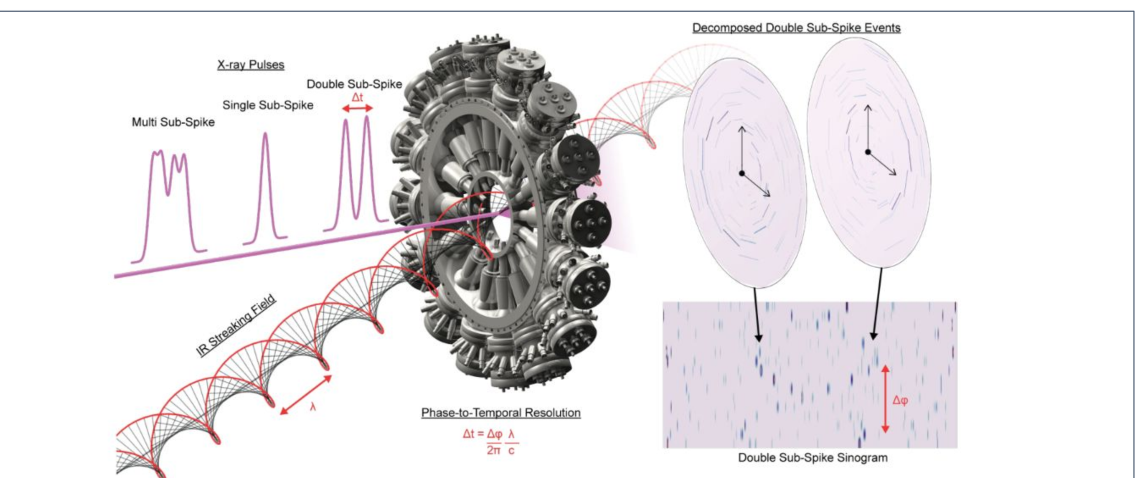
Machine Learning for Real Time Single Shot Pulse Reconstruction Using MRCO

Mia Edmondson[1,2], Jack Hirschman[1], John Walters[1], Luca Scomparin[1], Benjamin Mercer[1], Don Schafer[1], Justin James[1], Ryan Coffee[1], Razib Obaid[1]

[1] Linac Coherent Light Source, SLAC National Accelerator Laboratory, Menlo Park, CA, USA [2] University of California Berkeley, Berkeley, CA, USA

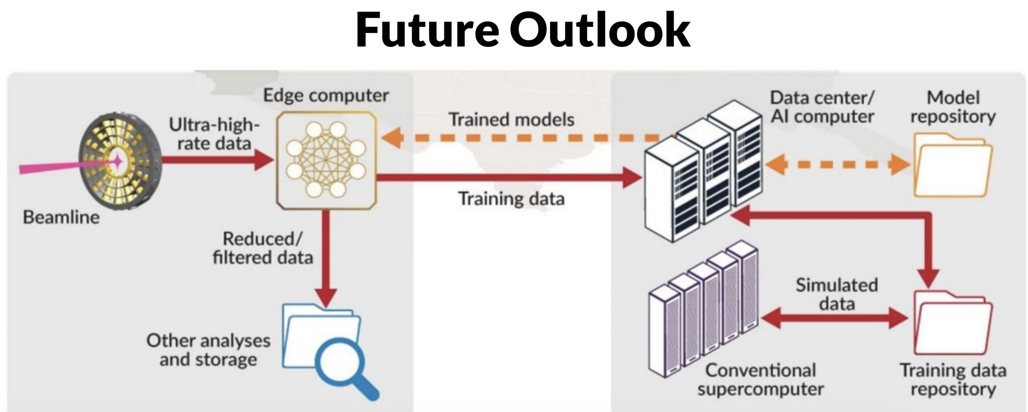
GITHUB



Background

- To understand the mechanisms behind chemical bond formation and breaking we must be able to capture electron dynamics at an attosecond resolution.
- Attosecond scale resolution is possible with the LCLS II upgrade
- For Diagnostics we need to know the structure of the incoming x-ray pulse
- Multi Resolution Cookiebox (MRCO) has 16 electron time of flight spectrometers or eToFs in a ring
- With higher repetition rates data is coming in at a rate that is too fast for old analytical methods to do pulse reconstruction on, necessitating machine learning

Future Outlook

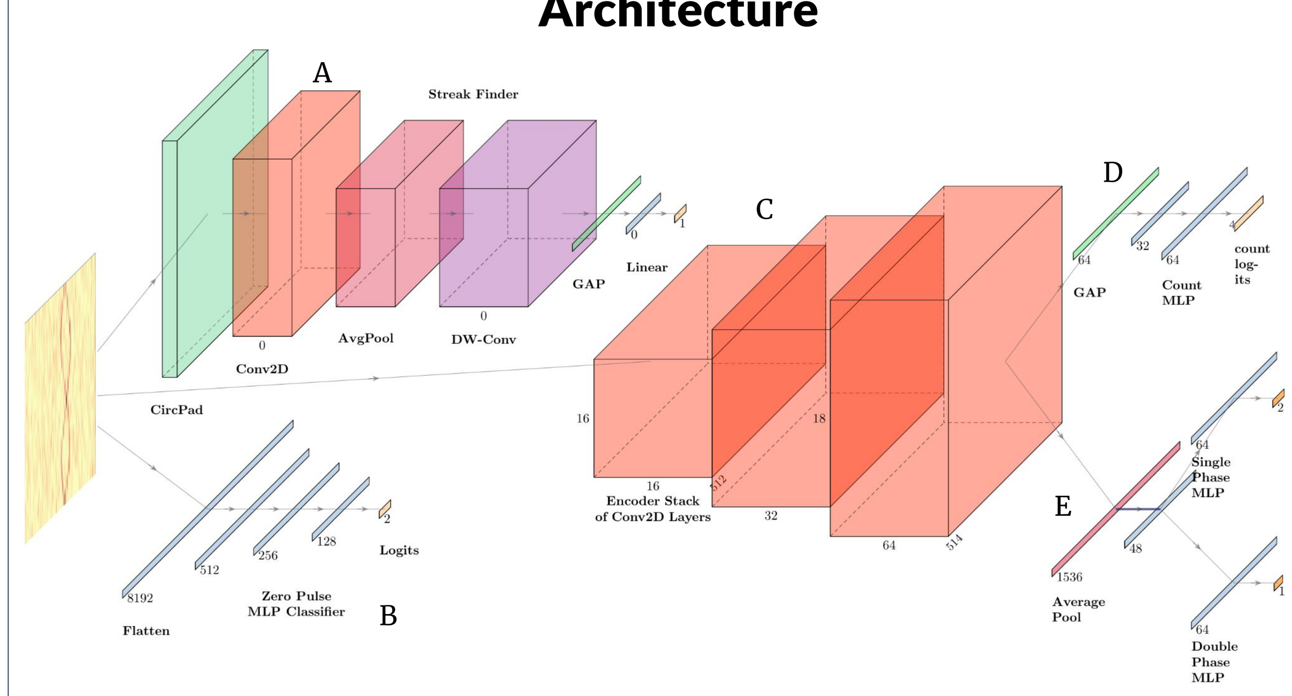


Objectives

I needed to modify an existing ML model for:

- **Model Optimization:** Modify an existing model for quicker execution and shrink it so it can fit on an FPGA.
- **Feature Detection:** Develop a streak finding network.
- **Realistic Simulation:** simulate a more realistic dataset
- **Validation:** run the full pipeline on real data.

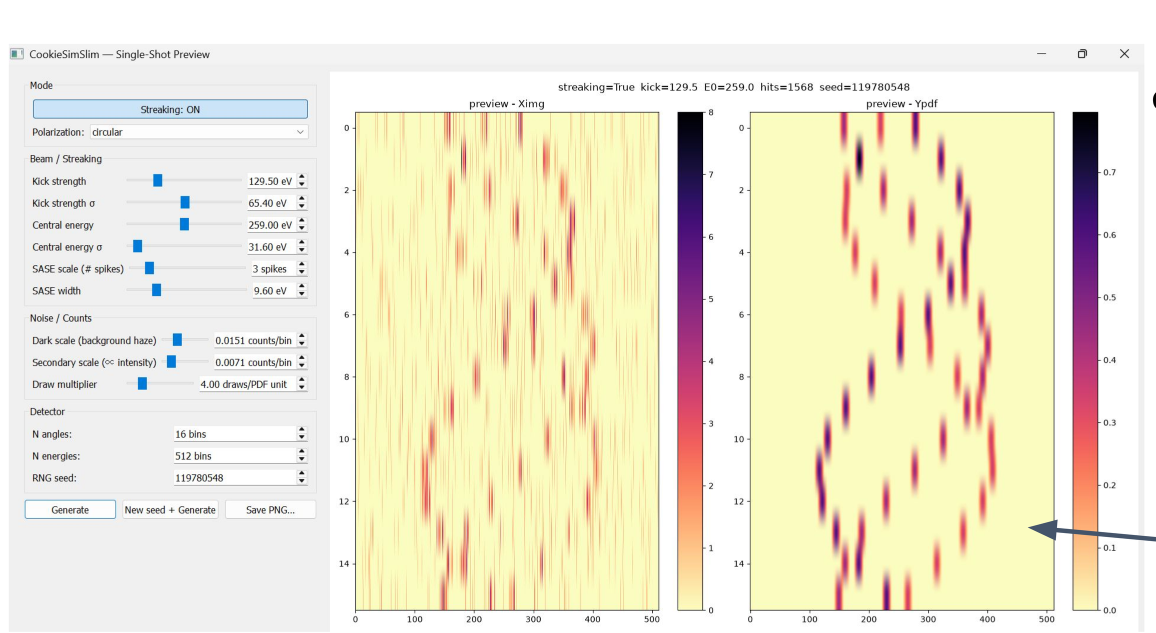
Architecture



The components of the model are:

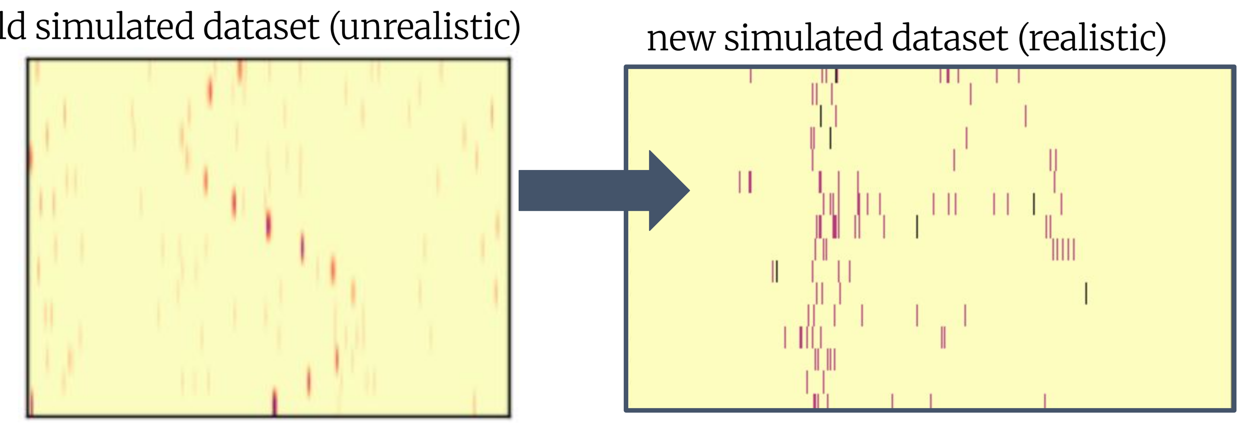
A. Streak Finder
B. Zero Pulse Classifier
C. Encoder (Decoder stripped at export)
D. Subspike Count Classifier
E. Single and Double Pulse Phase Regression

Where the Sinusoids Come From



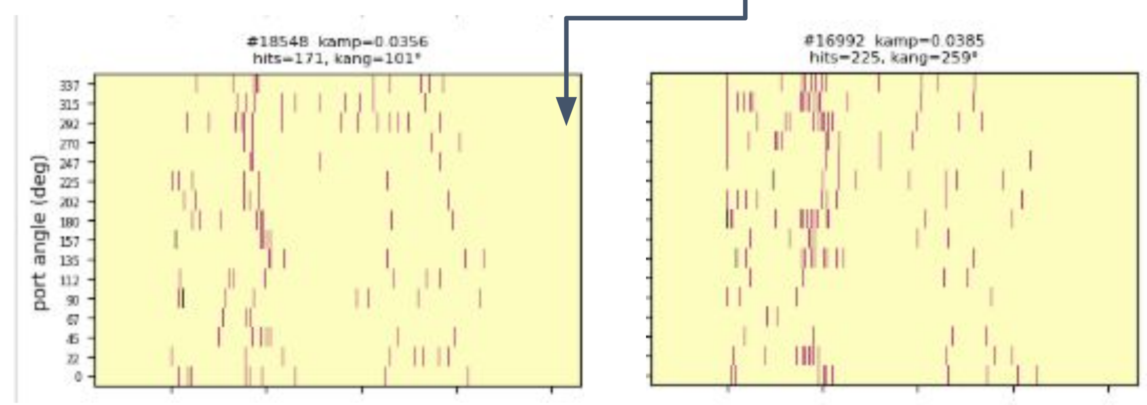
1. An XFEL pulse ionizes a spherical symmetric electron orbital.
2. A circularly polarized IR laser delivers a momentum kick so that electron kinetic energy is given by $W(W_0,\theta,t_i) \propto W_0 + \sigma \cos\left(\theta - 2\pi \frac{ct_i}{\lambda}\right)$
3. We can go from observed ToF -> KE by $\frac{\alpha}{(t-t_0)^2}$
4. Plotting eToF angle vs KE produces a sinusoid for each subspike.

Generated new dataset with more noise, lower SNR ratio, and some missing ToF signals to create more realistic training data



Visualization GUI: Developed a Simulation GUI for visually analyzing beam parameters

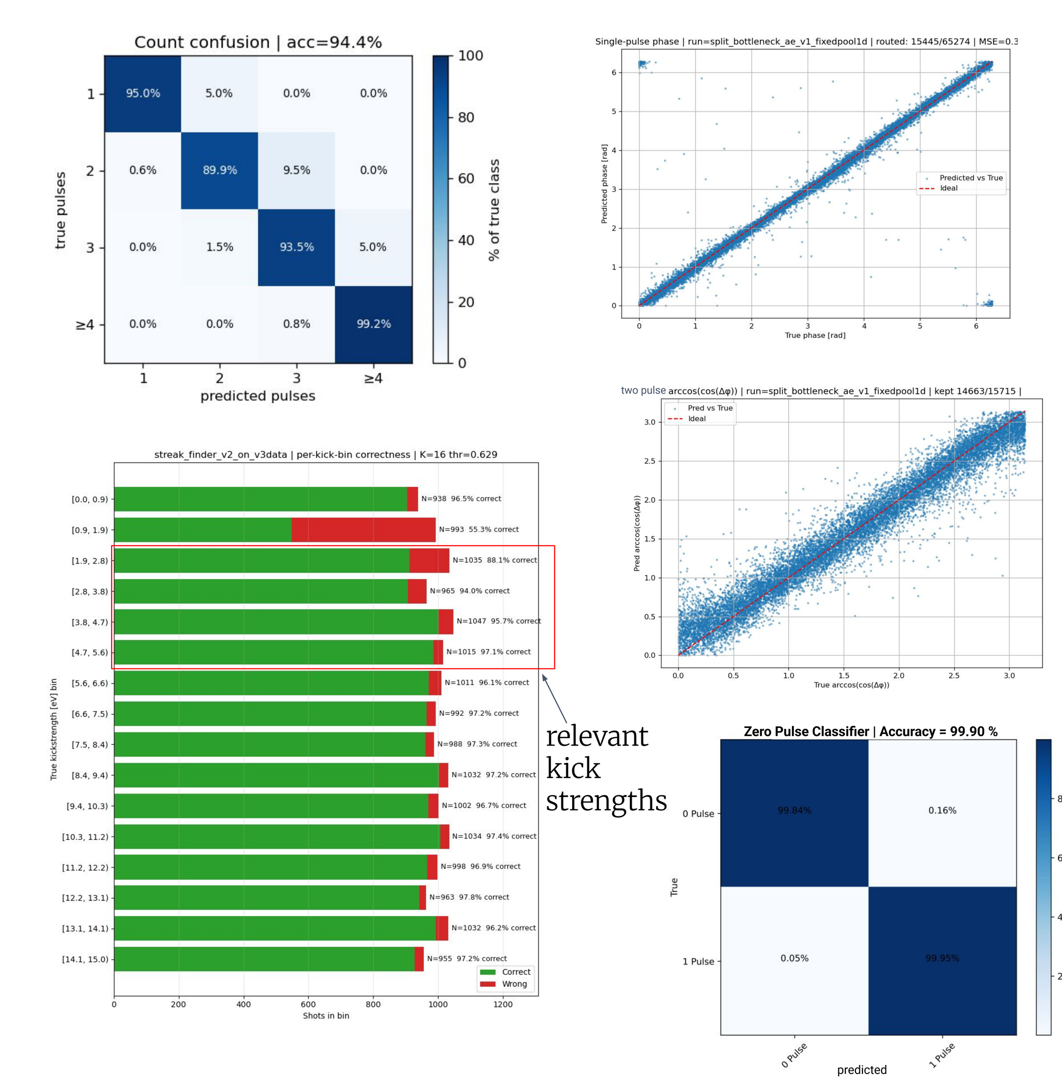
Raw Data Processing: in preparation to run through pipeline



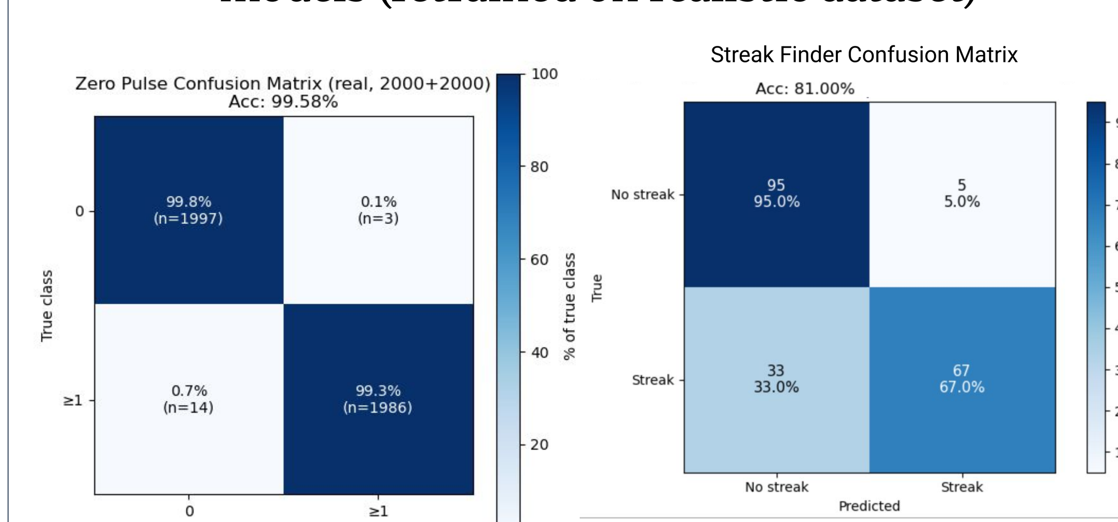
Results

Speed: redesigned encoder, with subspike count classification and phase regression was benchmarked with a FPGA single shot runtime of **52 µs** (over **3x** speedup from the previous model's 168.3 µs while maintaining accuracy). This should translate to under 10 µs on a Groq card. Implementation is ongoing. This means the inference can be performed at around 100 kHz rep rate on the Groq card.

On the (Unrealistic) Simulated Dataset



Validation: Running real XLEAP pulses through models (retrained on realistic dataset)



The preprocessing models were retrained on a realistic simulated dataset before evaluation with real data. Validation for phase regression and pulse classification is in progress.

Conclusions and Future Tasks

In order for this model could to be used for real time feedback during beamtime additional work is needed on hardware implementation, continuing training with realistic datasets, and validation with a wider variety of real data. My contributions include drastically decreasing model size and single shot interference time without sacrificing accuracy, developing realistic training data, and running the model on real data for the first time.

ACKNOWLEDGEMENTS

I am incredibly grateful to my mentor Razib Obaid for guidance and support throughout this internship. To Jack Hirschman for ML advice, John Walters for data processing guidance, and Luca Scomparin for FPGA benchmarking. Thank you to Alan Fry and the rest of the intern team for making this incredible opportunity possible. Finally, I would like to thank the SAGE program for introducing me to the national lab system and encouraging me through my academic journey.

REFERENCES

Hirschman, J., et al. "A Hybrid Neural Architecture: Online Attosecond X-ray Characterization.", APL Machine Learning, 21 Nov. 2025

Hartmann, N., Hartmann, G., Heider, R., et al. (2018). Attosecond time–energy structure of X-ray free-electron laser pulses. *Nature Photonics*, *12*, 215-220. https://doi.org/10.1038/s41566-018-0107-6