HAMLET Physics 2025

Imaging Electron Beams with Virtual Diagnostics

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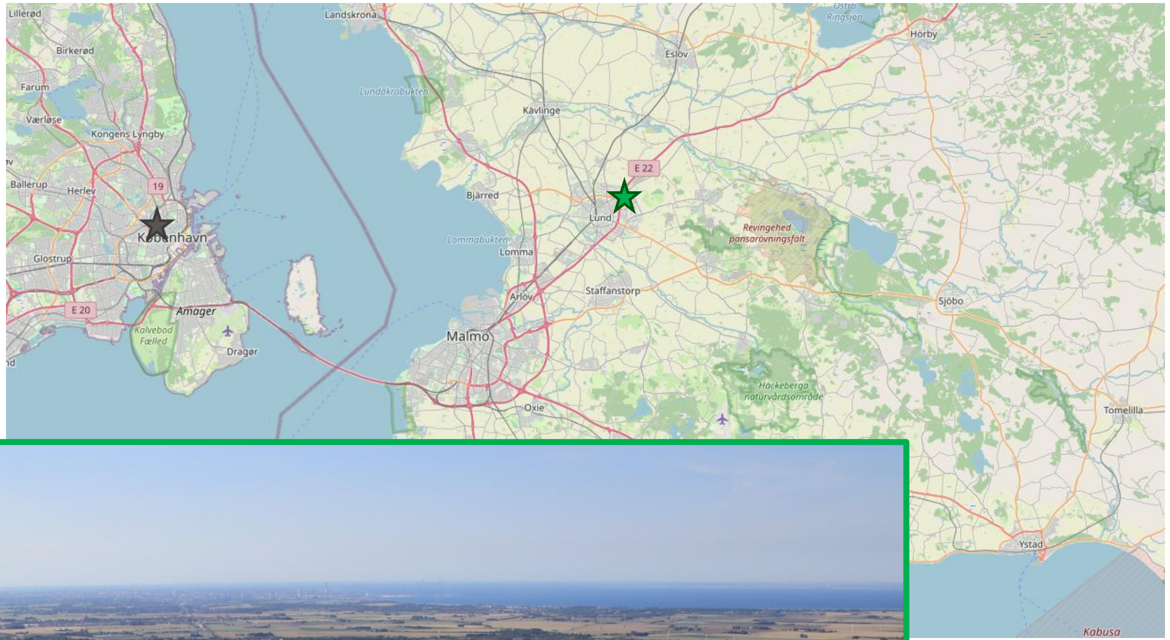
Overview

- Introduction
    - Linear Accelerators
    - Transverse Deflectors
    - Virtual Diagnostics
- MAX IV Virtual Diagnostic
- Multi-Facility Application
- Conclusion



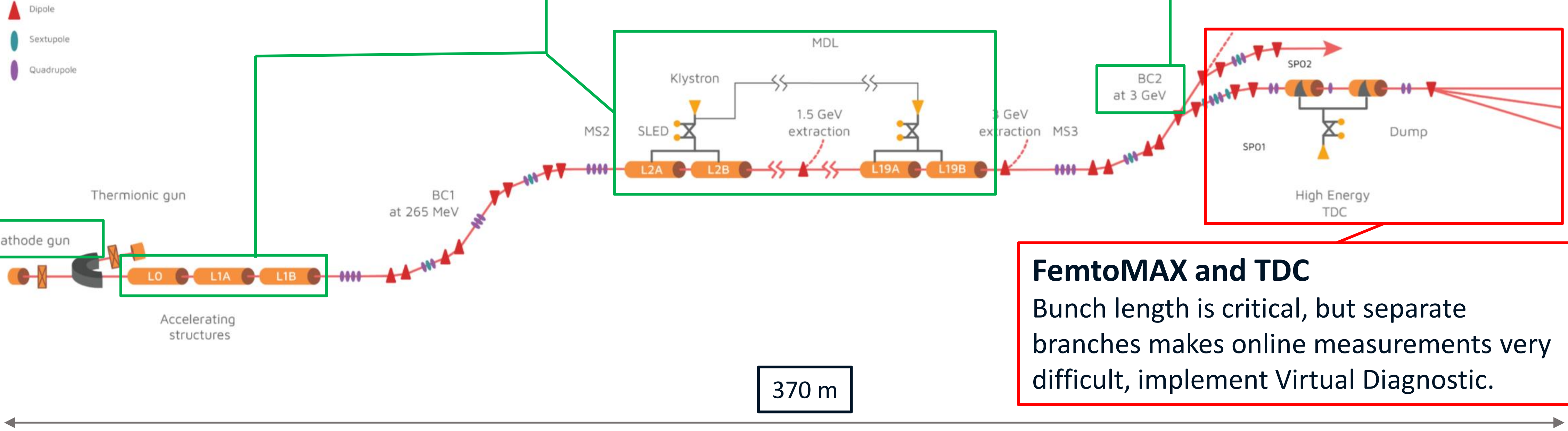
Accelerators – Modern Linear Accelerators

MAX IV Linac

GUN
Photoelectric effect to extract electrons from a cathode with a driving laser.

RF Acceleration
RF fields accelerate the beam. 265 MeV at first bunch compressor, 3 GeV at the second.

Bunch Compressors
Magnetic setup creates an energy-dependent path length, used to compress the final beam.

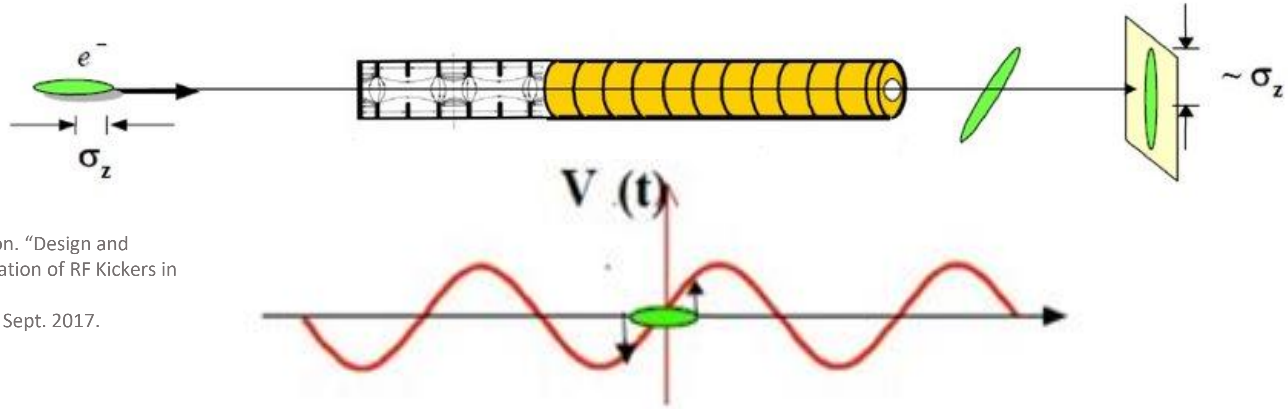


FemtoMAX and TDC
Bunch length is critical, but separate branches makes online measurements very difficult, implement Virtual Diagnostic.

370 m

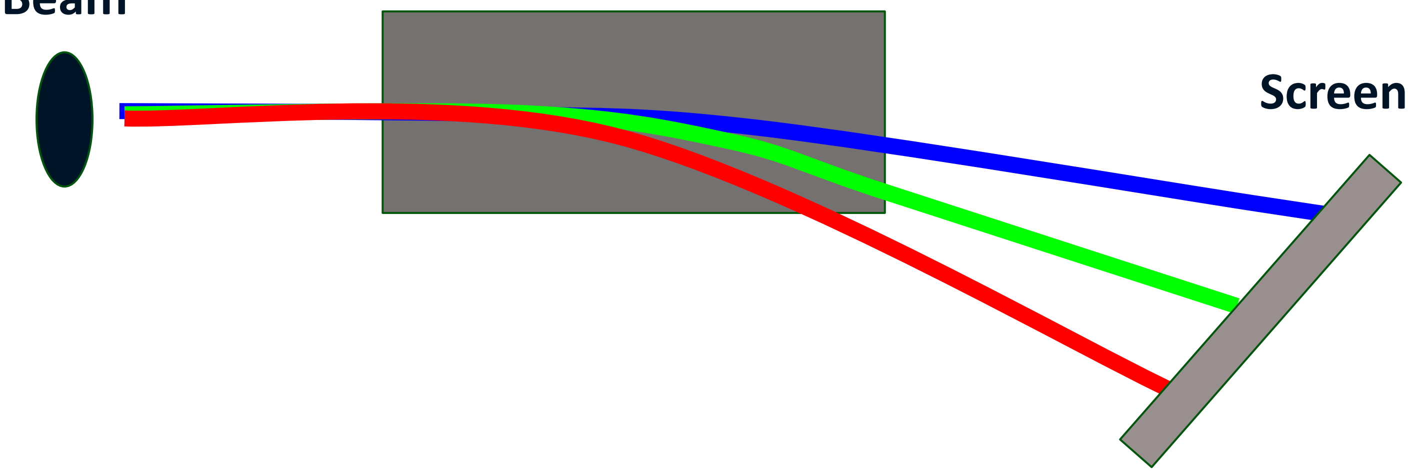
Accelerators – Transverse Deflecting Cavities

1.

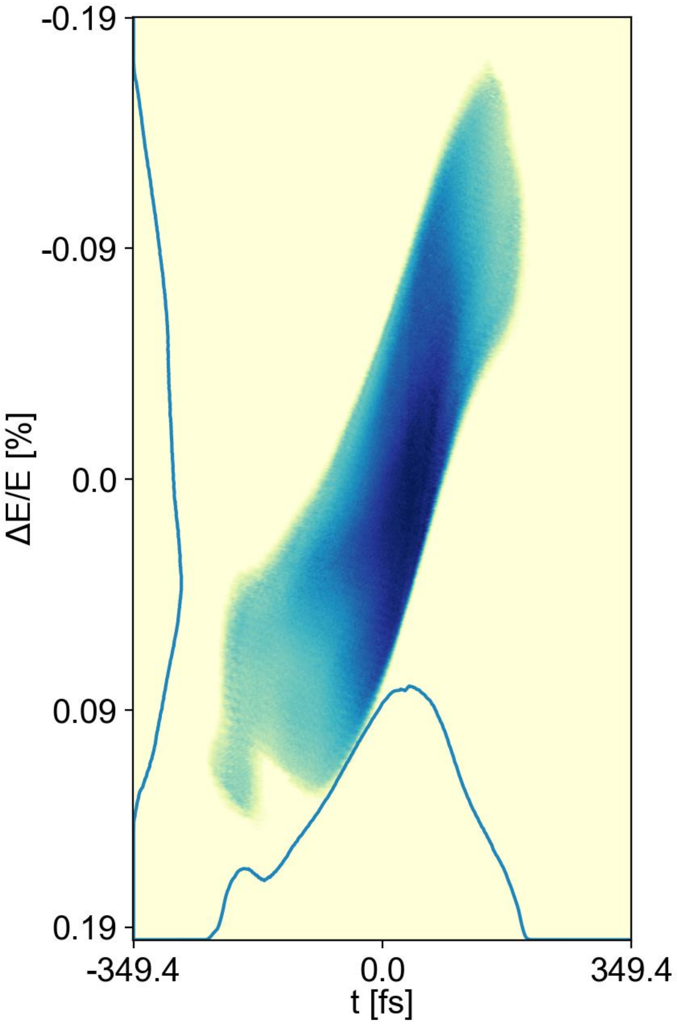


David Olsson. “Design and Implementation of RF Kickers in MAX IV”.
PhD thesis. Sept. 2017.

2.



Result:
Longitudinal Phase Space



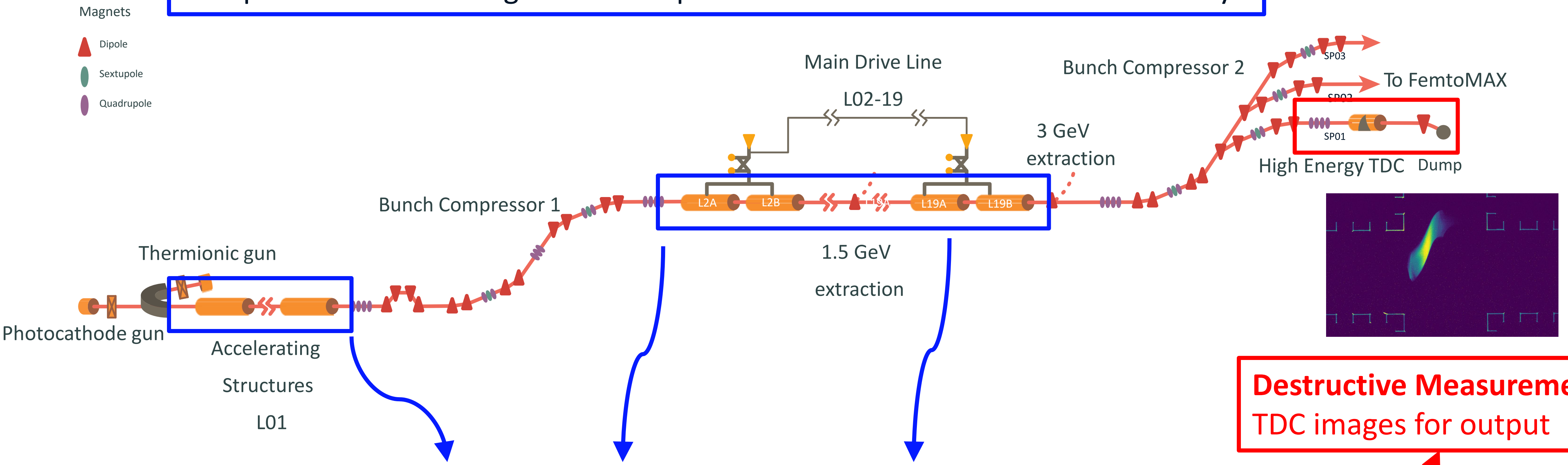
LPS Virtual Diagnostic – Motivation

- A full longitudinal understanding of the beam is often critical for Linac and FEL operations
- TDC usually provides a destructive measurement, disruptive to delivery of beam to users
- MAX IV has separate branch for TDC, can not measure LPS quickly during delivery

- **A Virtual Diagnostic (VD) would allow online measurement of LPS**
- **VD could be used for operations and feedback during delivery**

LPS Virtual Diagnostic – Experimental Setup

Scanning amplitude of accelerating fields before and after BC1
This provides similar range of LPS shapes to what is used in FemtoMAX delivery



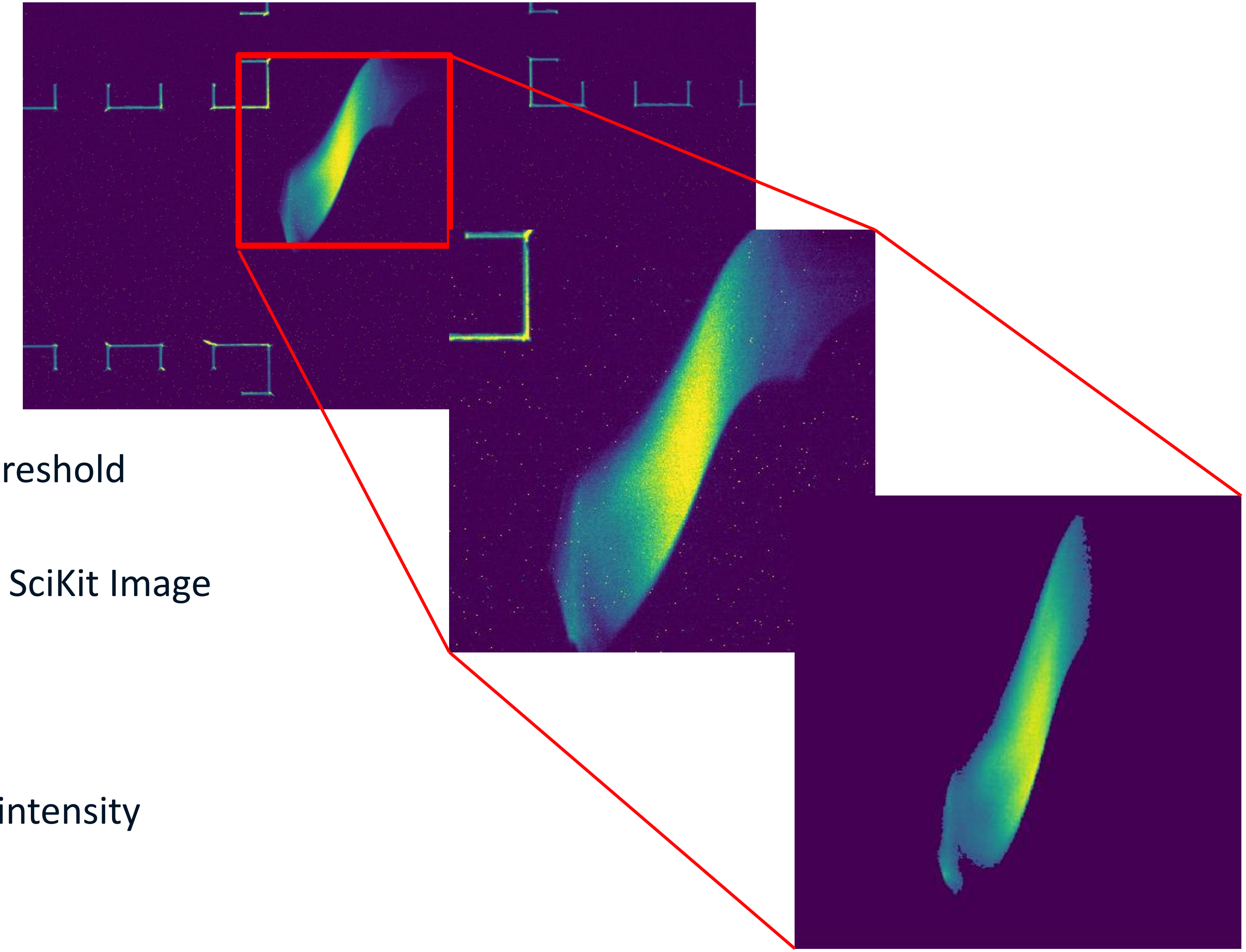
Destructive Measurement
TDC images for output

Non-destructive Beam Information
Scanned RF parameters + Beam Position Monitors + Current Tranformers + etc...

Virtual Diagnostic

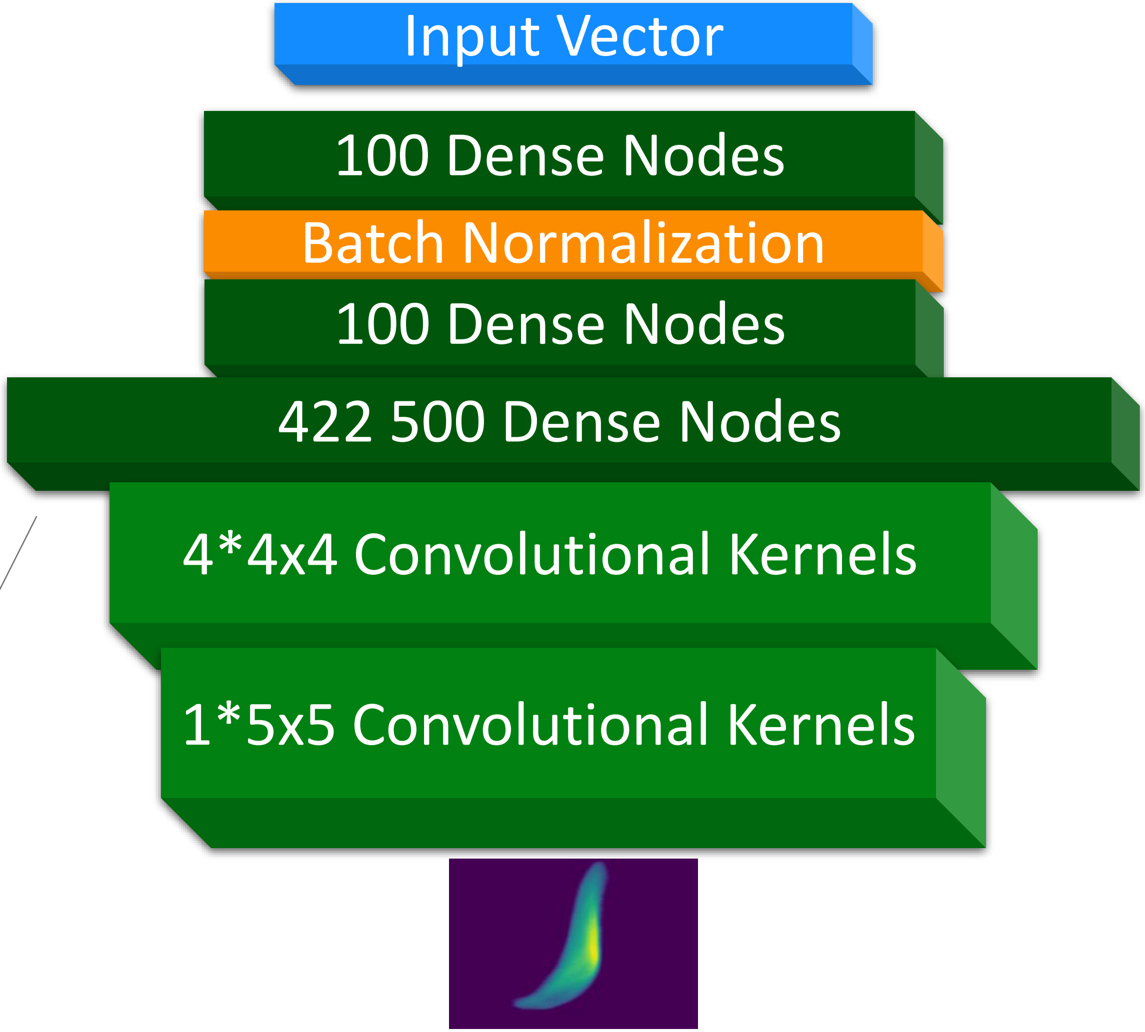
Image Preparation

- Background subtraction, negative pixels to 0
- 3x3 Median filter
- Region slice based on Otsu threshold
- Using Region Properties from SciKit Image
- Zero outside relevant region
- 650x650 output, Normalized intensity



Network Structure and Training

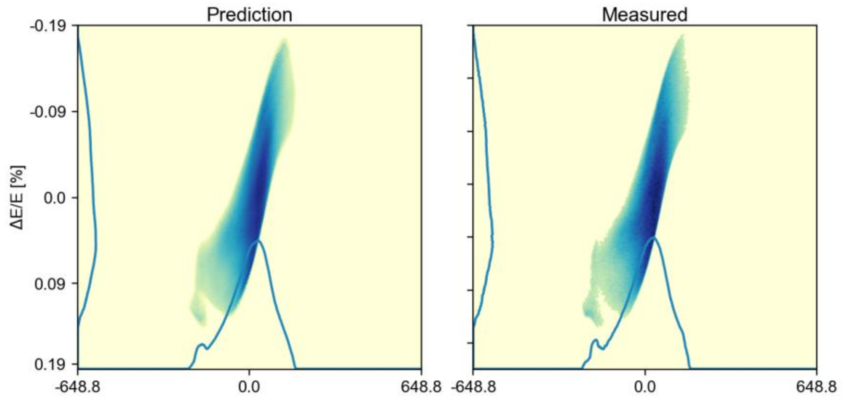
- 9000 images collected, ~6 hour beamtime
  - HDF5 set with 9000x650x650 images + 108 input params -> 28 GB of data
  - 90/10% Train/Test Split
- Dense Net + CNN trained with ADAM and MAE
  - Used scheduled learning rate and checkpoints for early stopping
  - Post-processing: Alignment using cross-correlation
- Large image size layer
  - Extends training time
  - Required for full LPS images
- Networks trained on LUNARC HPC Cluster
  - Training time on Nvidia A100 ~10 minutes
  - Training time on Laptop CPU ~1-2 hours



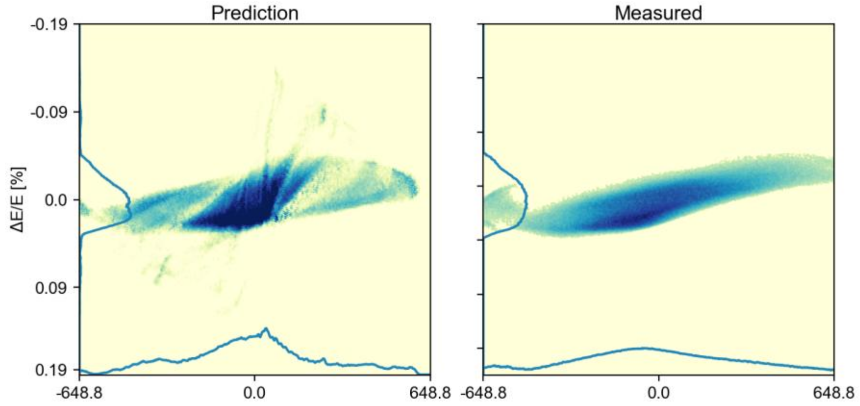
MAX IV – LPS Predictions

R^2: Mean = 95.5%, Median = 96.1%

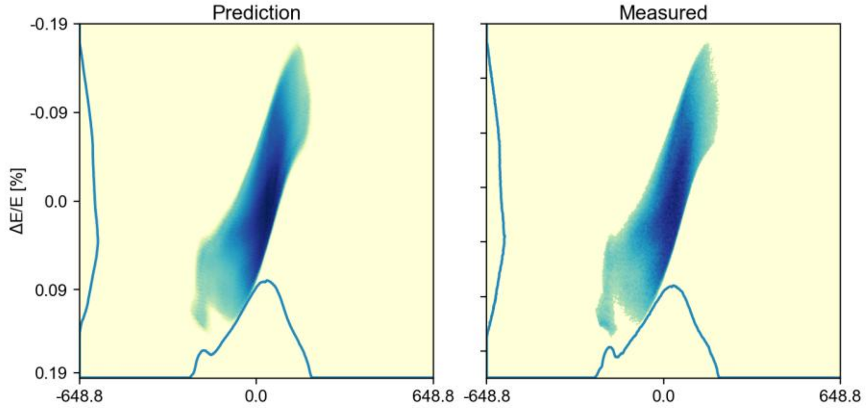
Best

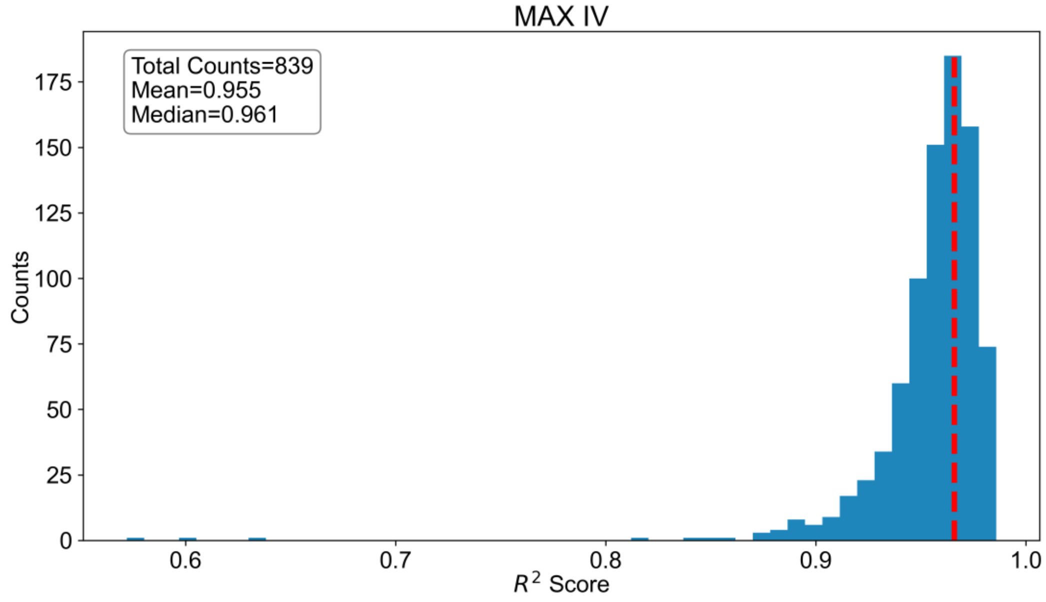


Worst

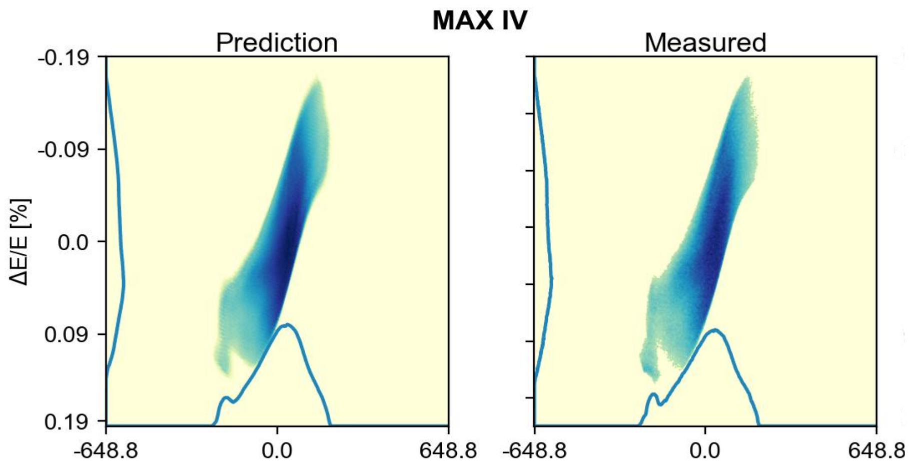


Median





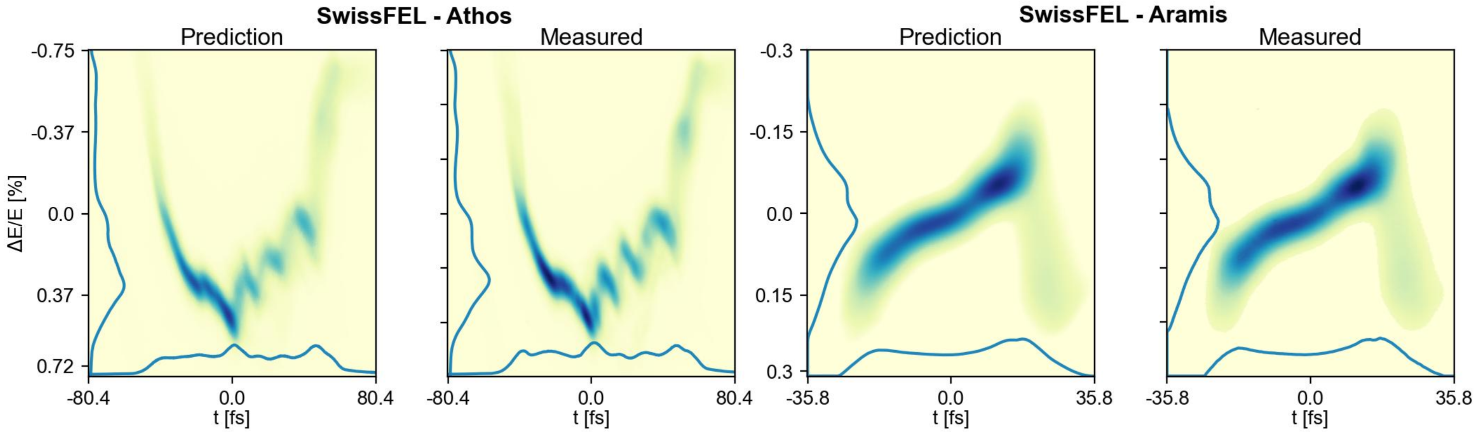
Multi-Facility Virtual Diagnostic - Involved Facilities

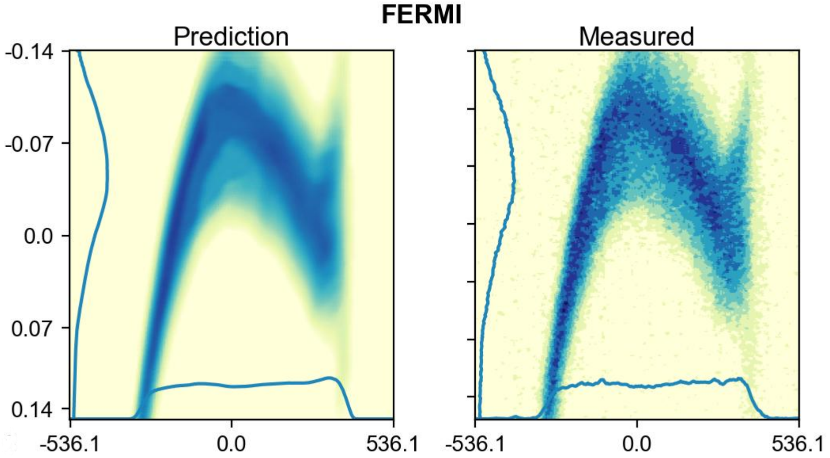


MAX IV

SwissFEL

FERMI

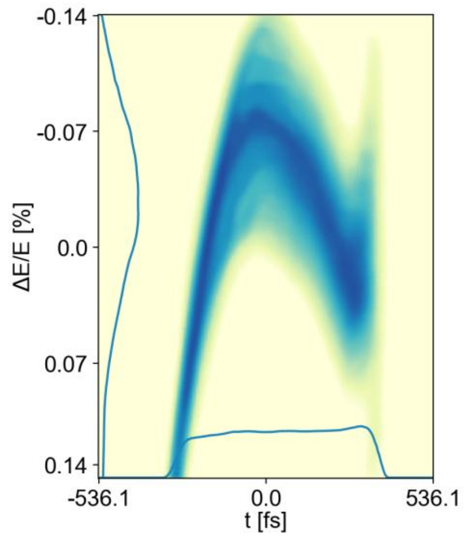




FERMI – Experimental Setup and Data

- Single Bunch Compressor (BC1) -->
  Required another scan parameter (Laser Heater)

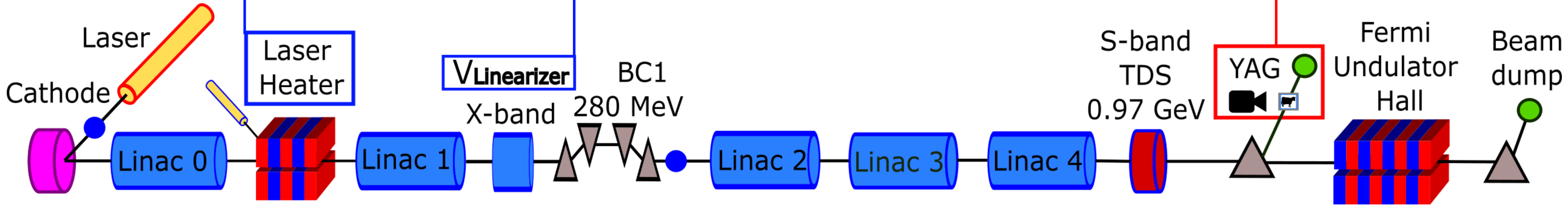
- Data: 3870x230x320 images + 97 input parameters -> 2.13 GB



TDC System

Laser Heater
Laser Heater system to scan bunch shape and energy spread.

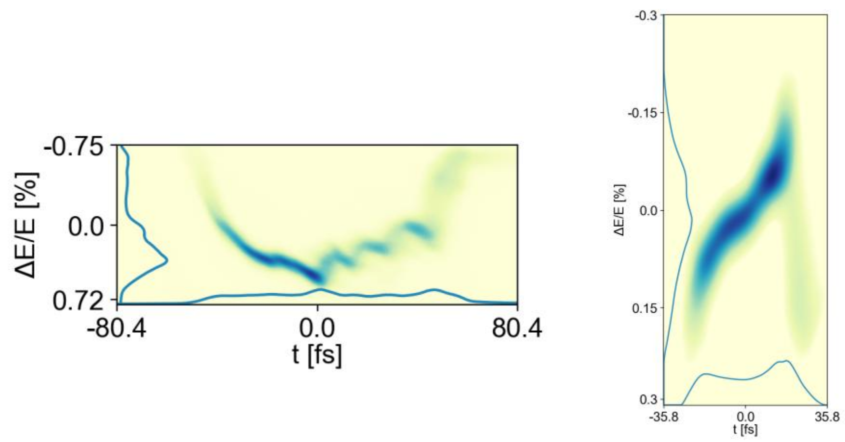
Linearizer
X-band accelerating cavity to scan compression, i.e. bunch length



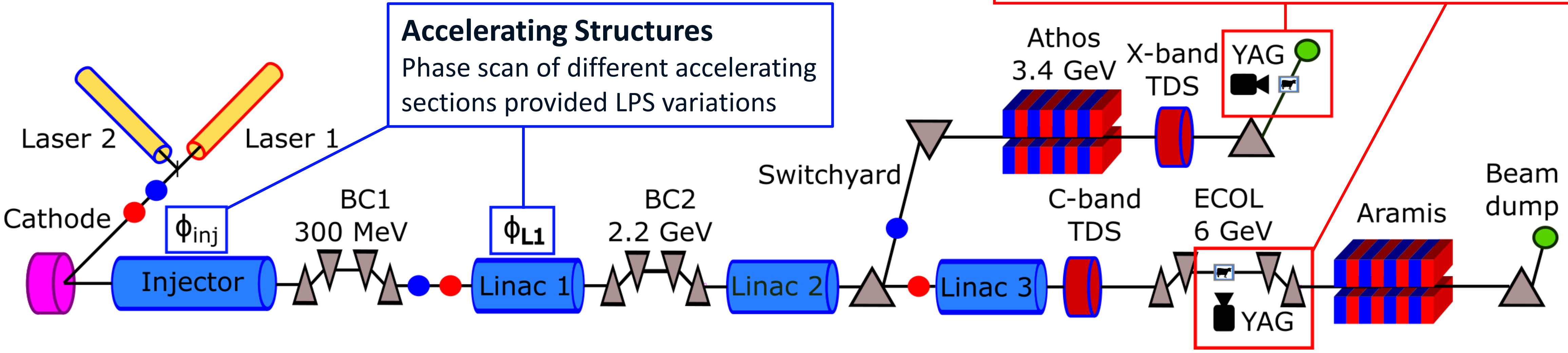
SwissFEL - Experimental Setup and Data

- Simultaneous acquisition from two different TDC systems during the same scan

- Data
  - Athos: 1750x300x750 images + 41 input parameters -> 3.07 GB
  - Aramis: 1750x250x600 images + 41 input parameters -> 2.05 GB



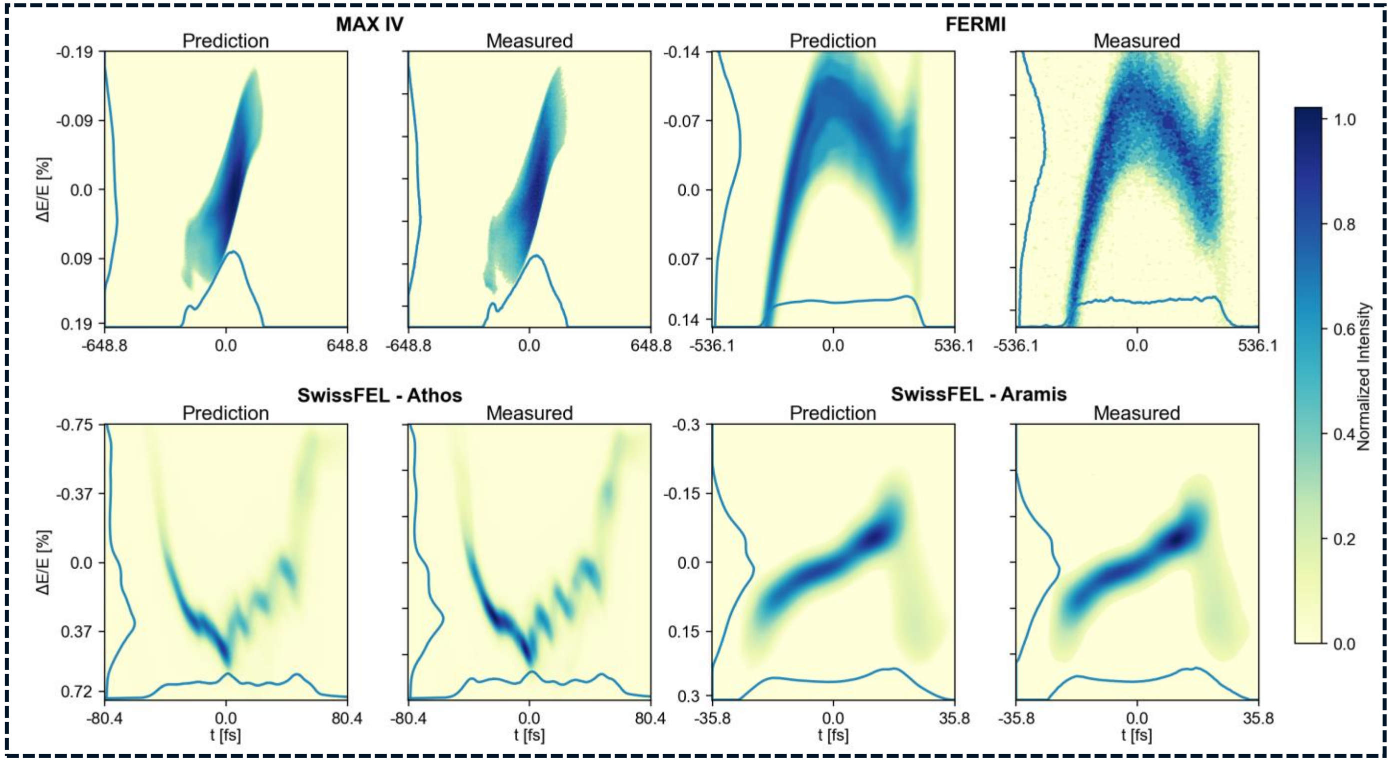
TDC Systems – Athos and Aramis

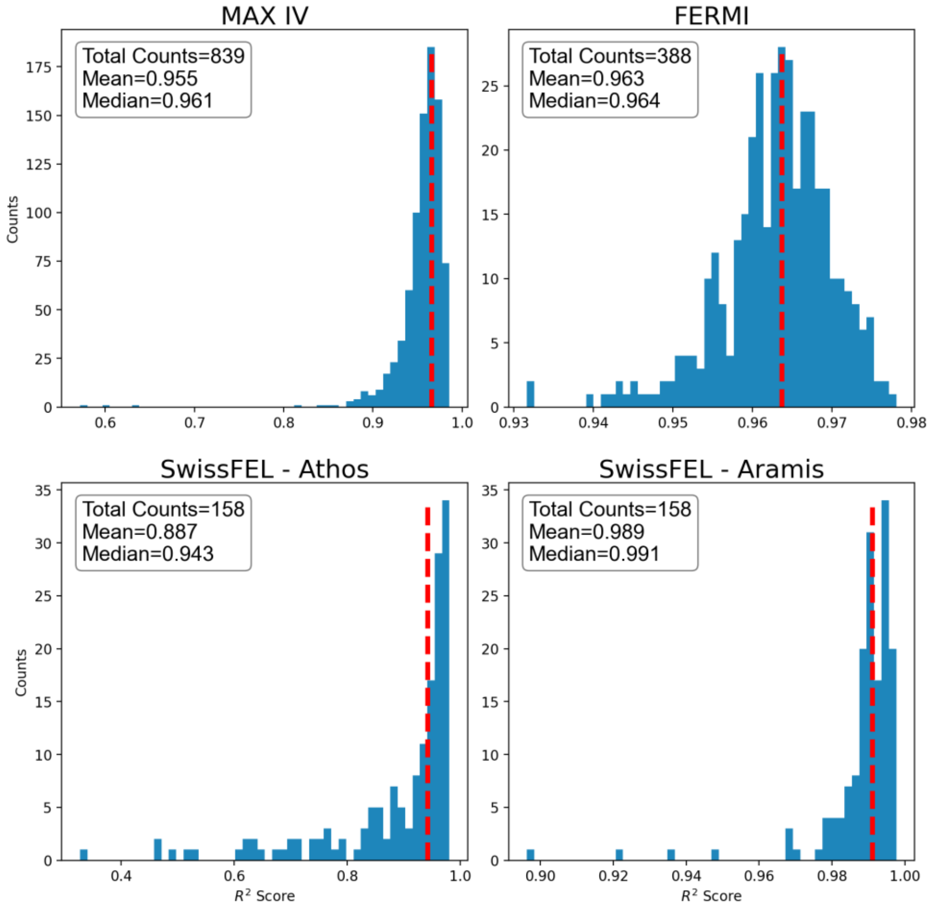


Multi-Facility Virtual Diagnostic – Final Results

R^2	MAX IV	FERMI	SwissFEL - Athos	SwissFEL - Aramis
Median	96.1%	96.4%	94.3%	99.1%
Mean	95.5%	96.3%	88.7%	98.9%

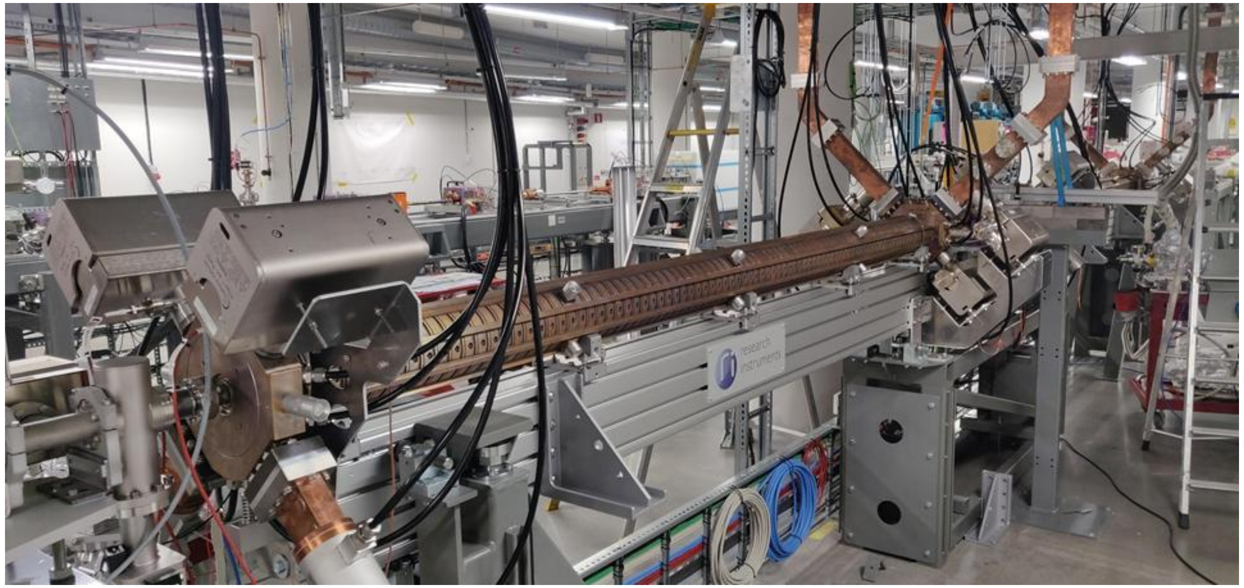
Median Images





Outlook

- Further developments for each facility:
  - MAX IV: Predictions with increased resolution using high-resolution simulations in training data.
  - SwissFEL: Lasing predictions, predicting the profile of the X-Ray pulses.
  - FERMI: Predictions at different energies, 0.97 GeV and 1.1 GeV complete and ready for training.



- General VD development:
  - Usability in controlrooms and daily operations.
  - Feedbacks on LPS shapes, constant online control.

Thank you!

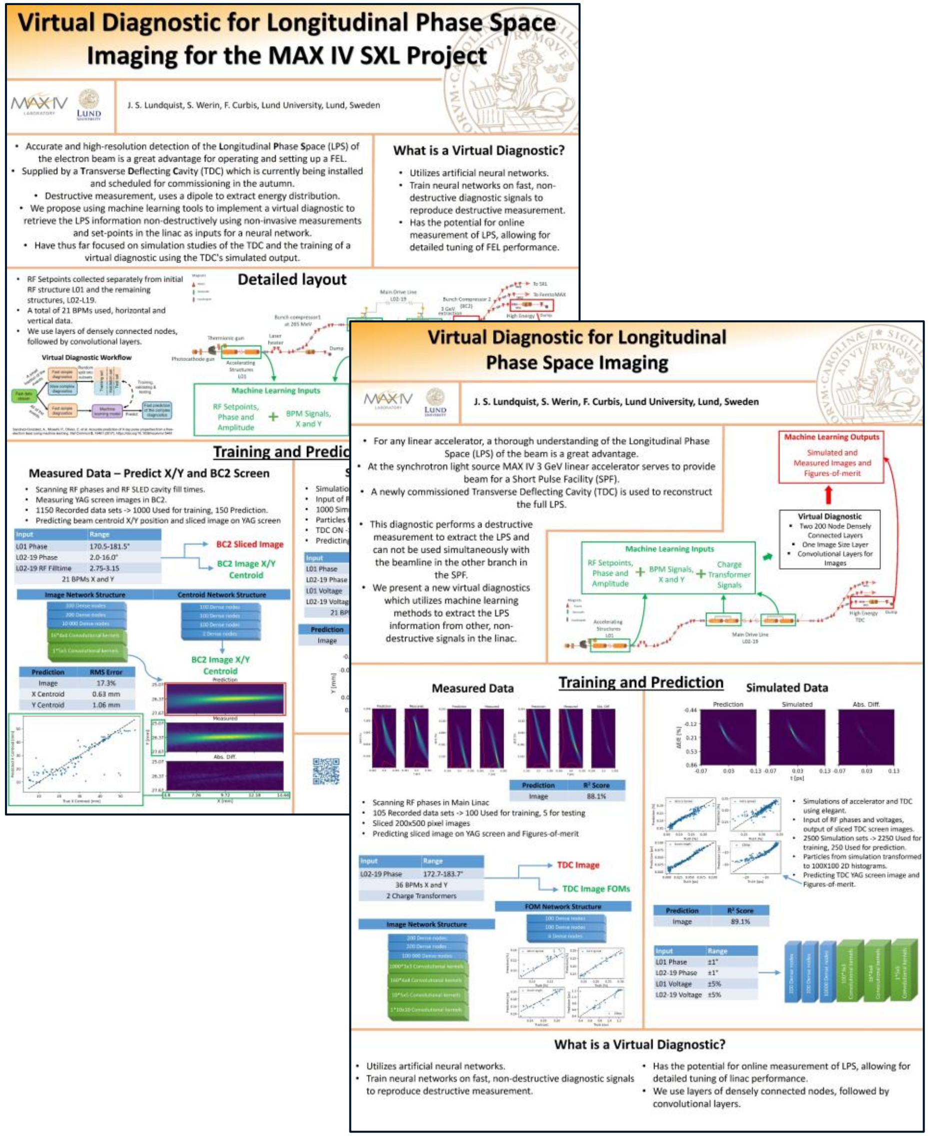
Proceedings articles:

J. Lundquist, S. Werin, and F. Curbis. “Virtual Diagnostic for Longitudinal Phase Space Imaging for the MAX IV SXL Project”. English. In: *Proc. FEL2022* (Trieste). International Free Electron Laser Conference 40. JACoW Publishing, Geneva, Switzerland, Aug. 2022, pp. 437–440. ISBN: 978-3-95450-220-2. DOI: 10.18429/JACoW-FEL2022-WEP25. URL: https://indico.jacow.org/event/44/contributions/420.

J. Lundquist, F. Curbis, and S. Werin. “Virtual diagnostics for longitudinal phase space imaging”. In: *Proc. IPAC’23* (Venice, Italy). International Particle Accelerator Conference 14. JACoW Publishing, Geneva, Switzerland, Sept. 2023, pp. 4471–4474. ISBN: 978-3-95-450231-8. DOI: 10.18429/JACoW-IPAC2023-THPL022.

Manuscript recently submitted to
Physical Review Accelerators and Beams:

“Multi-Facility Virtual Diagnostics for Longitudinal Phase Space Predictions”

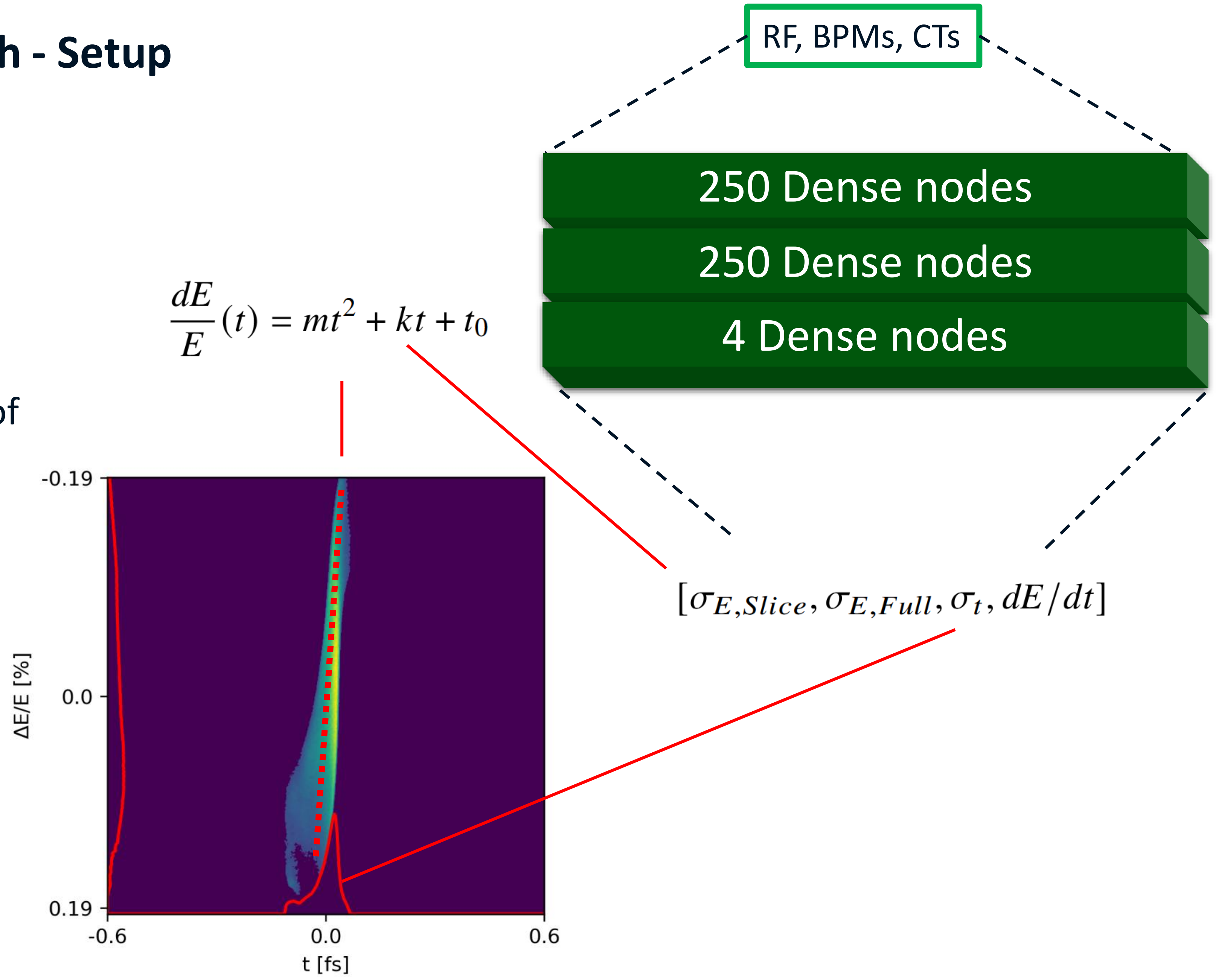


Network Hyperparameters

Category	Parameter	Value	Description
Data	Train/Test Split	0.9 test size	90% test, 10% train after cleaning
	Shuffle	True	Randomize before split
	Random State	1	Seed for reproducibility
Model Architecture	Layer 1	Dense(100, activation='relu')	Fully connected layer
	Layer 2	BatchNormalization()	Normalize activations
	Layer 3	Dense(100, activation='relu')	Fully connected layer
	Layer 4	Dense(np.prod(im_shape))	Output to match flattened image size
	Reshape 1	(im_shape[0]/2, im_shape[1]/2, 4)	Reduce spatial resolution, add channels
	Conv2D 1	4 filters, (4×4), relu, same	Convolution layer
	Reshape 2	(im_shape[0], im_shape[1], 1)	Restore image size
	Conv2D 2	1 filter, (5×5), relu, same	Output convolution
Training	Optimizer	Adam (legacy)	Adaptive optimizer
	Learning Rate	1.5×10^{-2}	Initial step size
	Clip Norm	1	Gradient clipping norm
	Loss Function	MAE	Mean Absolute Error
	Batch Size (train)	32	Mini-batch size
	Batch Size (no-train mode)	5000	Used if `trainb=False`
	Epochs	40 (train), 1 (no-train)	Training iterations
	Validation Split	0.01	For monitoring `val_loss`
Callbacks	ModelCheckpoint	Save best weights (`val_loss`)	Monitors validation loss
	LearningRateScheduler	decay_rate=0.5, decay_step=10	Halves LR every 10 epochs
Custom Metrics	`mssim2`	inverse mean SSIM	Image similarity metric
Post-processing	Image Alignment	2D cross-correlation + shift	Align predictions to measurements

Beam Parameter Approach - Setup

- Computationally heavy to predict full LPS images, perhaps unnecessary
- Predict beam parameters of interest instead
- RMS in both planes and energetic chirp



Beam Parameter Approach - Results