Developing Radiation-Tolerant Transverse Beam Imaging Using Synthetic Data and Multimode Fiber

Q. Xu[1,2,3] , G. Trad[1] F. Roncarolo[1], A. Hill[2,3], H. D. Zhang[2,3] and C. P. Welsch[2,3]

[1]CERN, Switzerland, [2]Cockcroft Institute, UK [3]University of Liverpool, UK,

Abstract

Beam imaging in high-radiation environments is challenging due to the radiation-induced degradation of cameras. This study proposes a solution that employs a single large-core **multimode fiber (MMF)** to eventually relay light from a scintillating screen to a standard **CMOS camera** positioned outside the radiation zone. To reconstruct the complex intensity patterns caused by mode coupling and scattering within the MMF, a laser-illuminated digital micromirror device (DMD) is used to simulate a scintillating screen and generate a high-variance **synthetic training set**, where **Gaussian mixture models (GMMs)** simulate the distribution of input patterns. A convolutional **autoencoder**, trained only on this synthetic data, is then used to reconstruct the original beam profile from the fiber output.

This approach is validated using the DMD and the transverse beam image samples from the CLEAR facility at CERN[1]. The results demonstrate the method's potential for radiation-resistant beam diagnostics in **high-radiation facilities**.

Experiment, Dataset and Model

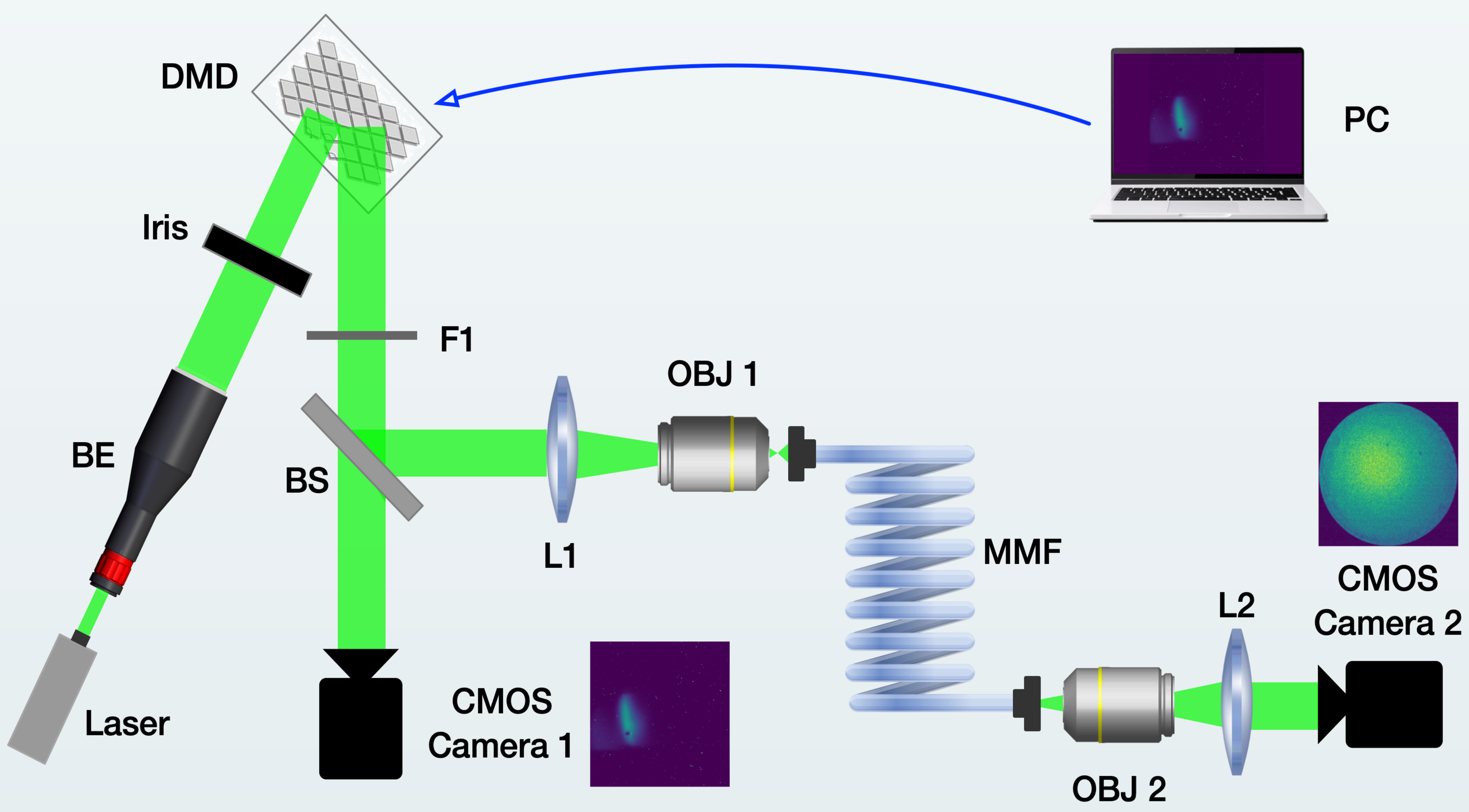

Fig. 1 Schematic illustration of the dataset collection setup at DITALab. A laser illuminates the DMD, projecting GMM-generated synthetic data and real beam data through the fiber for training and testing. CMOS1 records the ground truth, while CMOS2 captures the fiber output speckles.

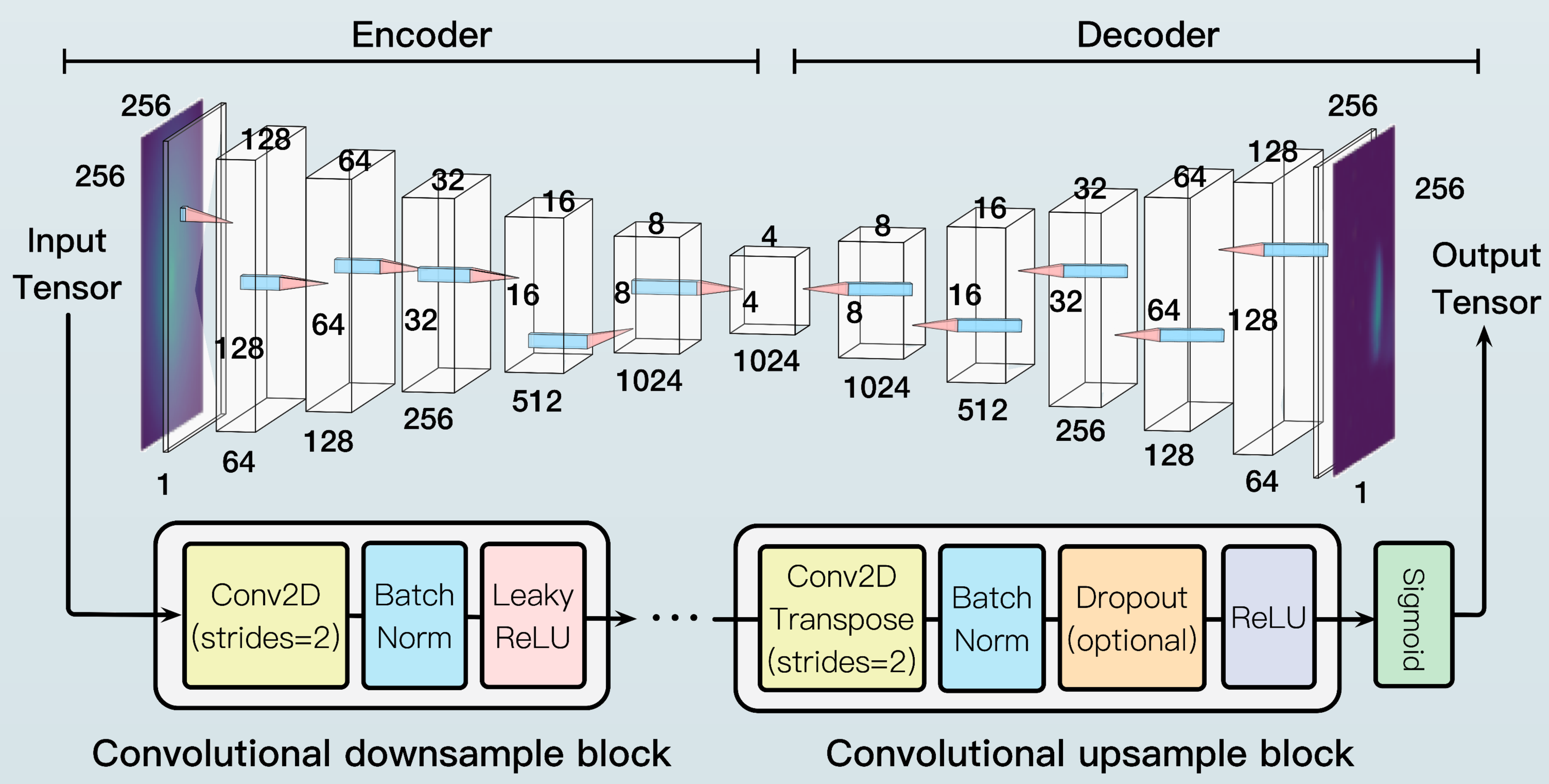

Fig. 2 Architecture of the 2D convolutional autoencoder for MMF image reconstruction. Stride-2 convolutions compress spatial dimensions to 4×4 bottleneck feature maps, replacing pooling layers. Skip connections are removed for better generalization. The model is trained on synthetic data using pixel-wise MSE loss.

Transverse Beam Reconstruction

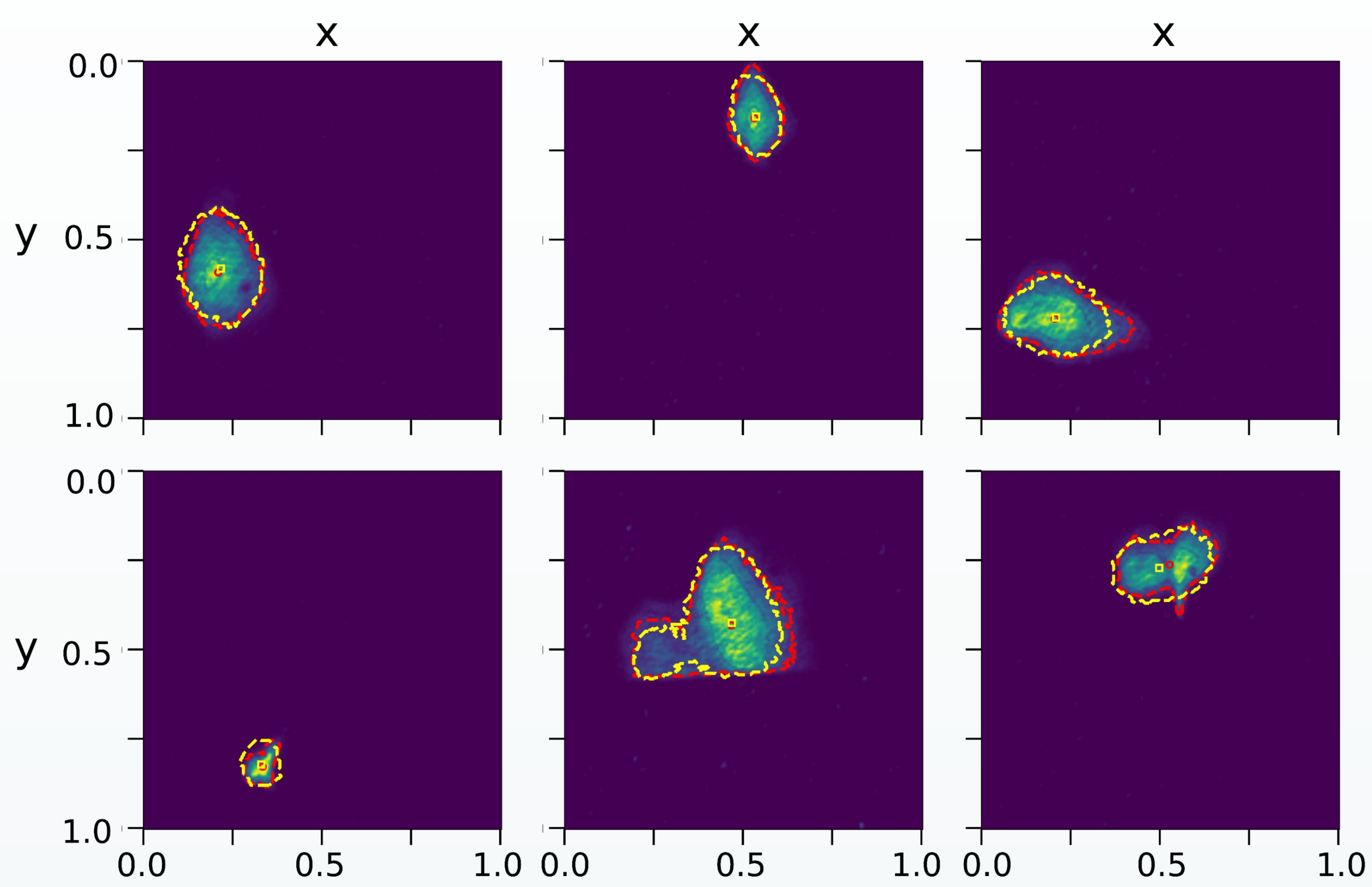

Fig. 3 Representative reconstruction results from the test dataset. The background shows the ground truth beam image. Red and yellow dashed lines mark the 90th percentile intensity levels of the ground truth and reconstruction respectively, with beam centroids indicated. Pixel values are rescaled to the plot's min and max for visibility.

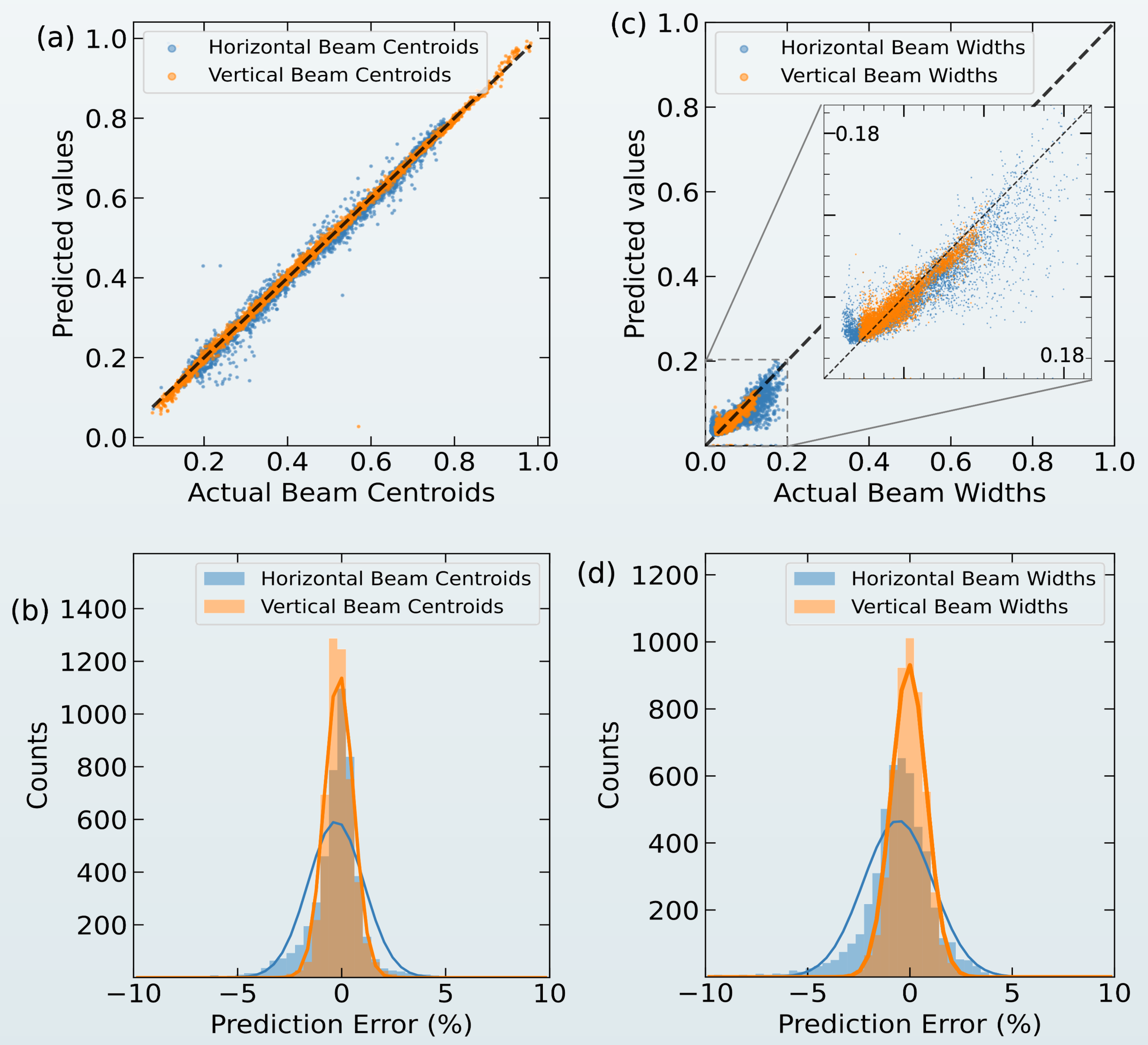

Fig. 4 Statistical results of the final reconstruction on 5,000 test samples from the previous CLEAR experiment. The transverse beam distribution is reconstructed, followed by beam parameter calculations. Subfigures (a) and (b) show beam centroid reconstruction, while (c) and (d) show beam width. Blue indicates the horizontal direction, yellow the vertical. Both dimensions are normalized.

Conclusion & Future Plans

Our approach achieved a final score of 1.65% RMSE in reconstructing test set transverse beam parameters, showing good generalization to unseen data. For future works:

- **Light source optimization**: Match the scintillating screen's emission bandwidth to better simulate real conditions.
- **Fiber perturbation study**: Systematically examine temperature and geometric variations effects to the fiber.
- **Radiation degradation**: Investigate degradation effects on the MMF.

References

[1] Trad, Georges, and Stephane Burger. "Artificial Intelligence-Assisted Beam Distribution Imaging Using a Single Multimode Fiber at CERN." JACoW IPAC 2022 (2022): 339-342.

Acknowledgements

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https://www.cockcroft.ac.uk/
https://www.liverpool.ac.uk/quasar/
qiyuanxu@liverpool.ac.uk

LIV.INNO QUASAR Group GitHub LinkedIn