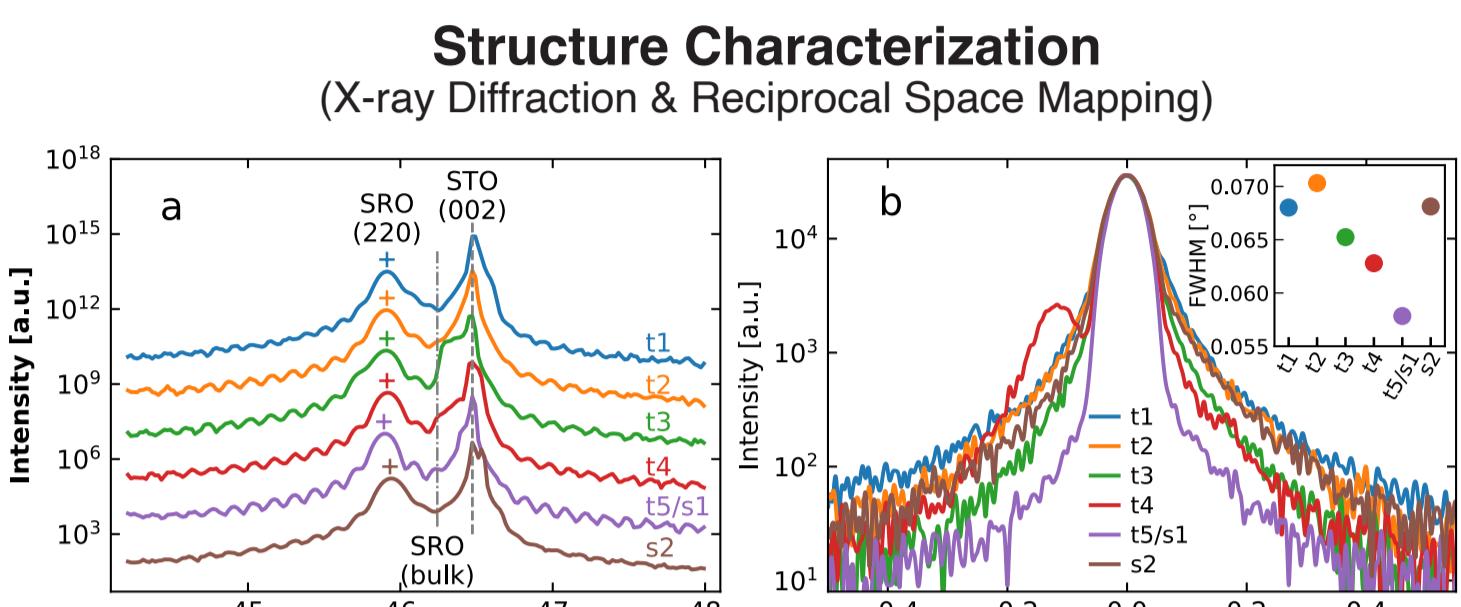
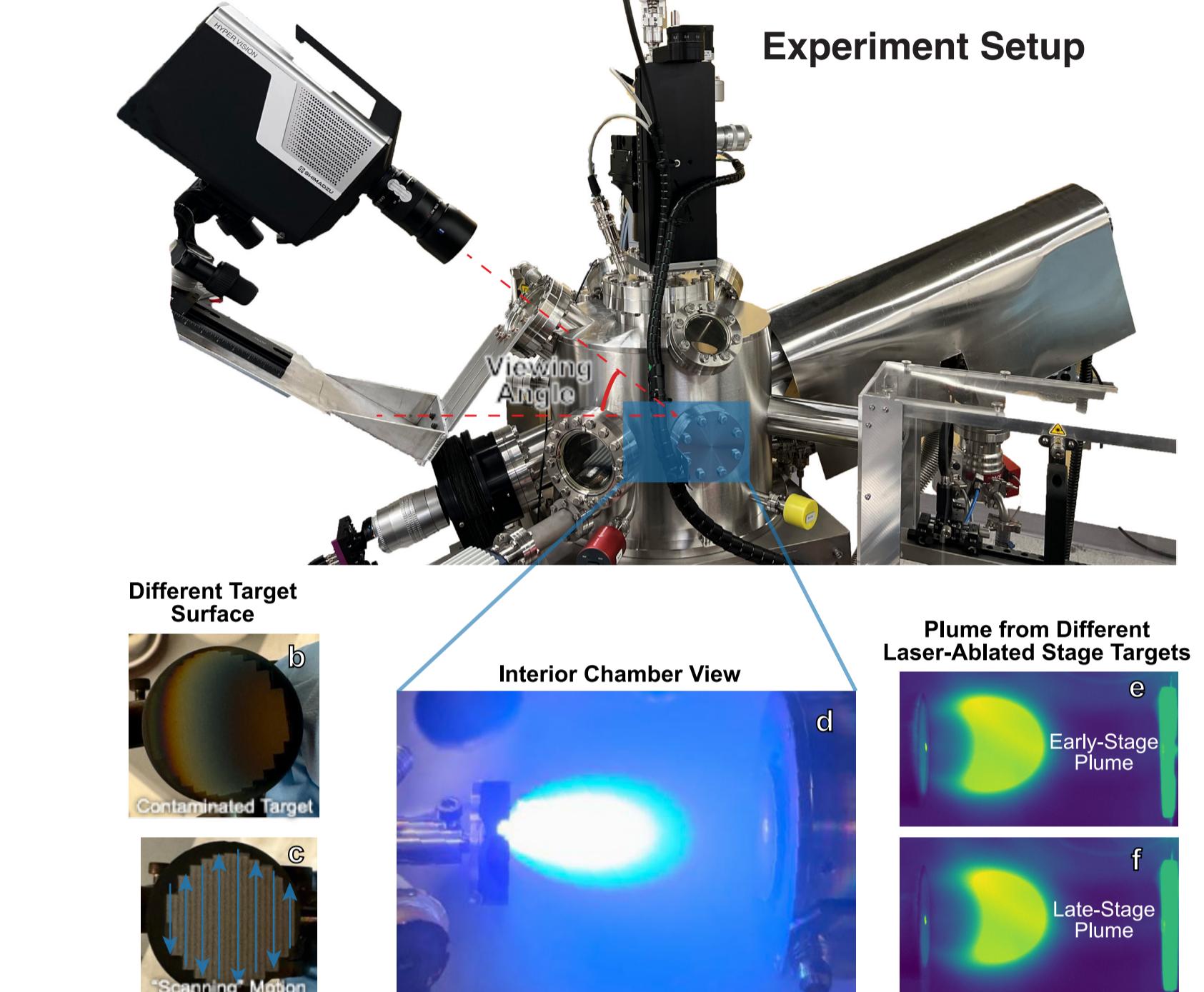
## Growth Mechanism Comparison between Sample Termination



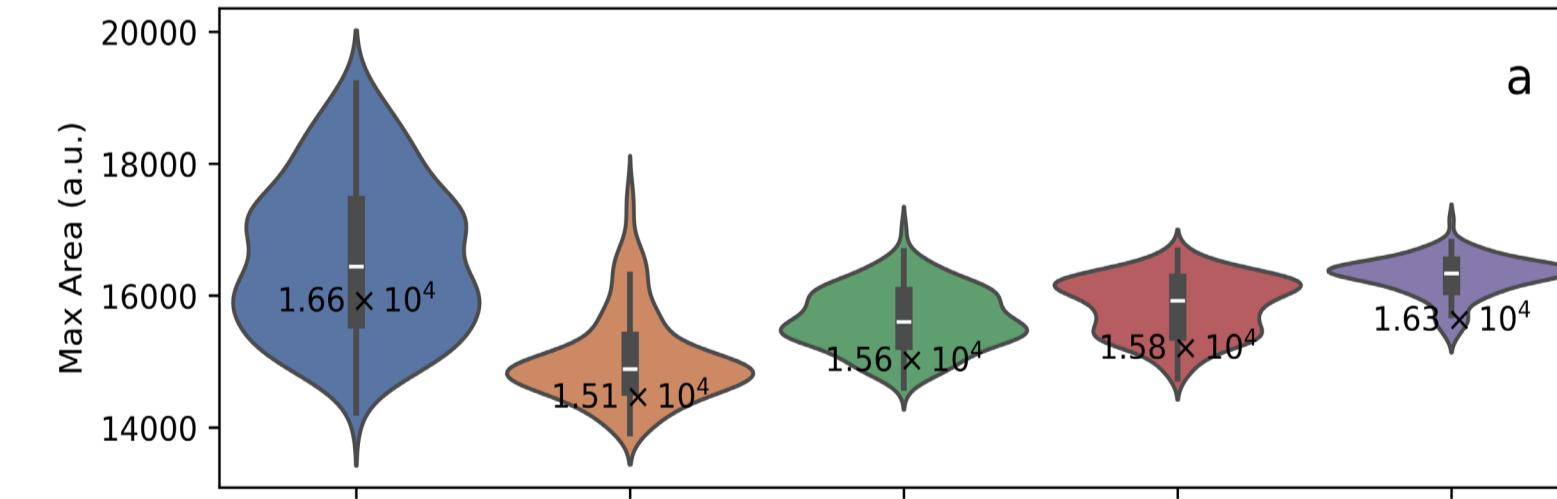
## Sample Surfaces



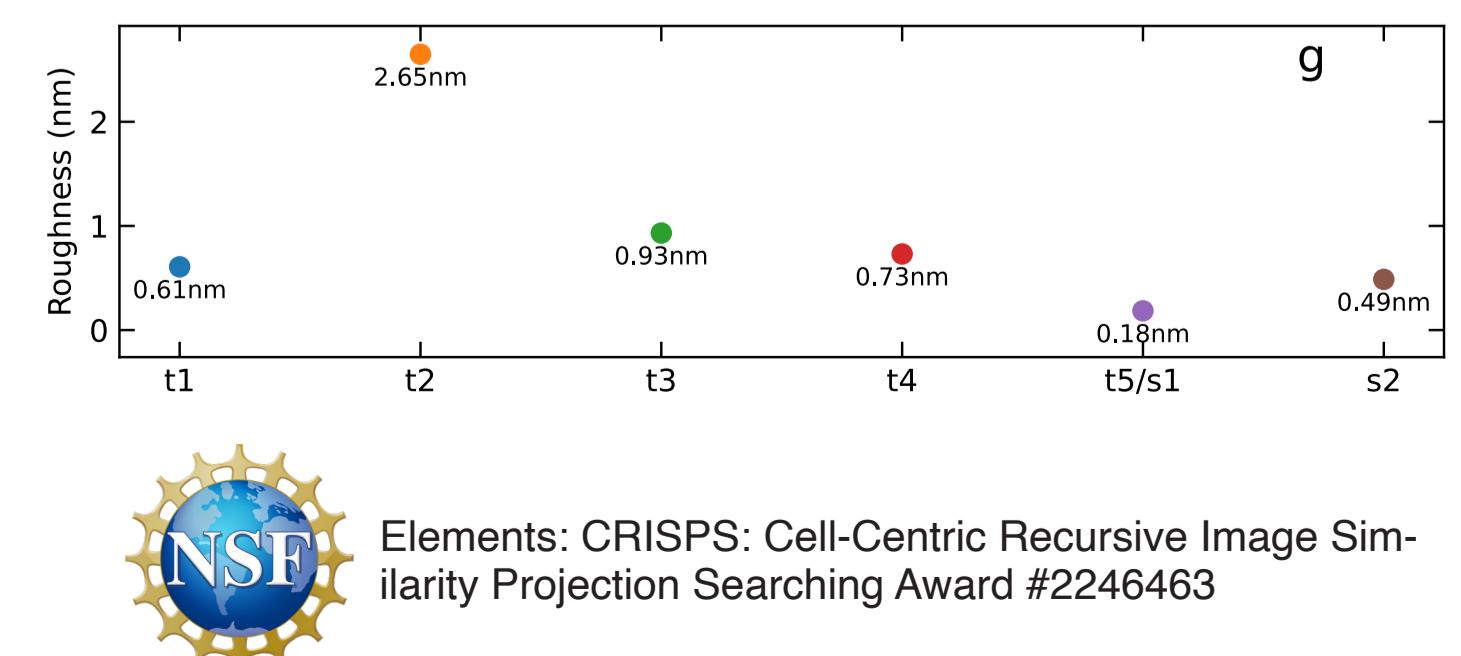
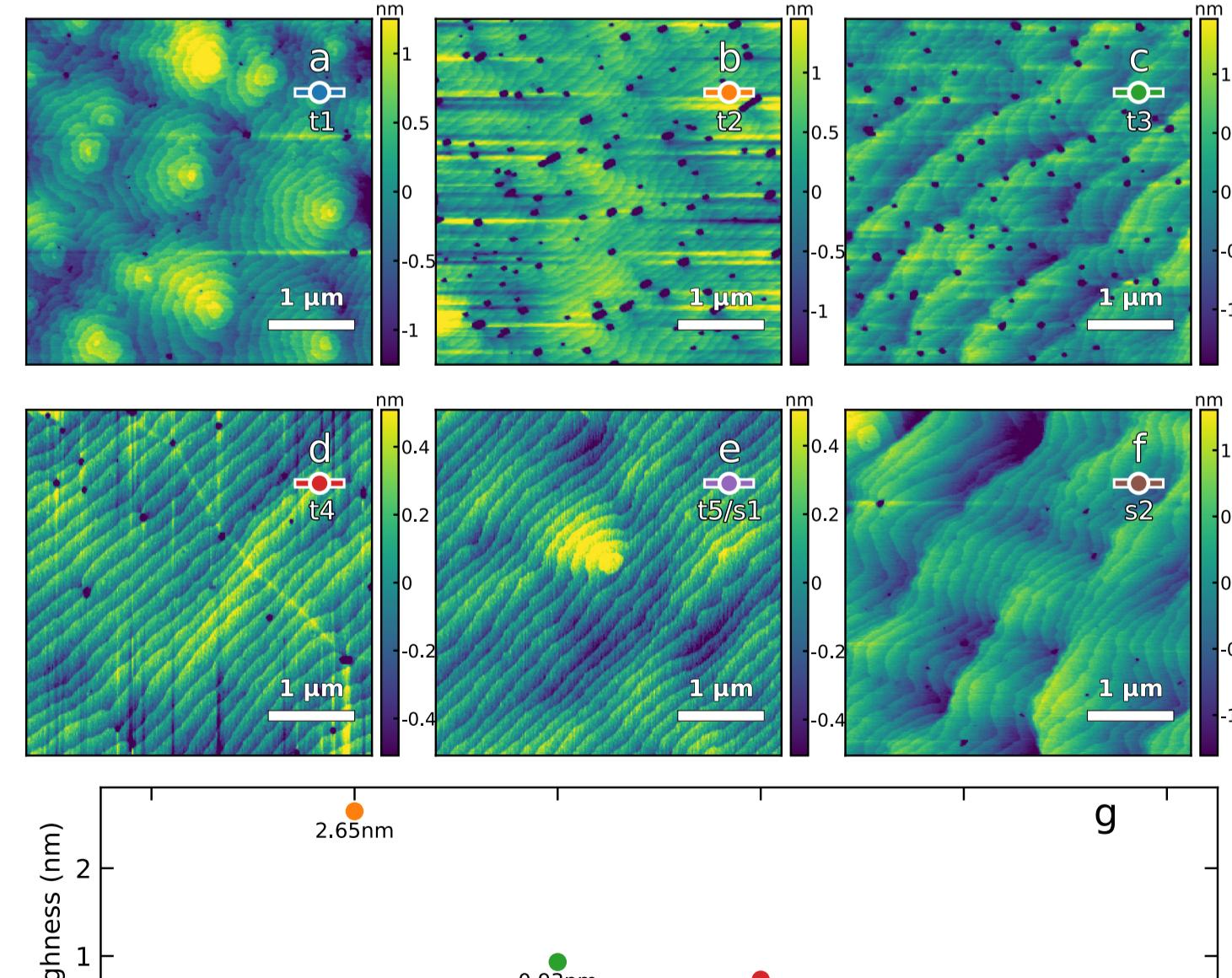
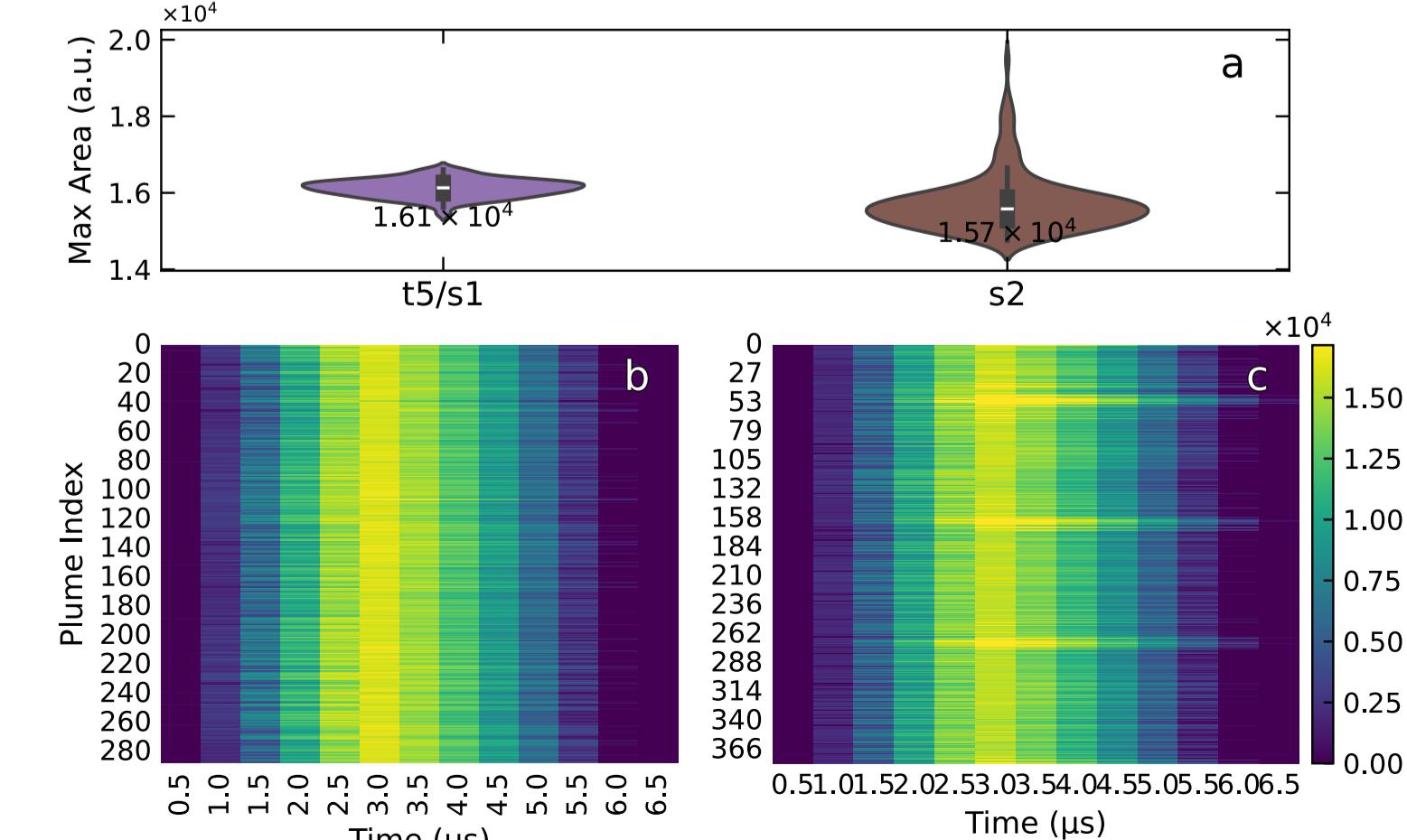
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## Plume Dynamic - Temporal Variation



## Plume Dynamic - Spatial Inhomogeneity



Elements: CRISPS: Cell-Centric Recursive Image Similarity Projection Searching Award #2246463