Workshop on Accelerator Physics

Virtual Accelerator Diagnostics using Machine Learning

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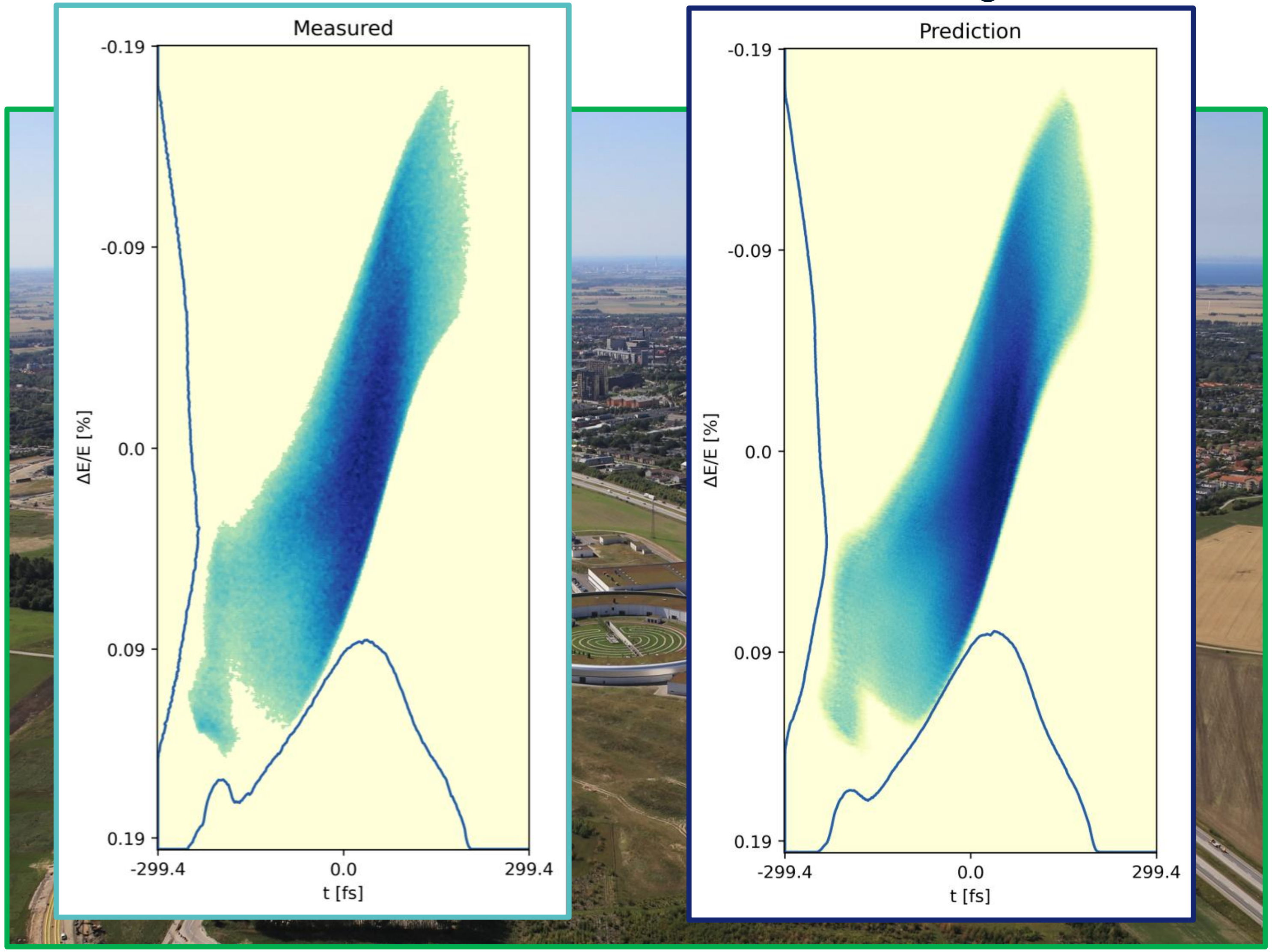
Overview

- Introduction
  - MAX IV Linac
  - Transverse Deflector
  - Virtual Diagnostic
- MAX IV Virtual Diagnostic
- Multi-Facility Application
  - Beam Parameter Predictions
- Conclusion

Real Destructive Measurement

Machine Learning Prediction

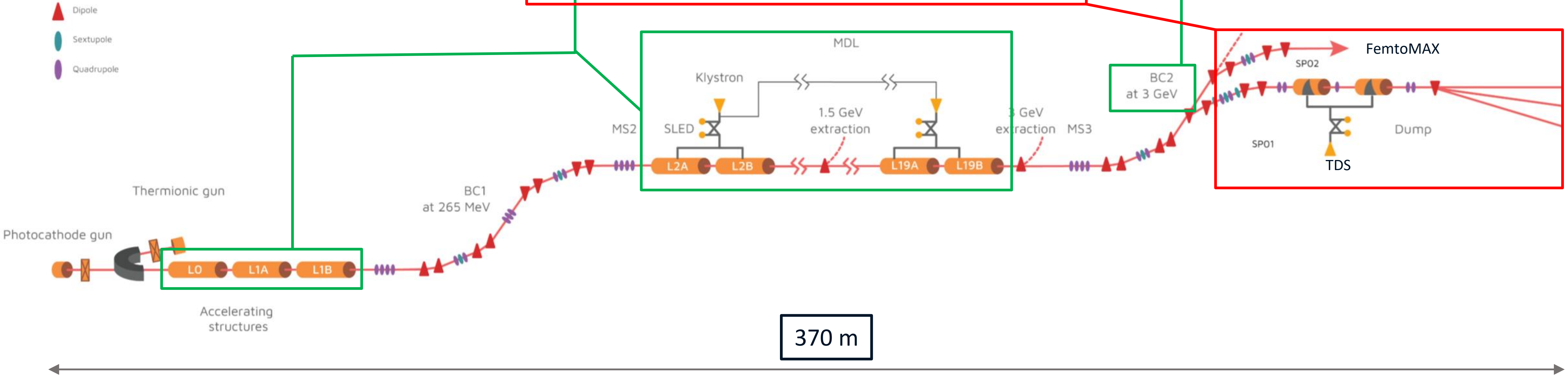


MAX IV – Linear Accelerator

Acceleration
40 S-band normal conducting RF structures. 265 MeV at first bunch compressor, 3 GeV at the second.

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

Bunch Compressors
Arc-like bunch compressors allow for tunable, non-linear compression.

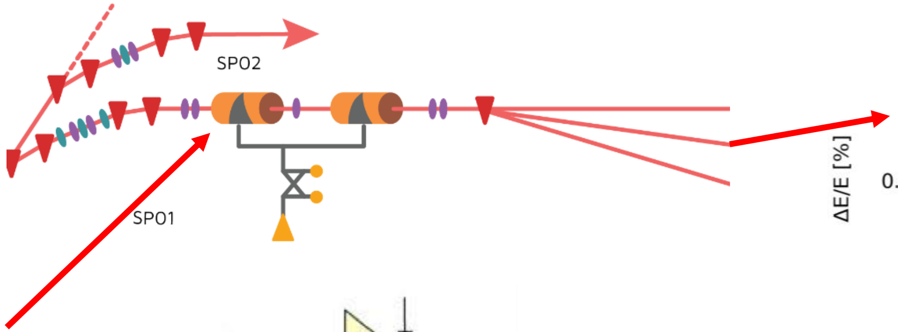


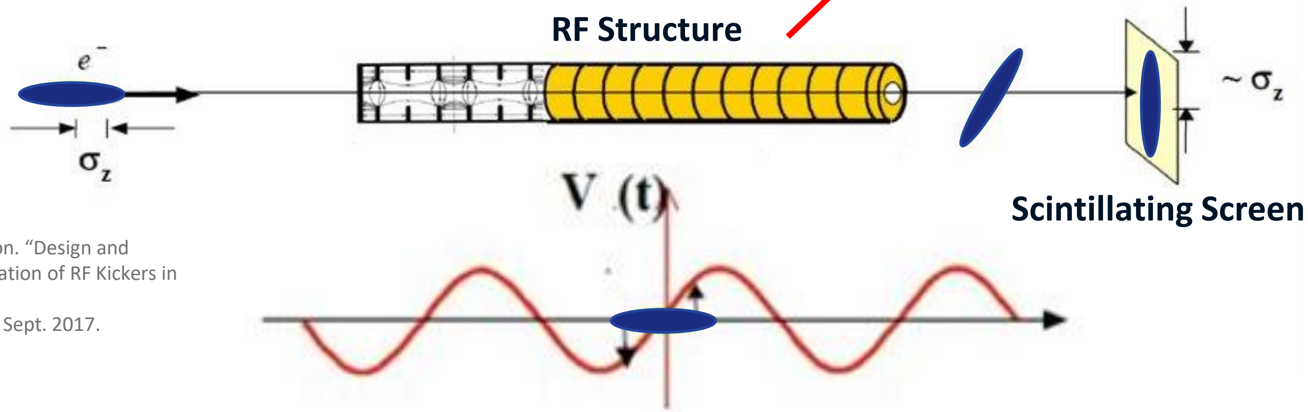
MAX IV – Transverse Deflecting Structure

- MAX IV TDS line includes two 3 m deflecting structures. Presented in more detail in E. Mansten IBIC’23.

- 3 separate branches with multiple YAG screens for varied dispersion and streak

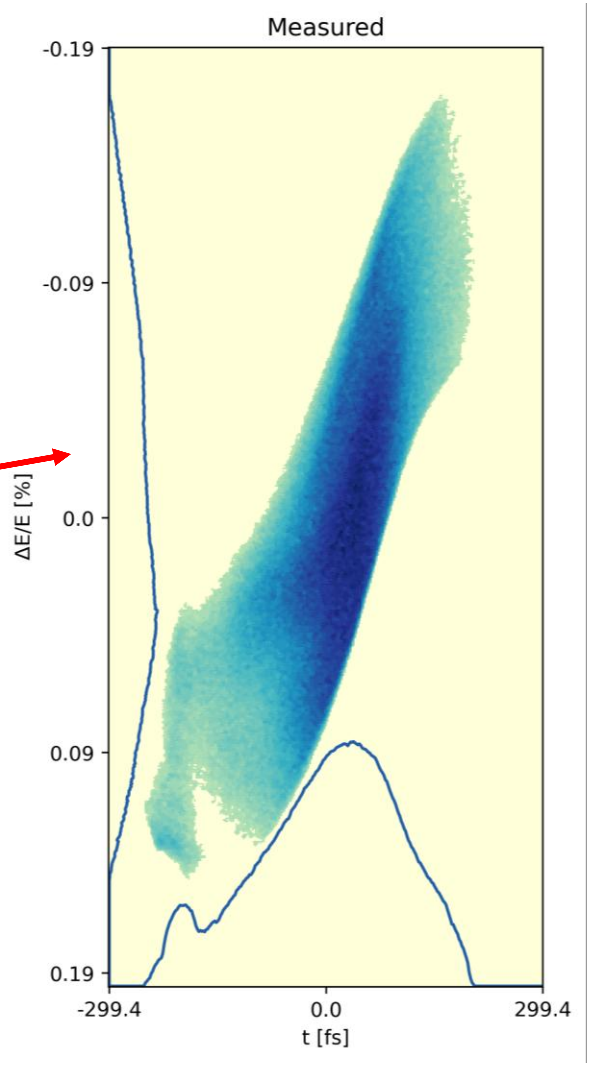
- Parameters for data:
  - Streak parameter 2.92 $\frac{\mu\mathrm{m}}{\mathrm{fs}}$
  - Dispersion 1.02 m





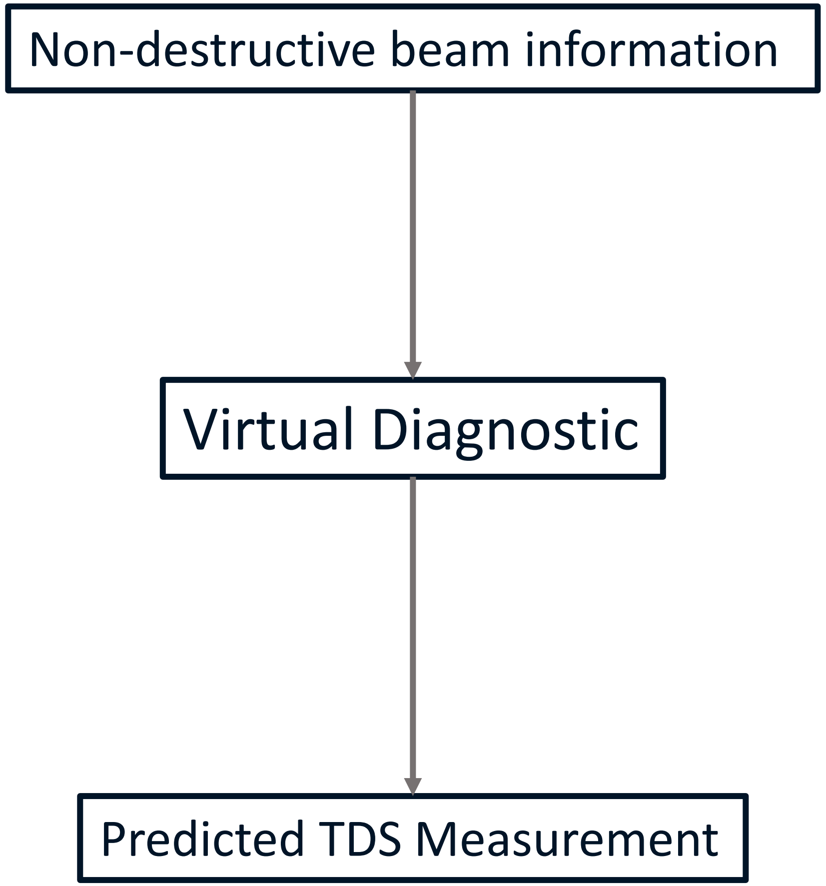
David Olsson. “Design and Implementation of RF Kickers in MAX IV”. PhD thesis. Sept. 2017.

Longitudinal Phase Space



LPS Virtual Diagnostic – Motivation

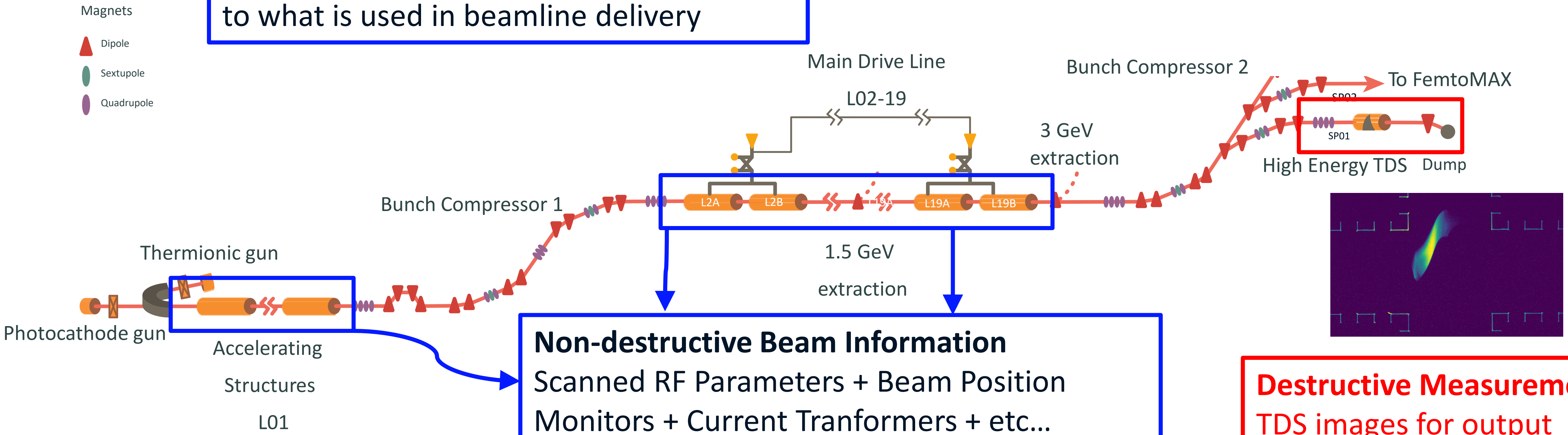
- A full longitudinal understanding of the beam is often critical for Linac and FEL operations
- MAX IV has separate branch for TDS, can not measure LPS online during delivery
- **A Virtual Diagnostic (VD) would allow online measurement of LPS**
- **VD could be used for operations and feedback during delivery**



LPS Virtual Diagnostic – Experimental Setup

MAX IV		
Parameter	Range	Steps
L01 Phase	$\pm 3.97°$	30
MDL Phase	$\pm 3.18°$	30
L01 Filltime	$\pm 0.1\,\mu s$	–
MDL Filltime	$\pm 0.25\,\mu s$	–

Scanning RF phases before BC1 and BC2
This provides similar range of LPS shapes to what is used in beamline delivery



Non-destructive Beam Information
Scanned RF Parameters + Beam Position Monitors + Current Tranformers + etc…

Destructive Measurement
TDS images for output

Virtual Diagnostic

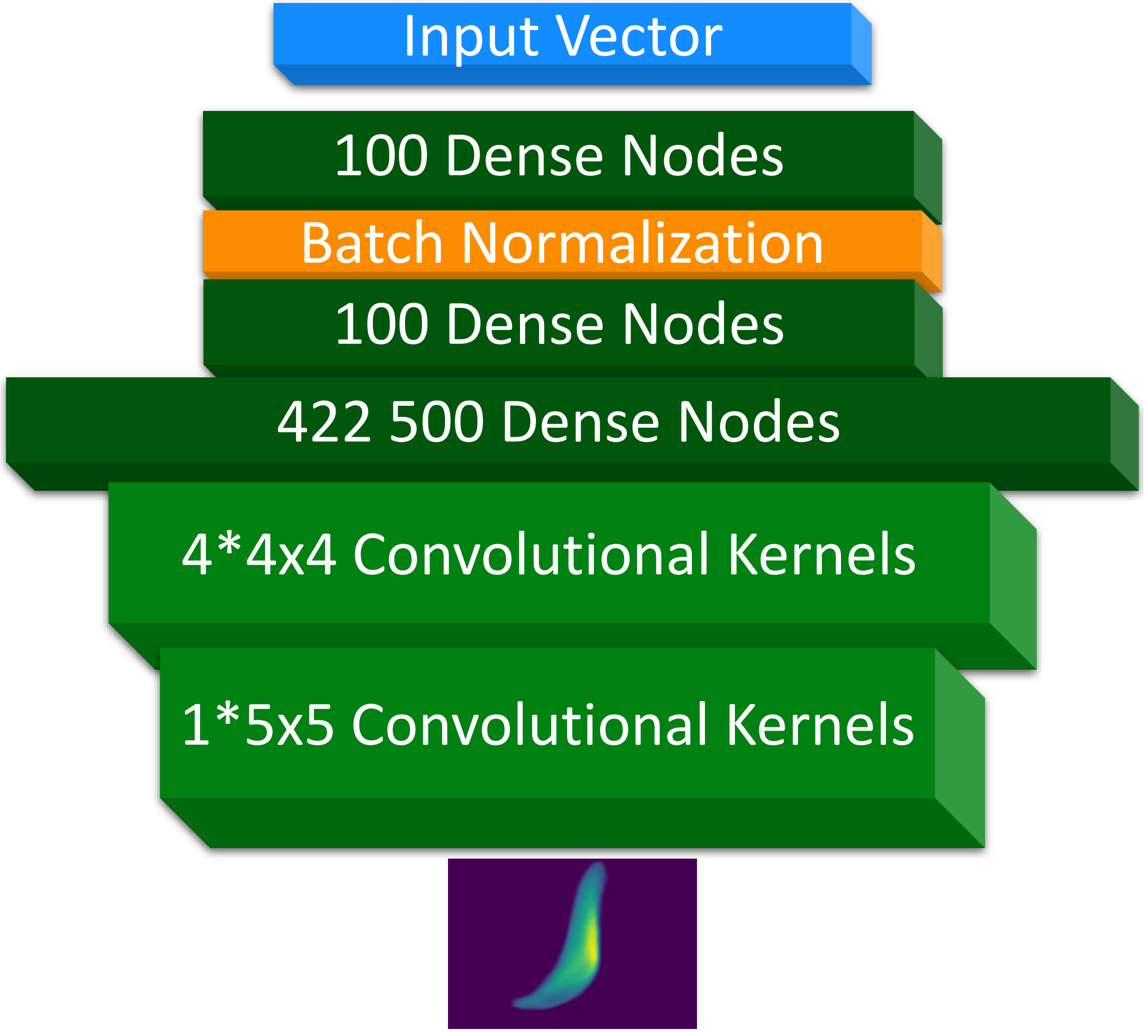
- 9000 images collected, ~6 hour beamtime
  - HDF5 set with 9000x650x650 images + 108 input params

VD - Network Structure and Training

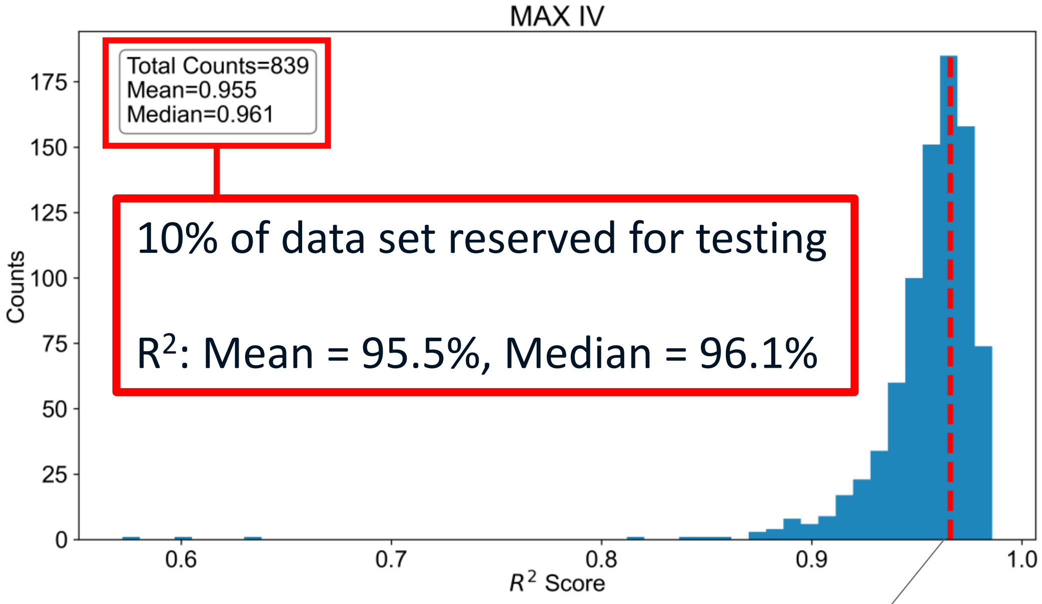
- Dense Net + CNN trained with ADAM and MAE
  - Used scheduled learning rate and checkpoints for early stopping
  - Post-processing: Align beam distributions using cross-correlation

- Large image size layer
  - Extends training time
  - Required for full LPS images
  - Could be smaller -> lower resolution

- Networks trained on LUNARC HPC Cluster
  - Training time on Nvidia A100 ~10 minutes
  - Training time on Laptop CPU ~1-2 hours



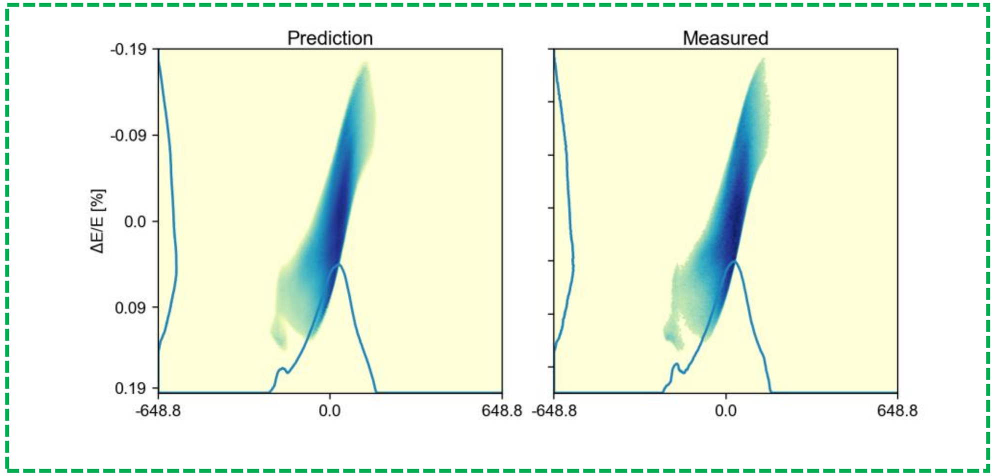
MAX IV – LPS Predictions



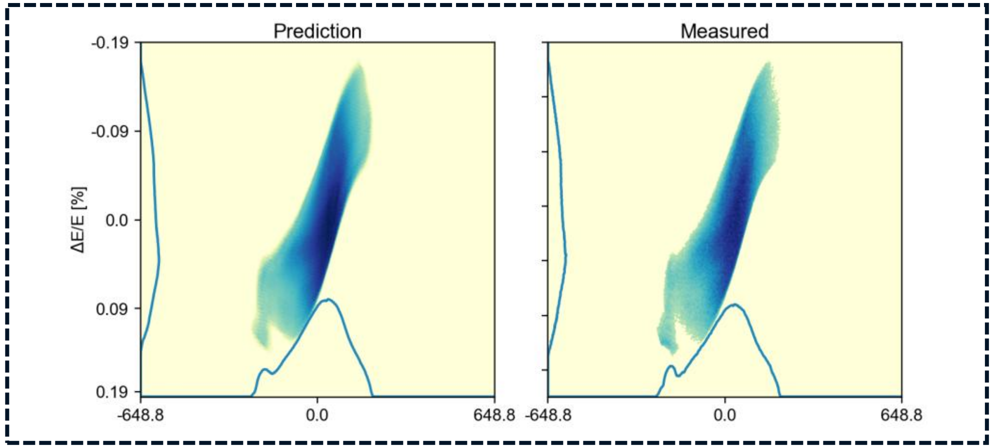
10% of data set reserved for testing

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

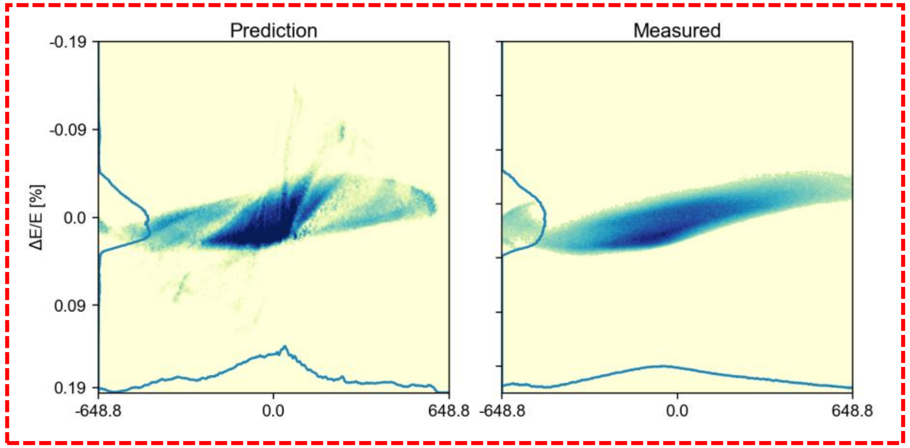
Best



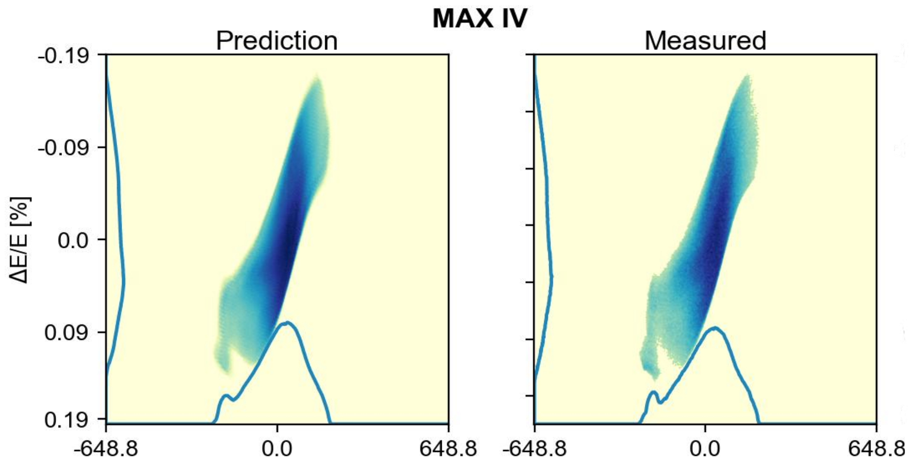
Median



Worst



Multi-Facility Virtual Diagnostic - Involved Facilities



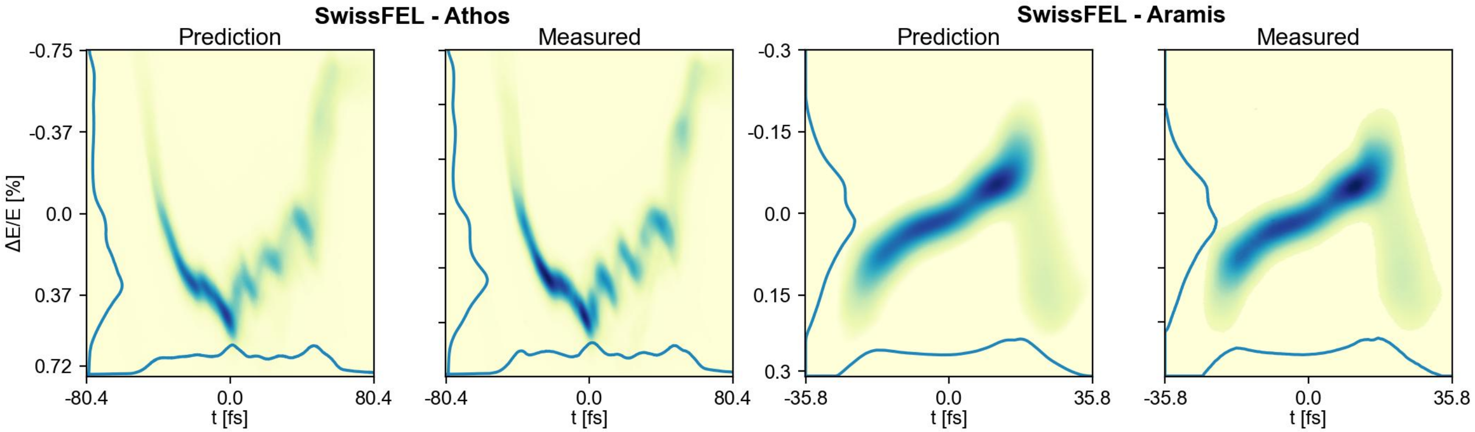
MAX IV

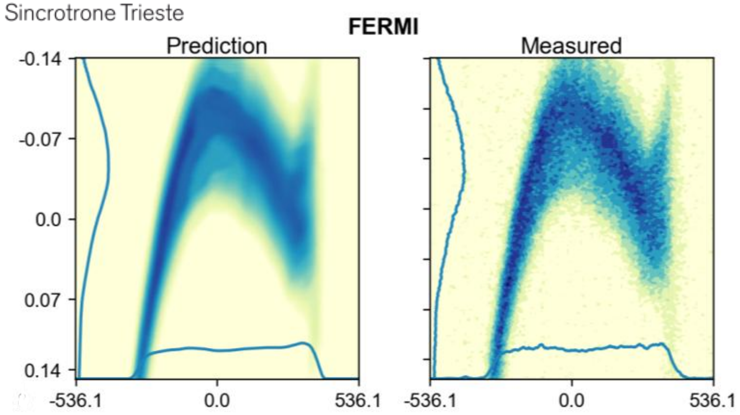
PSI

SwissFEL

FERMI

Elettra Sincrotrone Trieste

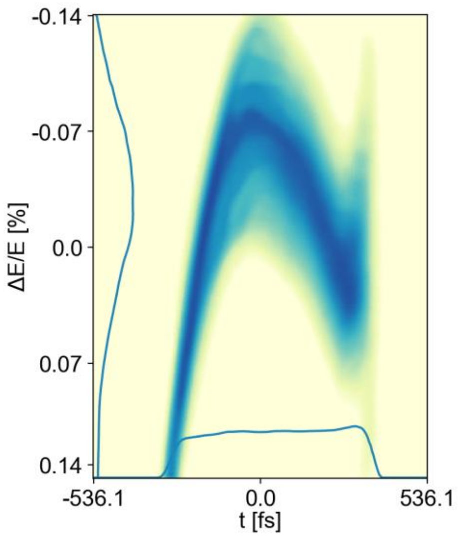




FERMI – Experimental Setup and Data

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

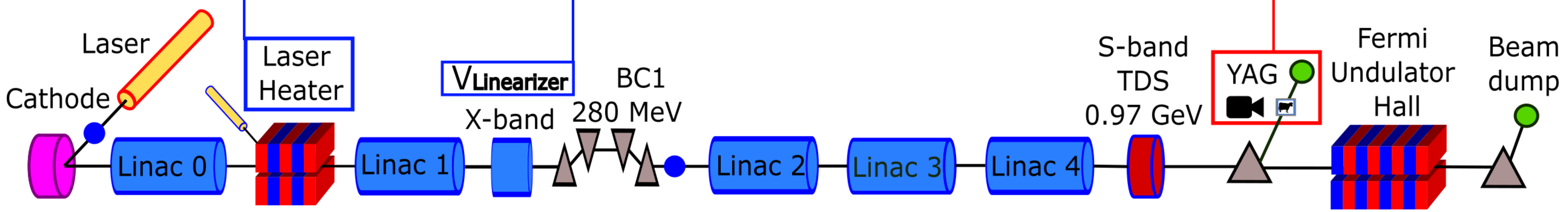
- Data: 3870x230x320 images + 97 input parameters
  - Streaking param: $2.33\ \frac{\mu m}{fs}$, Dispersion: 1.72 m



TDS System

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

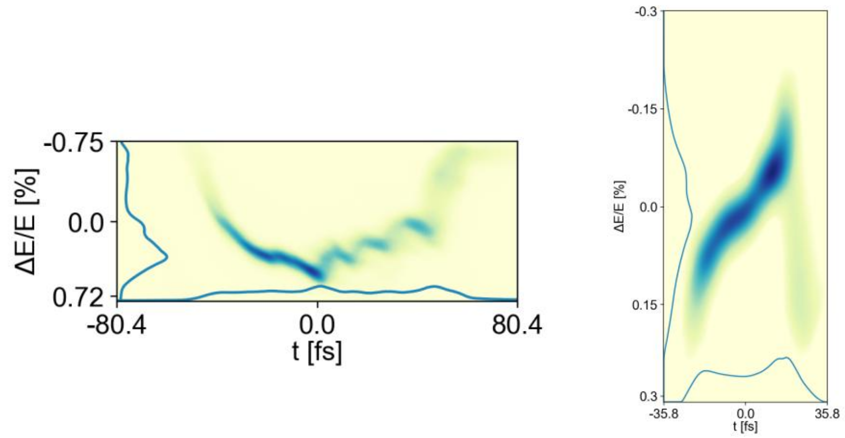
Linearizer
X-band accelerating cavity to scan compression using BLM feedback.



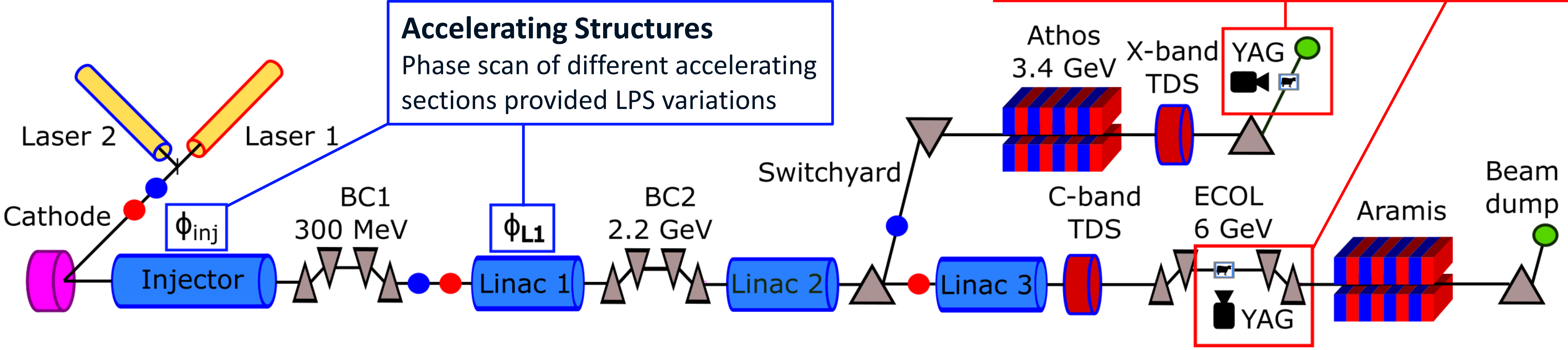
FERMI		
LH Laser Energy	0–10 μJ	20
BLM Reading	$1.5 \cdot 10^6$–$4 \cdot 10^6$	20

SwissFEL - Experimental Setup and Data

- Simultaneous acquisition from two different TDS systems during the same scan
- Data
  - Athos: 1750x300x750 images + 41 input parameters
    - Streaking param: $41.2\ \frac{\mu m}{fs}$, Dispersion: 0.18 m
  - Aramis: 1750x250x600 images + 41 input parameters
    - Streaking param: $30.8\ \frac{\mu m}{fs}$, Dispersion: 0.88 m



TDS Systems – Athos and Aramis



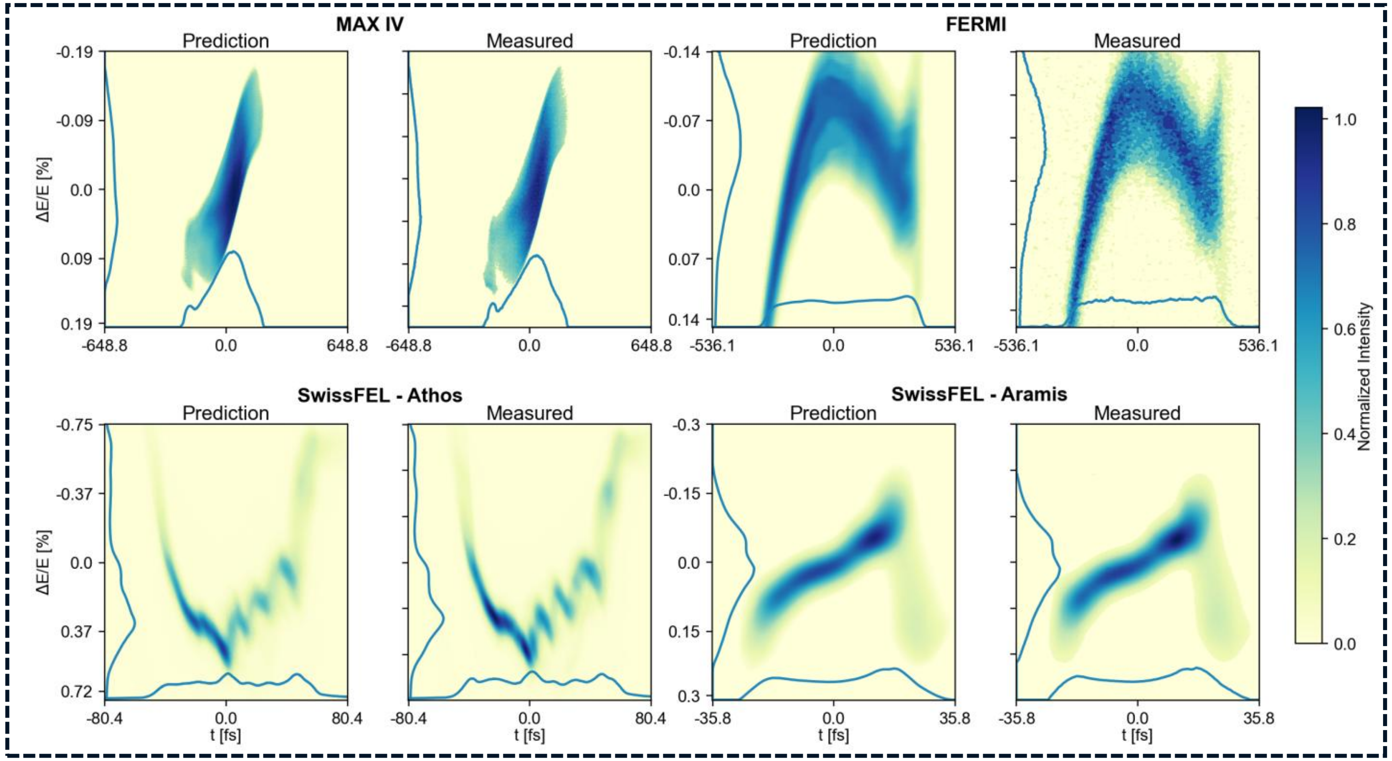
SwissFEL

Injector Phase	$\pm 0.2^\circ$	≈ 18
Linac 1 Phase	$\pm 0.3^\circ$	≈ 18

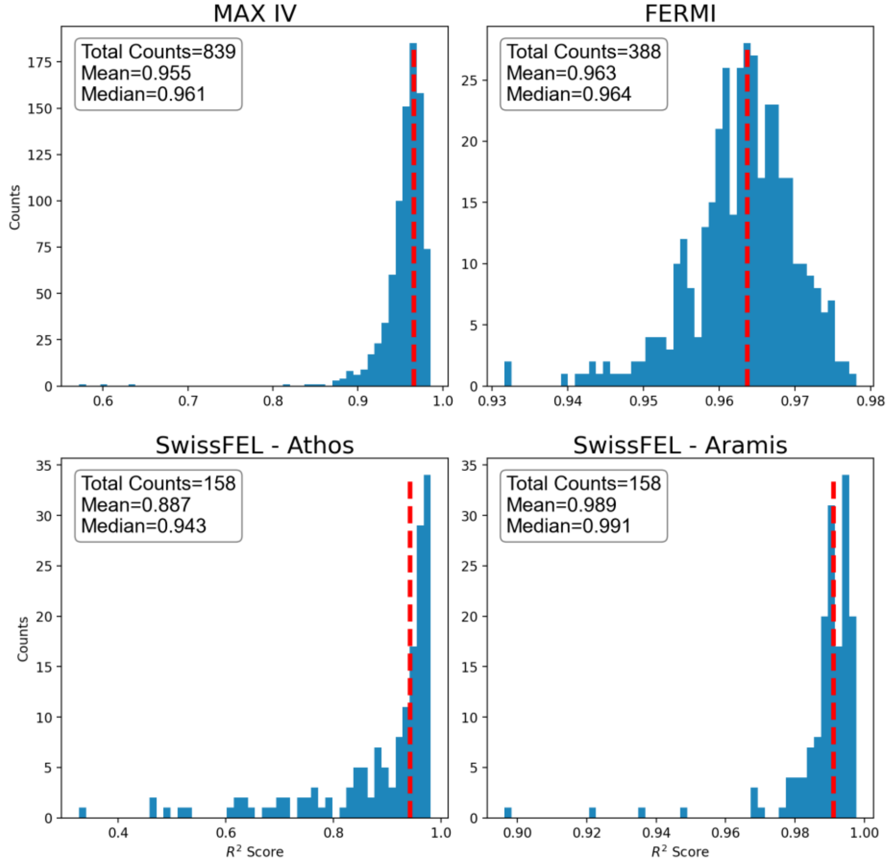
Multi-Facility Virtual Diagnostic – Final Results

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

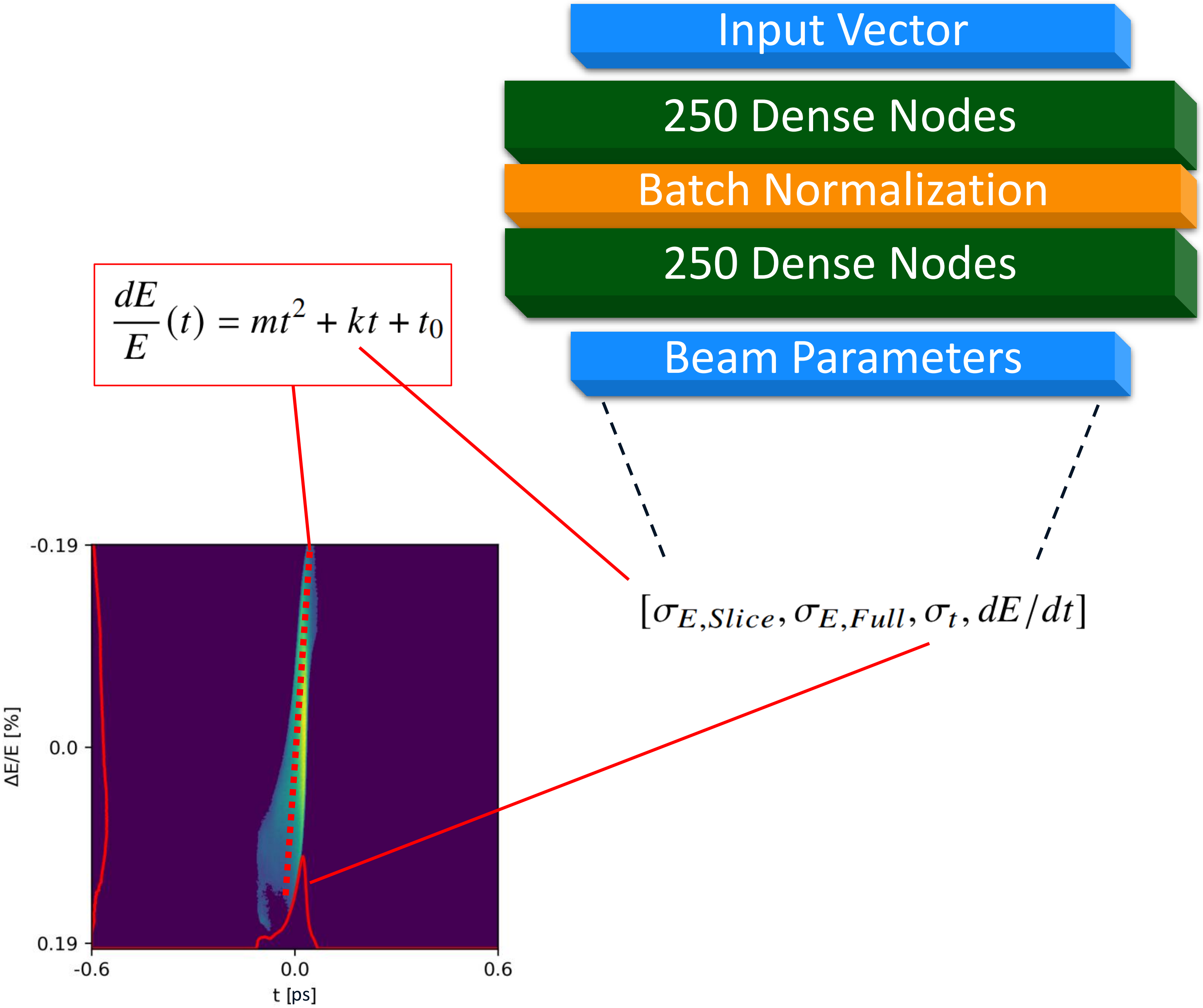


Performance on 10% of each full dataset



Beam Parameter Approach - Setup

- Computationally heavy to predict full LPS images, perhaps unnecessary
- Predict beam parameters of interest instead
- RMS in both planes and energy chirp
  - Extracted from all datasets
- Training times <5 min on laptop CPU



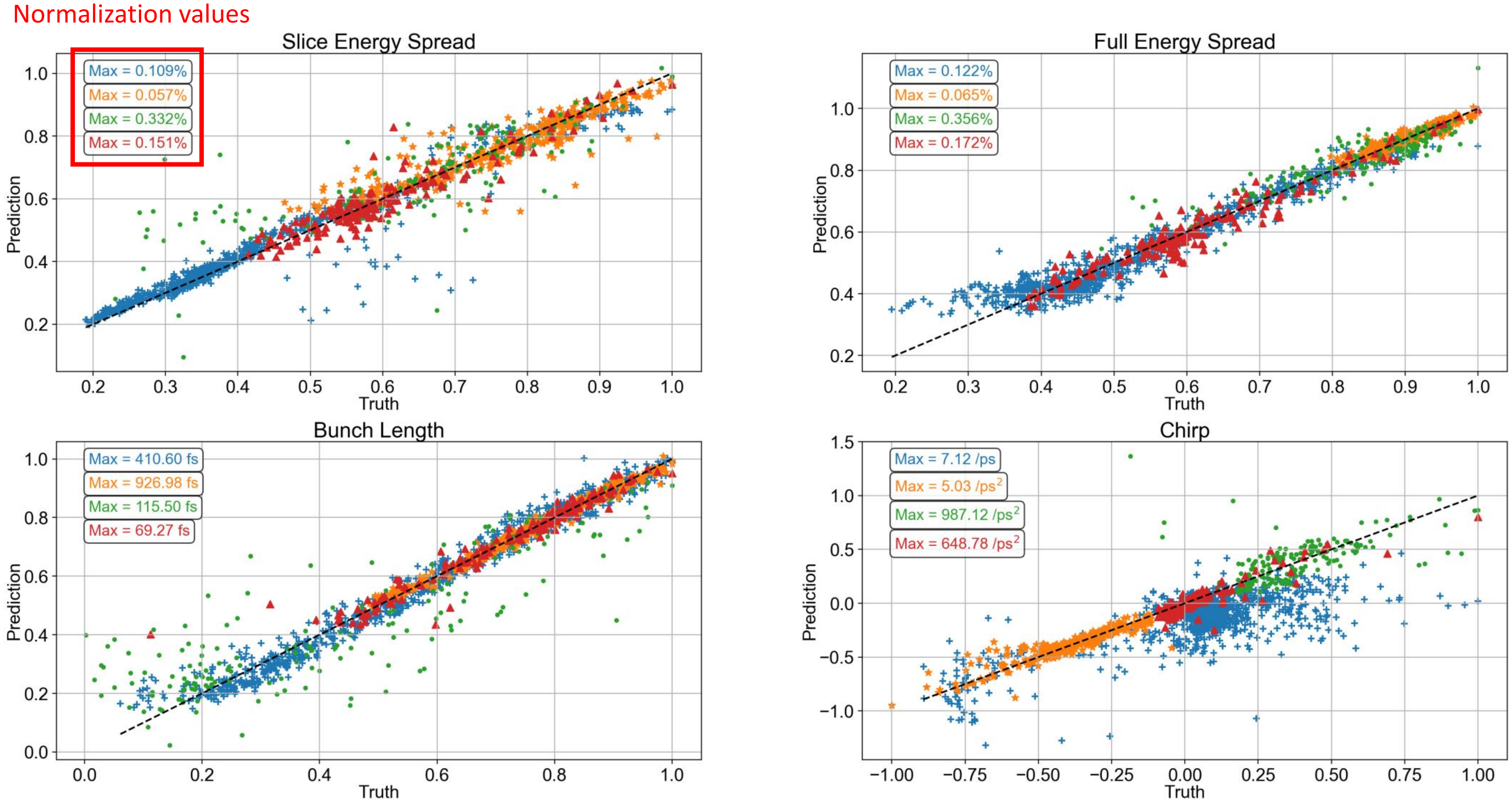
Beam Parameter Approach - Results

MAX IV

FERMI

SwissFEL - Aramis

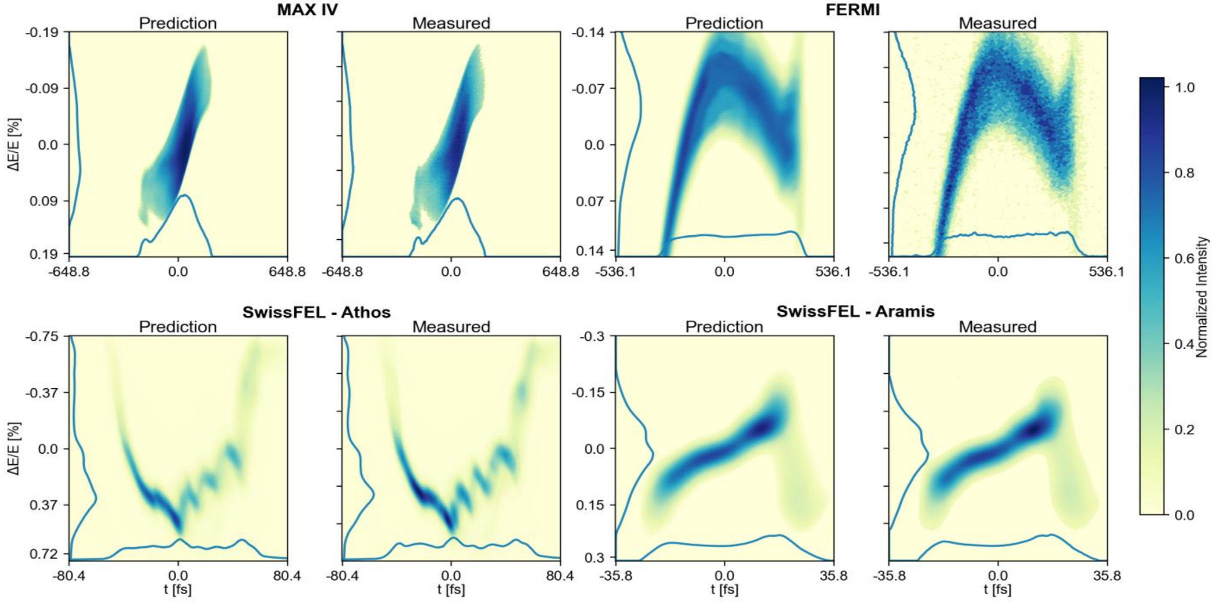
SwissFEL - Athos

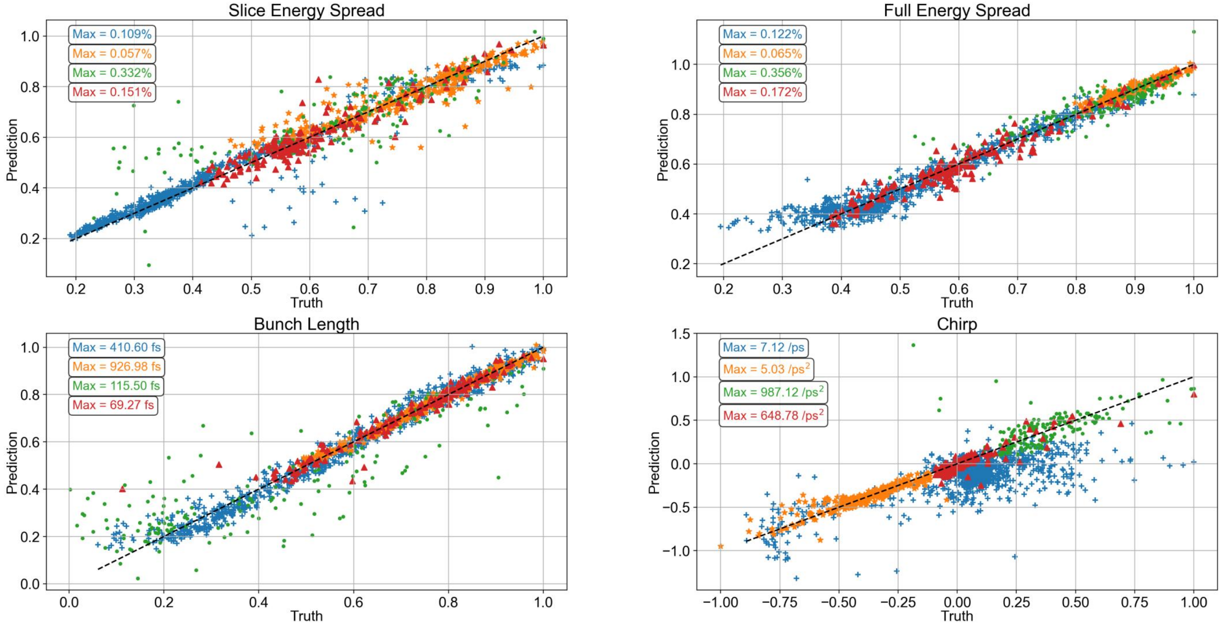


Summary and Outlook

- VDs produced, trained and working for three facilities
- Two approaches, both fully functional

- Further developments for each facility:
  - MAX IV: Bayesian Optimization with VD.
  - SwissFEL: X-Ray profile predictions. Dechirper calibration.
  - FERMI: Predictions at different energies.
- General VD development:
  - Usability in controlrooms and daily operations.
  - Feedbacks on LPS shapes, constant online control.





Thank you!

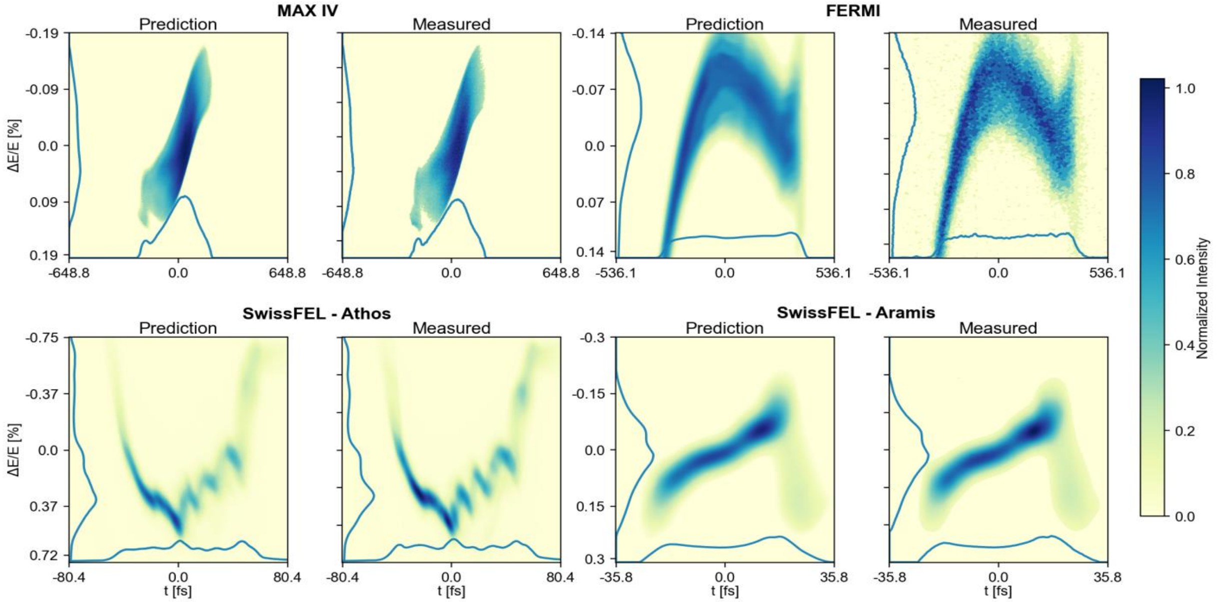
Proceedings articles:

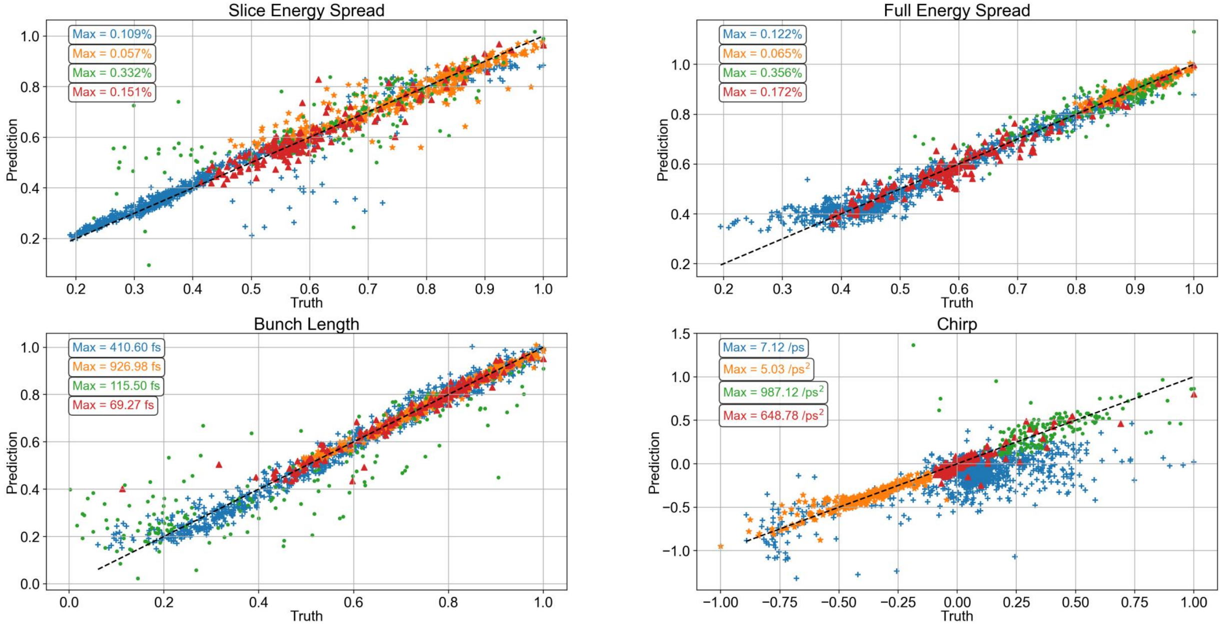
Lundquist *et al.*, FEL2022
“Virtual Diagnostic for Longitudinal Phase Space Imaging for the MAX IV SXL Project”

Lundquist *et al.*, IPAC’23
“Virtual Diagnostics for Longitudinal Phase Space Imaging”

Manuscript pending:

“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

Parameter Scans

MAX IV		
Parameter	**Range**	**Steps**
L01 Phase	$\pm 3.97^\circ$	30
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L01 Filltime	$\pm 0.1\,\mu s$	–
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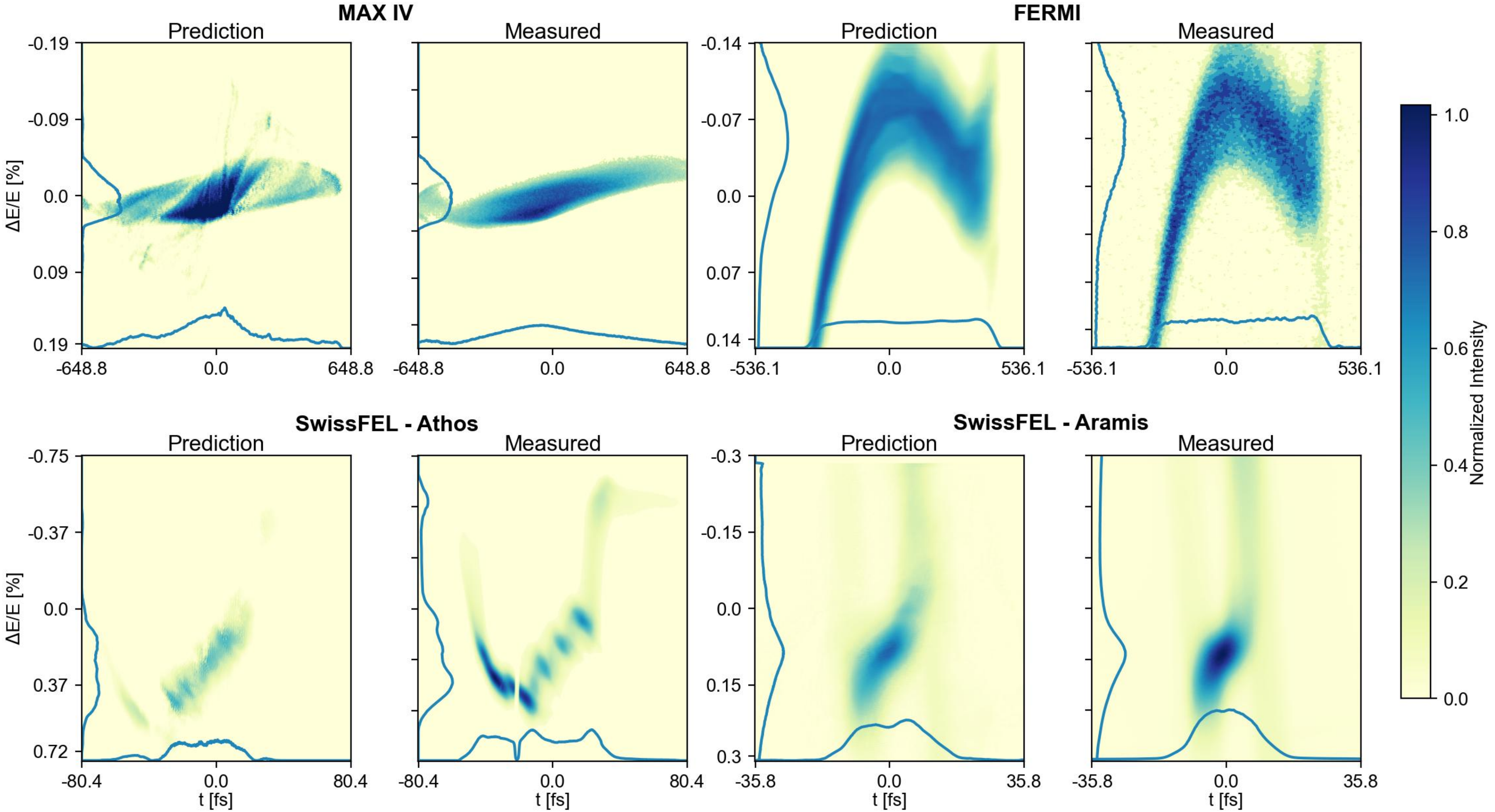
FERMI		
LH Laser Energy	0–$10\,\mu J$	20
BLM Reading	$1.5 \cdot 10^6$–$4 \cdot 10^6$	20
SwissFEL		
Injector Phase	$\pm 0.2^\circ$	≈ 18
Linac 1 Phase	$\pm 0.3^\circ$	≈ 18

MFVD - Worst Predictions



Beam Parameter Approach – Results – Error Histograms

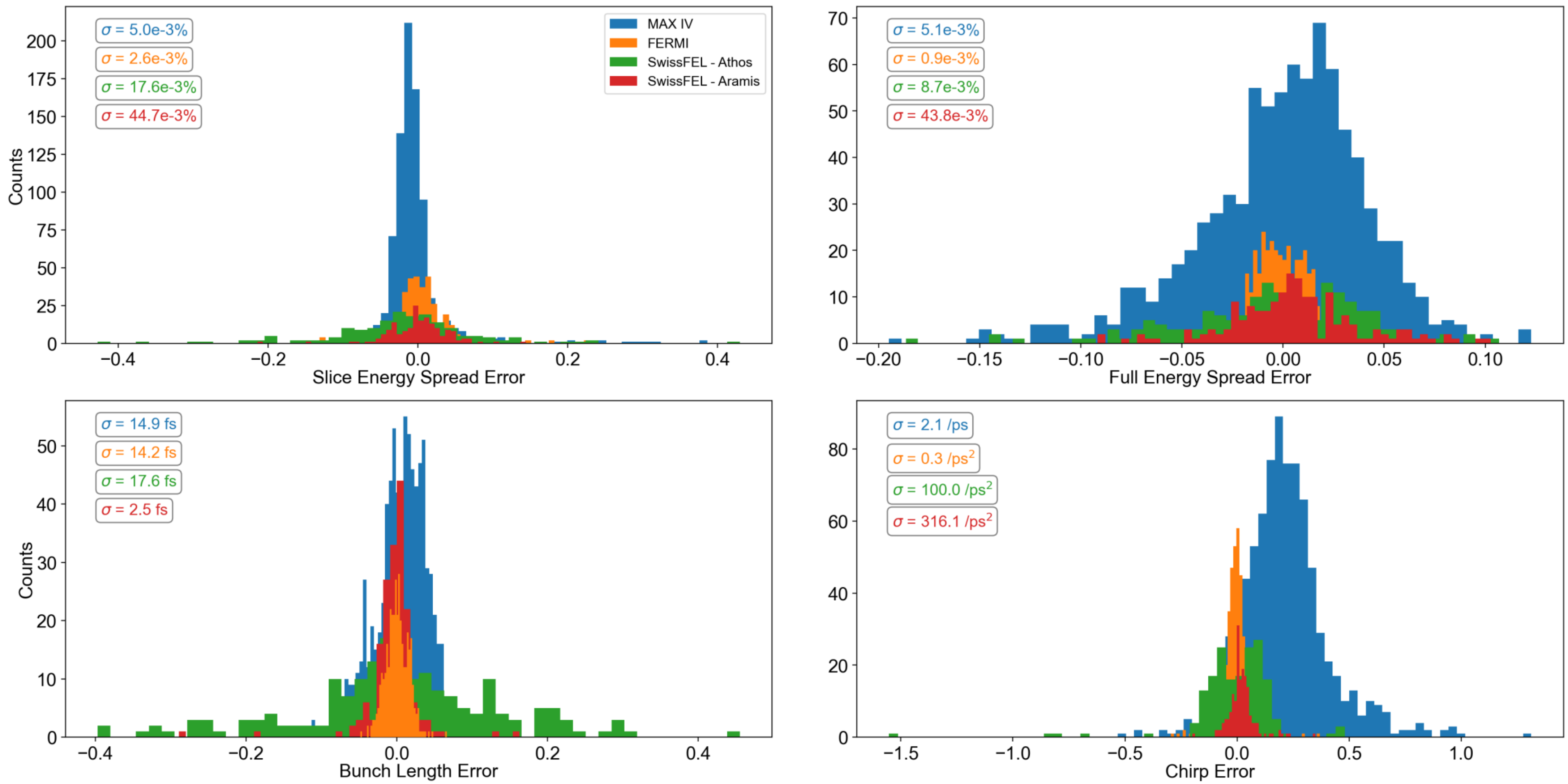
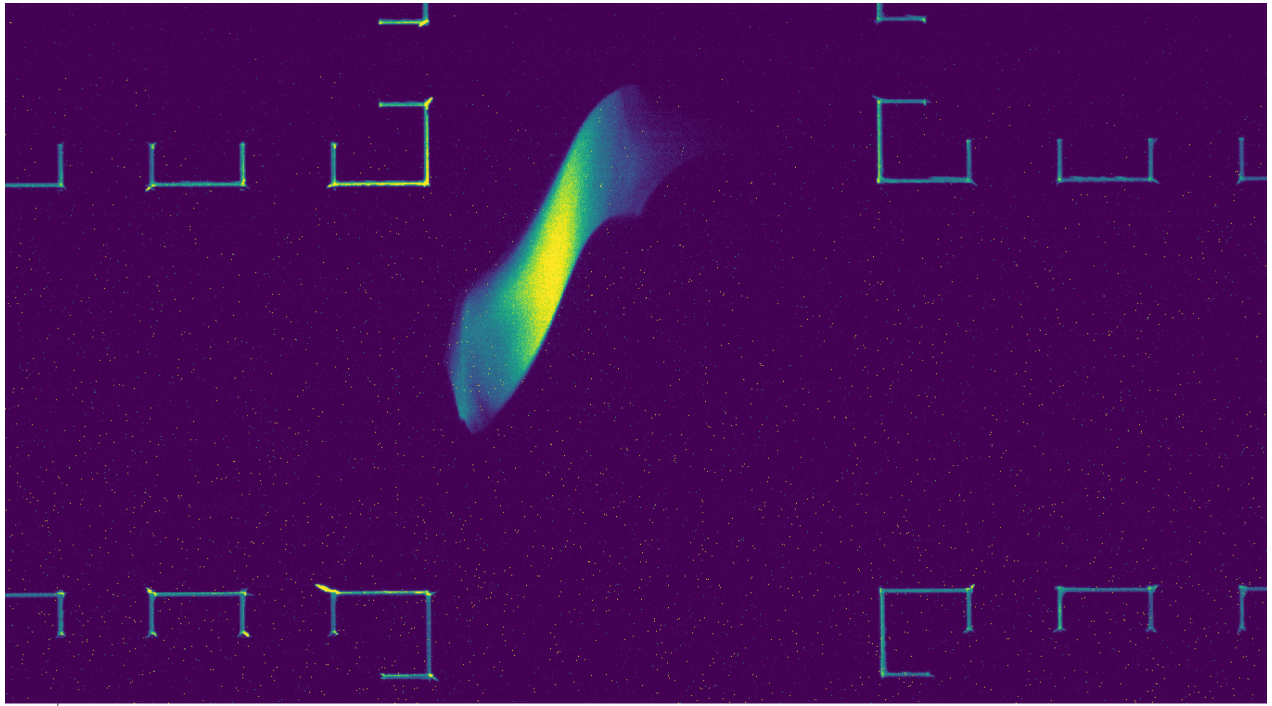
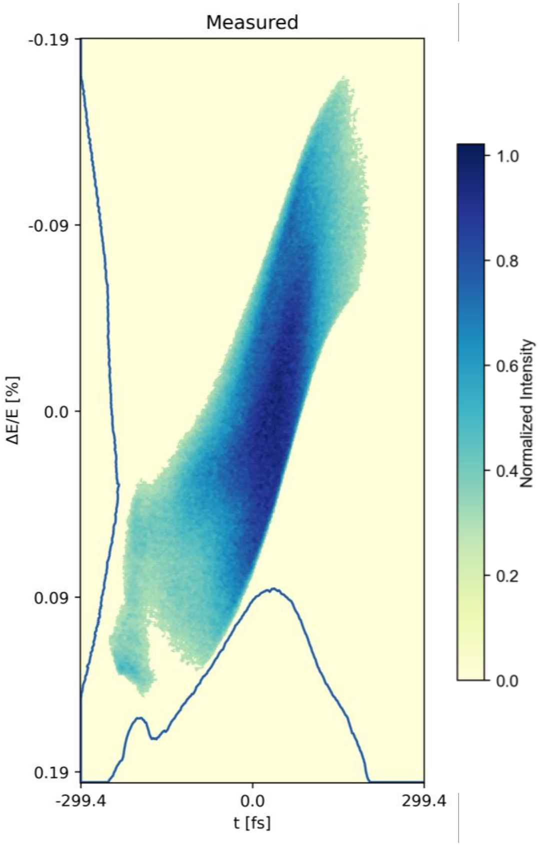


Image Preparation

Raw Detector Output



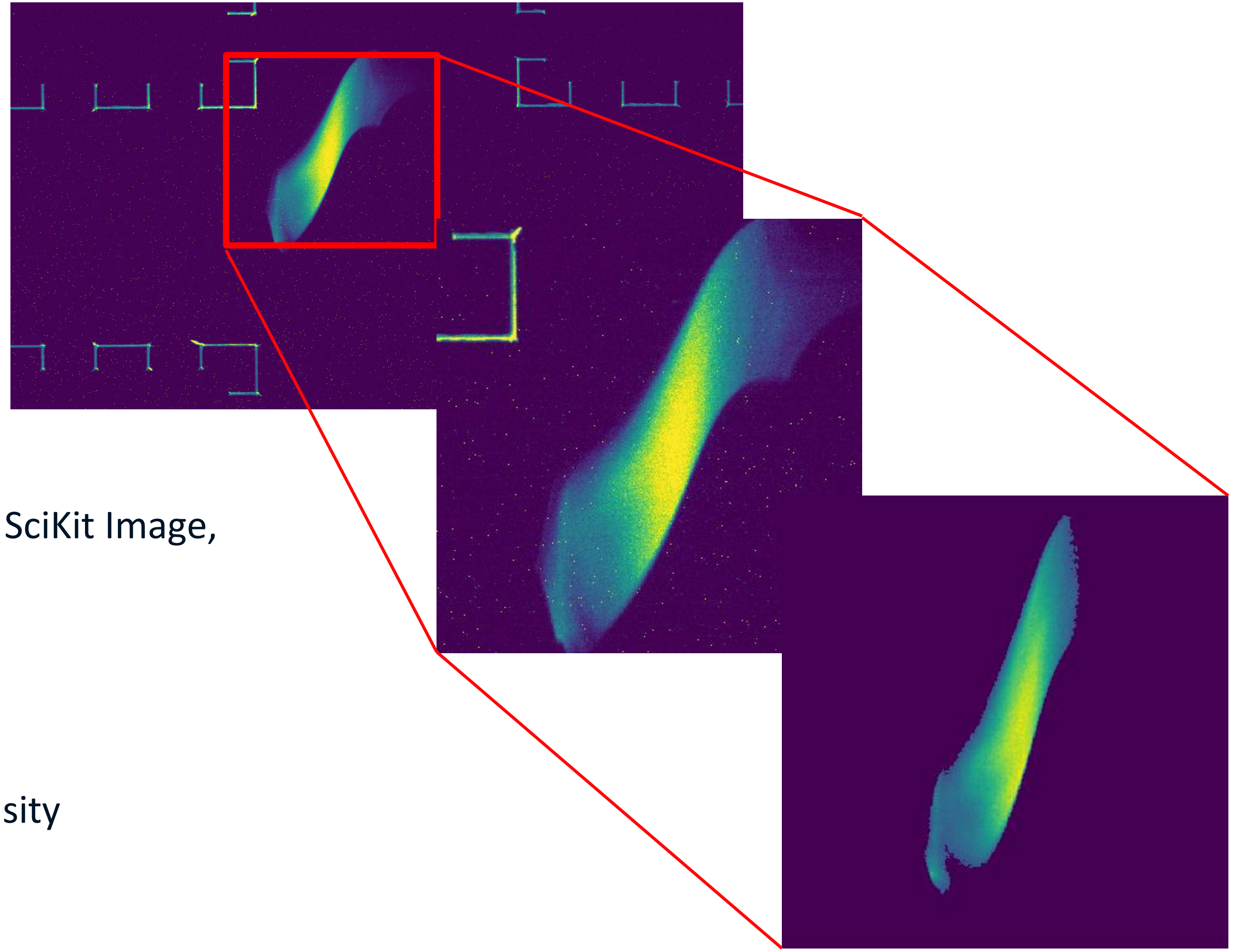
Images in ML Dataset



Subtract Background → Filter → Crop → Threshold → Normalize

Image Preparation - Details

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



Passive Streaker Calibration w. ML