Neural Network Based Virtual Diagnostics at FAST

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(FAST collaboration meeting)

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Big picture

Fast-executing, accurate machine model

Online: *facilitate studies*

Offline: *study planning*
downstream component design
controller training

One piece of a larger set of studies:

- *Accounting for laser spot changes*
- *NN controller (starting with round-to-flat beam transform)*
- ***The vision is to combine these***

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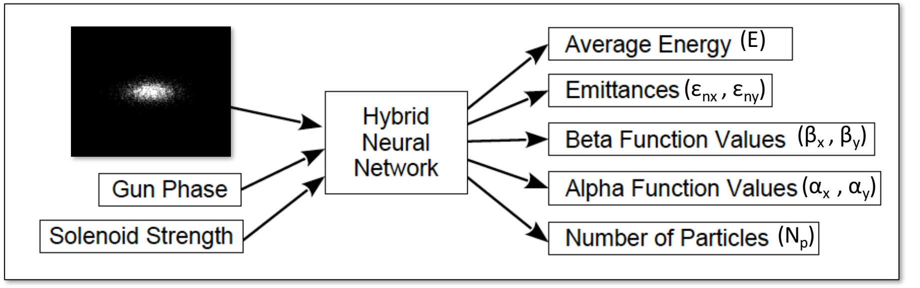
Goal: Full phase-space control at the entrance of the cryomodule using virtual cathode images, magnet settings, cavity phases, and cavity amplitudes



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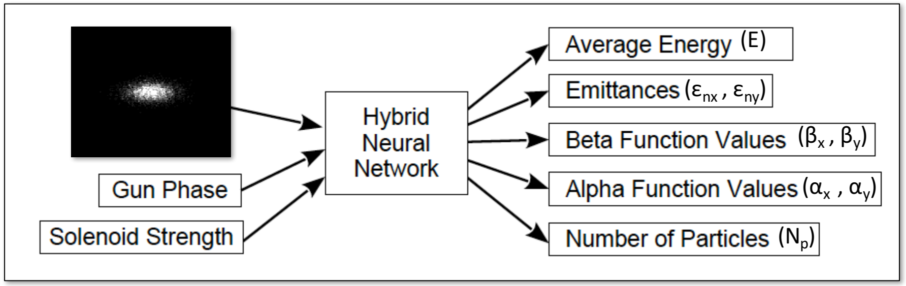


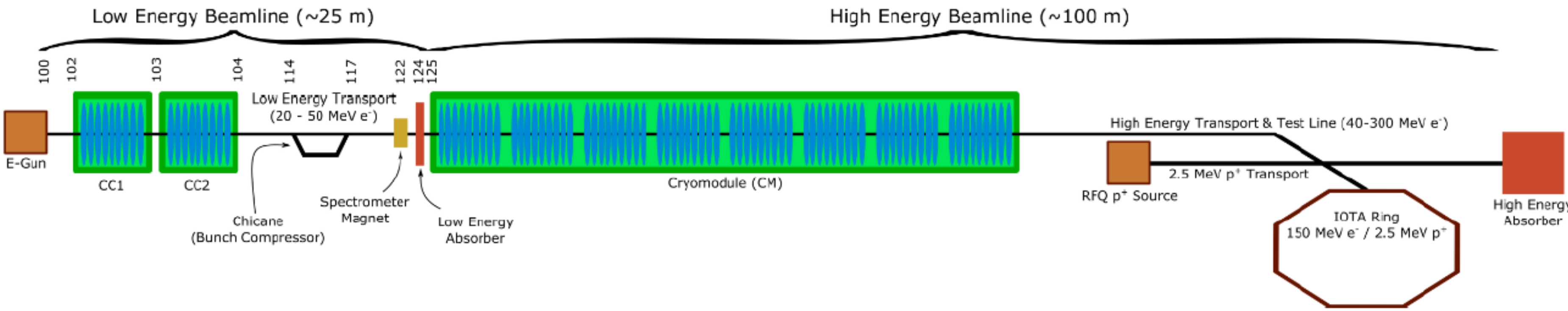
A.L. Edelen et al. "Results and Discussion of Recent Applications of Neural Network-Based Approaches to the Modeling and Control of Particle Accelerators" Proc. IPAC 2018 (THYGBE2)

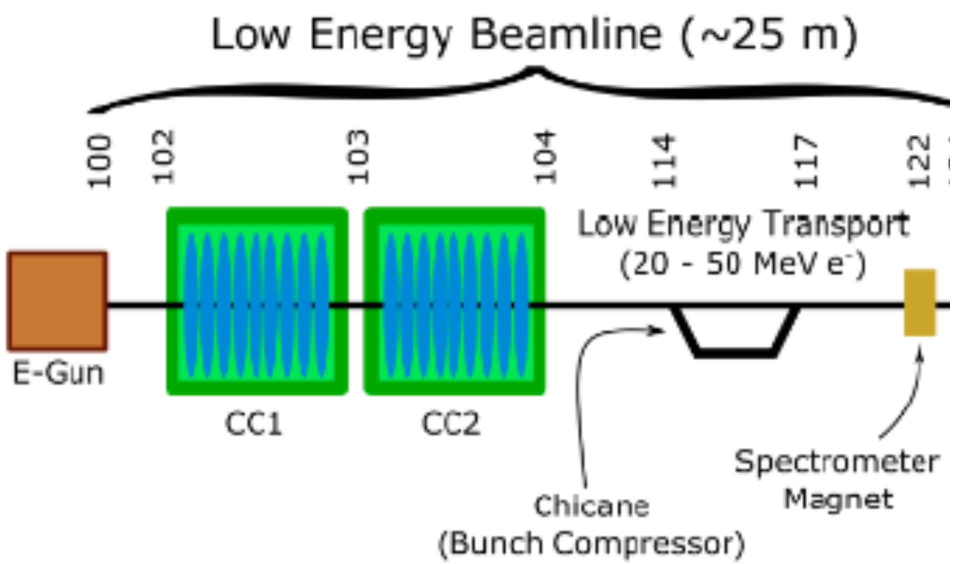
A.L. Edelen et al " Neural Network Virtual Diagnostic and Tuning for the FAST Low Energy Beamline" IPAC 2018 (SUSPL054)

J.P. Edelen, A.L. Edelen & D. Edstrom, "Neural network modeling and virtual diagnostics at FAST," presented at ICFA Beam Dynamics Mini-Workshop: Machine Learning Applications for Particle Accelerators (SLAC, 2018).

A.L. Edelen, S.G. Biedron, S.V. Milton & J.P. Edelen, , "First steps towards incorporating image based diagnostics into particle accelerator control systems using convolutional neural networks," Proc. North American Part. Accel. Conf., TUPOA51 (2016)

Overview of the FAST Linac





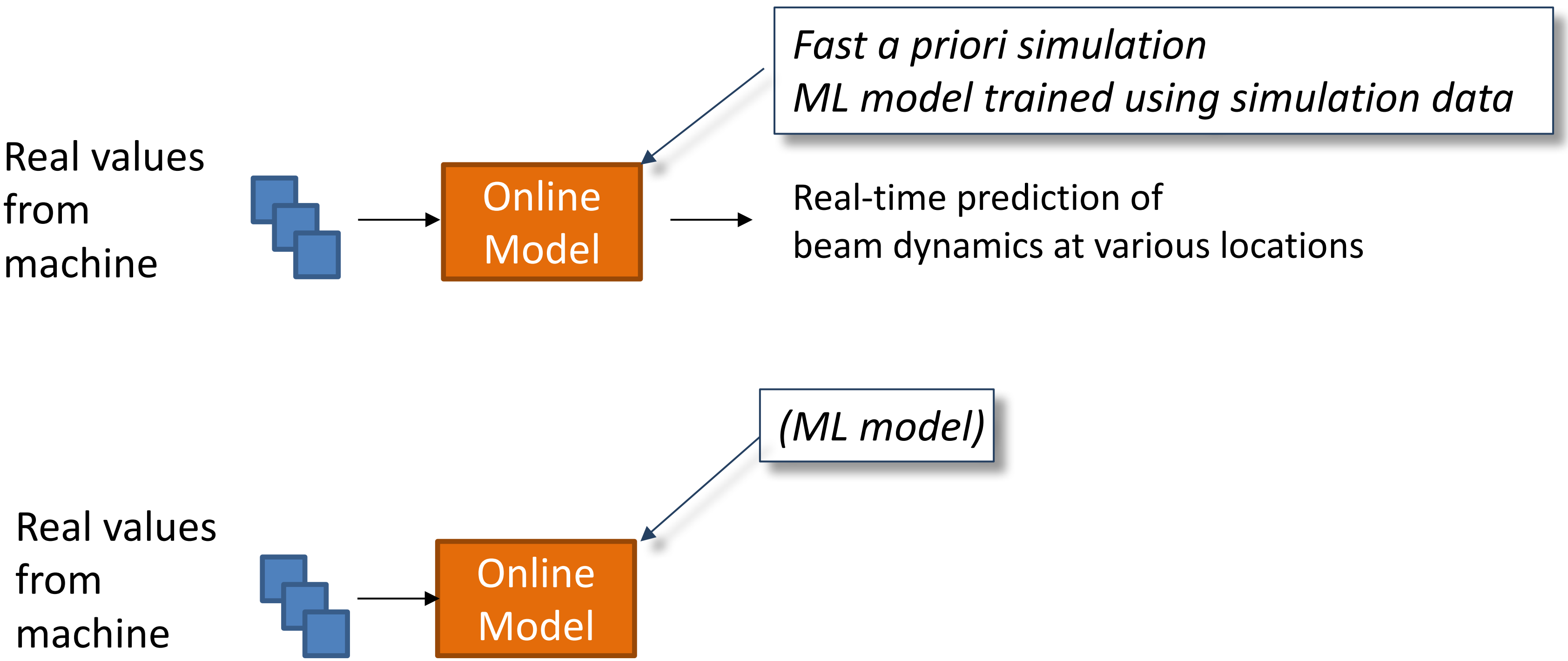
- 1.3 GHz photocathode RF gun
  - *PITZ style gun with solenoid and bucking coil*
  - *Beam accelerated to ~4 MeV*
- 1.3 GHz 9-cell Tesla type cavities
  - *Beam accelerated to ~35 MeV*

Virtual Diagnostics

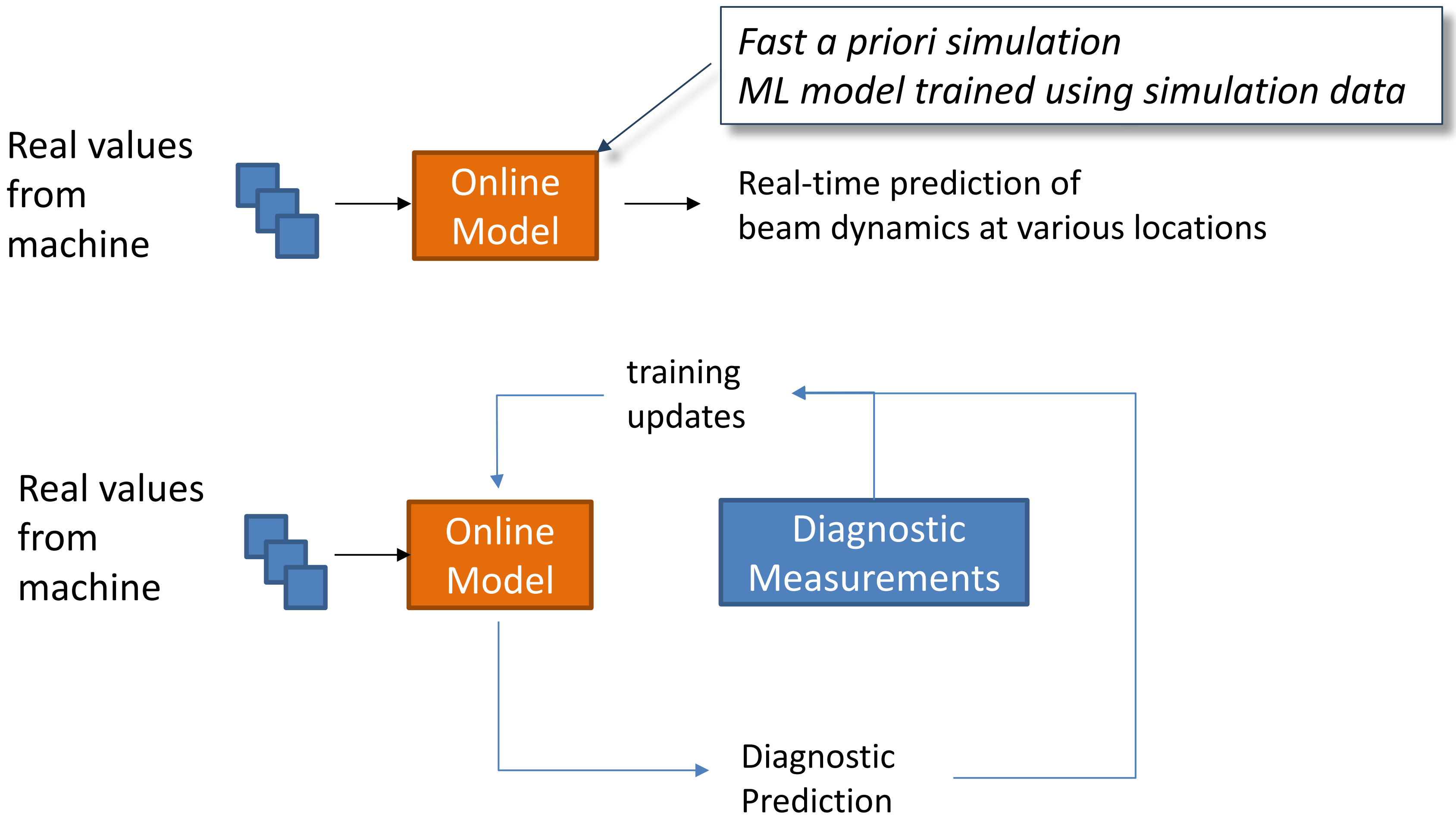
Fast a priori simulation
ML model trained using simulation data

Real values from machine → Online Model → Real-time prediction of beam dynamics at various locations

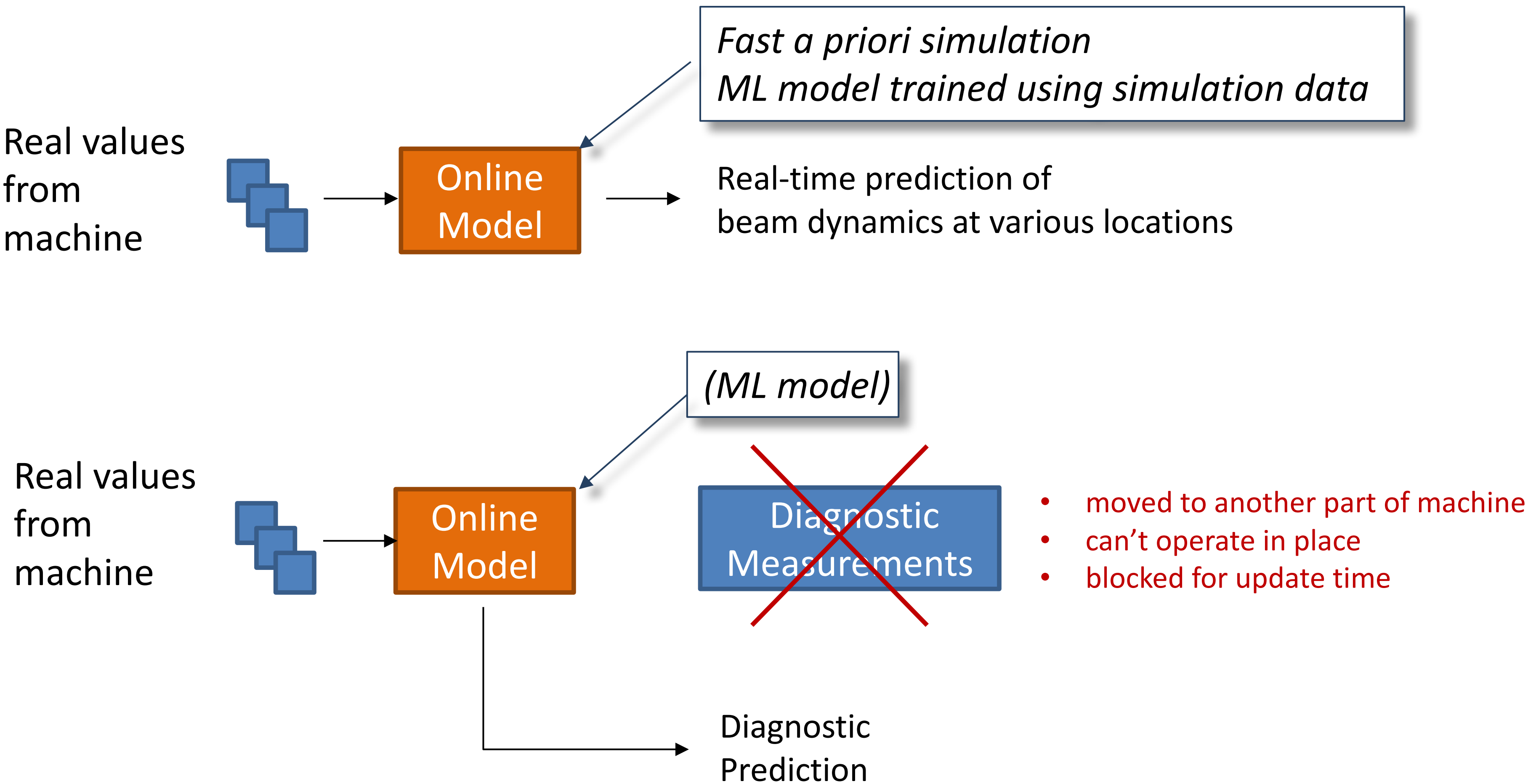
Virtual Diagnostics



Virtual Diagnostics



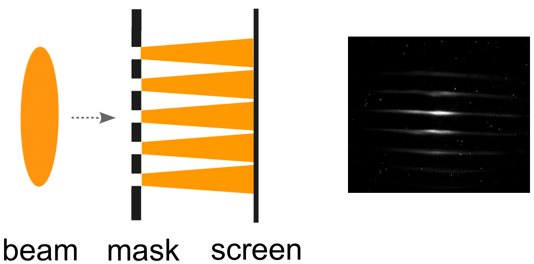
Virtual Diagnostics



Developing our simulation model

gun phase scans
solenoid current scans
(with two different laser intensities)

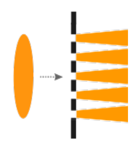
→



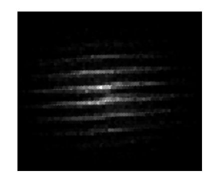
→ fit to obtain subset of phase space parameters

$\langle y^2 \rangle$
$\langle yy' \rangle$
$\langle y'^2 \rangle$

other setting combinations → OPAL



elegant →



\+ full sigma matrix

cathode → CC2
with 3-D space charge routine

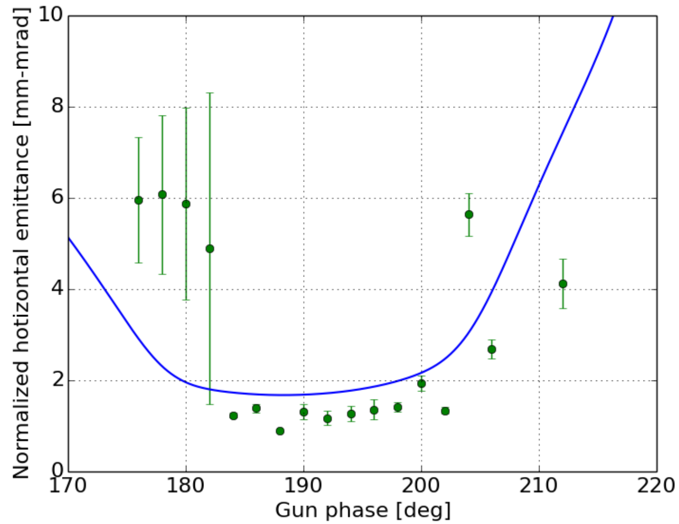
Train neural network on simulations

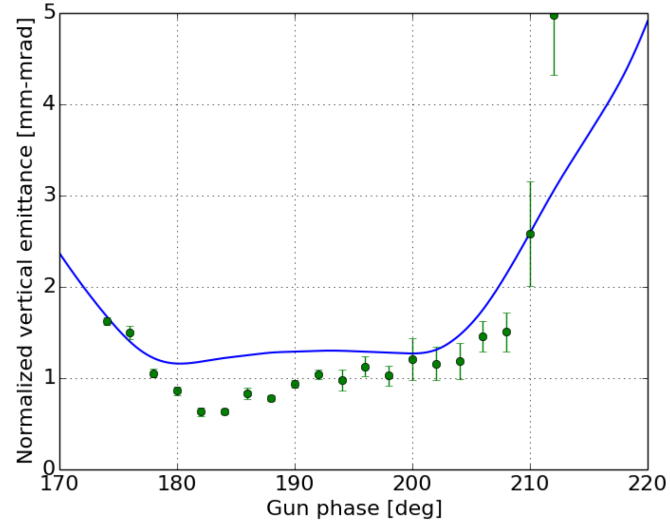
- Two-pronged approach
  - *Use rms parameters calculated directly from the beam distribution*
    - Easy to compute
    - Restricts the number of outputs of the network to 18 parameters
  - *Use images generated from a simulated multi-slit*
    - More difficult to compute, each pixel is now an output of the network
    - More accurately represents the diagnostic output - see later slides

- Initial dataset from Nov 2017 measurements and suite of simulation scans in OPAL
  - *Solenoid scans for 100pC and 250pC bunch charges*
  - *Phase scans for 100pC and 250pC bunch charges*

Comparison of simulations and measurements

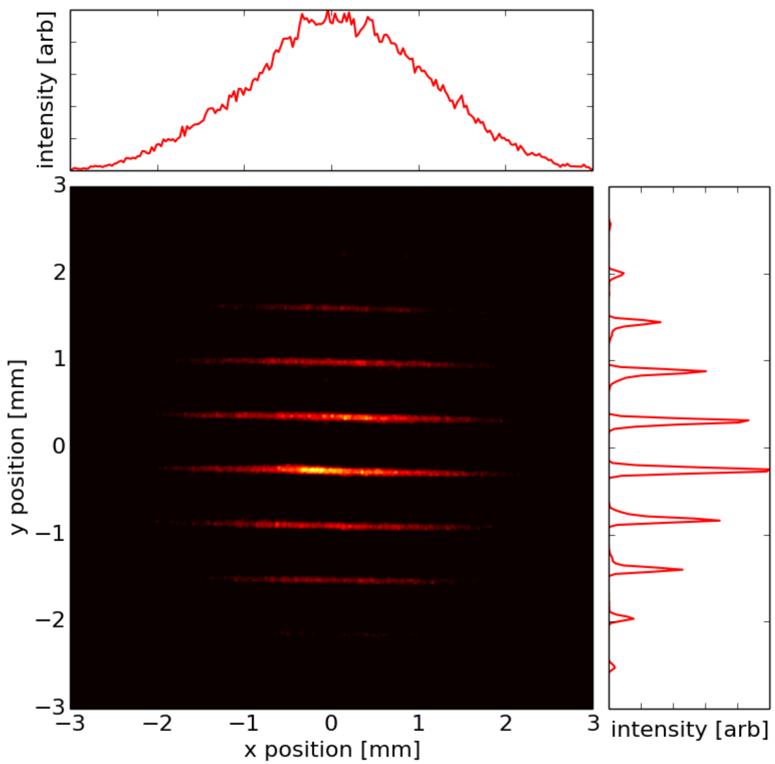
- Comparison with measurements
  - *Top: Horizontal emittance as a function of gun phase for a bunch charge of 250pC*
  - *Bottom: Vertical emittance as a function of gun phase for a bunch charge of 135pC*
- Modest agreement for both cases
- Things to watch out for
  - *Changing the gun phase changes the synchronous phase of CC1 and CC2*
  - *Schottky emission model needed to calibrate the gun phase*

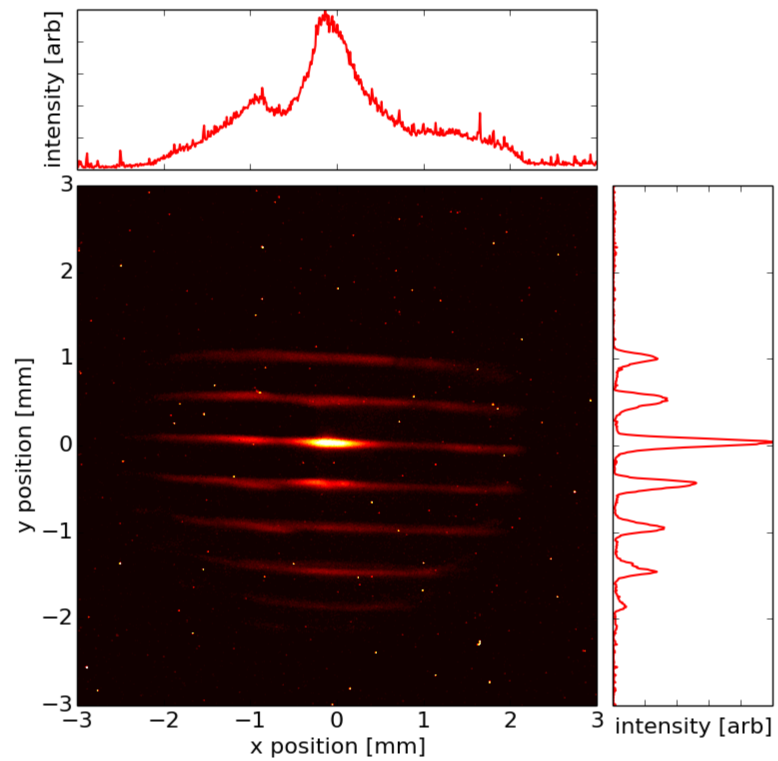




Comparison of simulations and measurements

- Simulating the multi-slit diagnostic
  - *Export beam distribution at X107, apply mask, propagate to X111*
  - *Generate simulated images from 2-d histograms*
  - *Process images in the same manor as is done on the machine*
  - *Compare simulated images with measured images and compare processed results*





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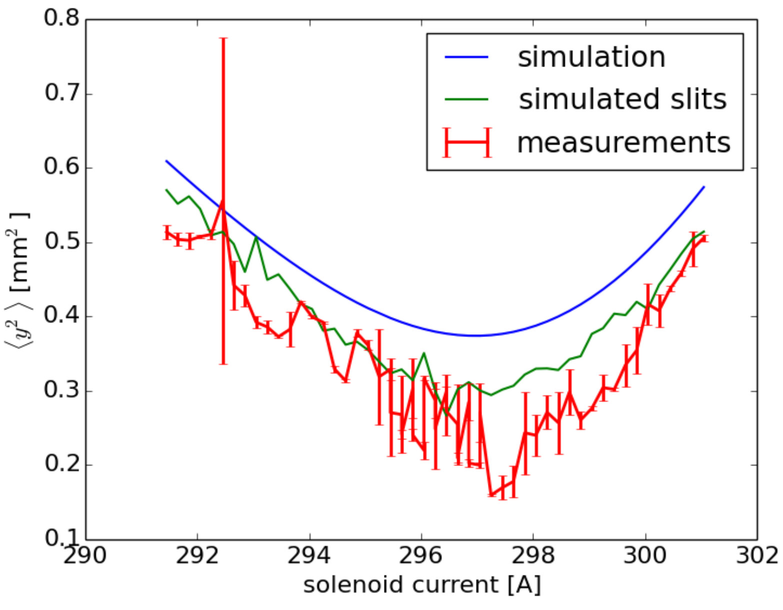
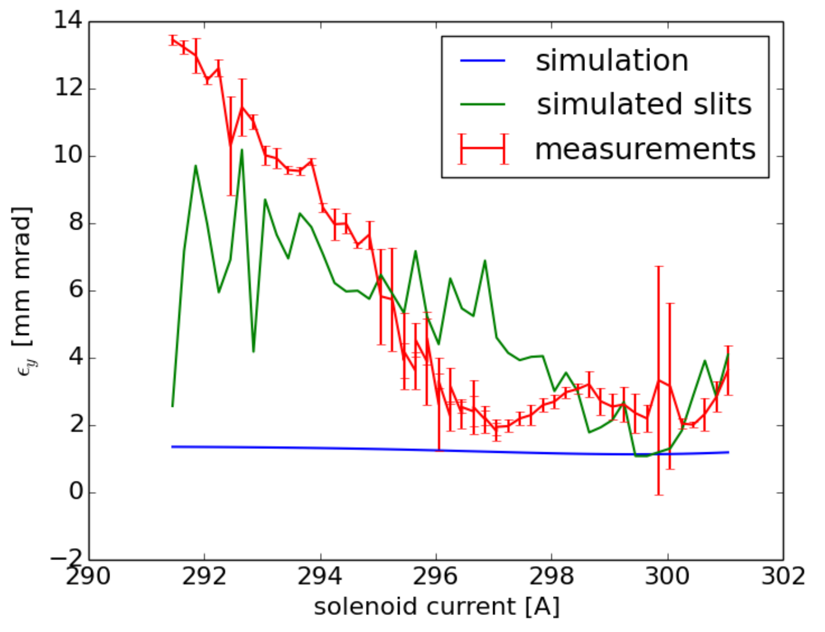
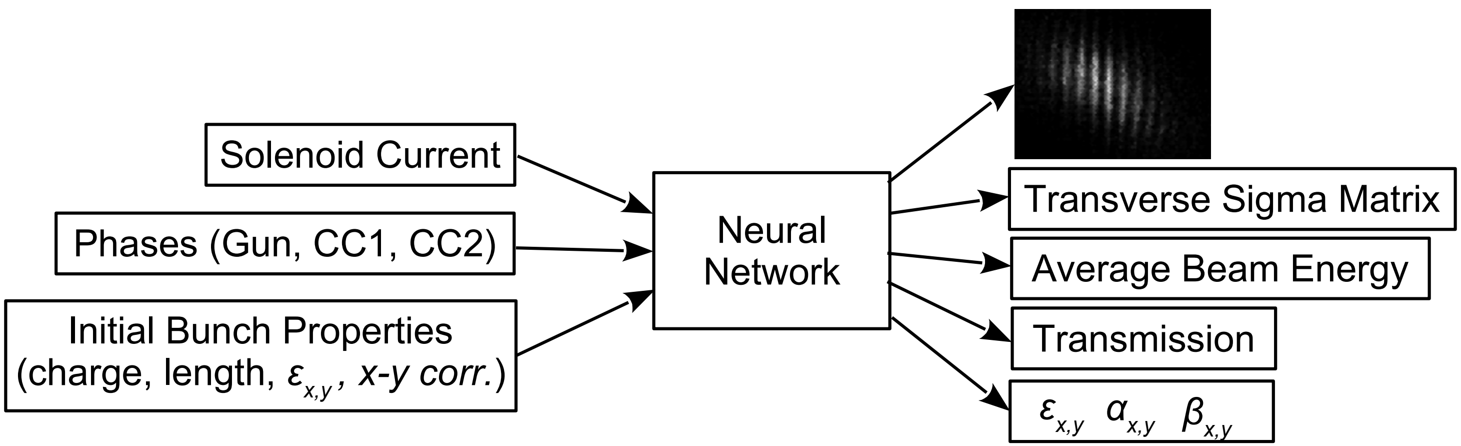


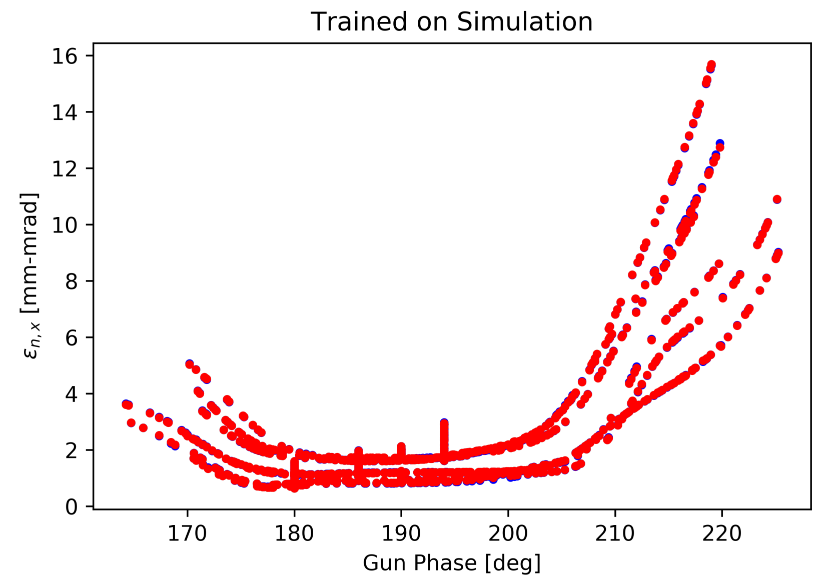


Neural Network Modeling



NN Architecture and performance

- Data separated into Training, Validation, and Test sets
  - *Training set: used directly in training*
  - *Validation set: interleaved with training data but not used explicitly in training*
  - *Test set: outside range of training data*
- Noise added to the data before training
- Performance across validation and test set
  - *Top: prediction and simulation as a function of gun phase*
  - *Bottom: rms percent error between neural network and simulations*
- All output parameters perform well except transmission
  - *All transmission is 100% in our range of simulations so this is dominated by noise added during training*



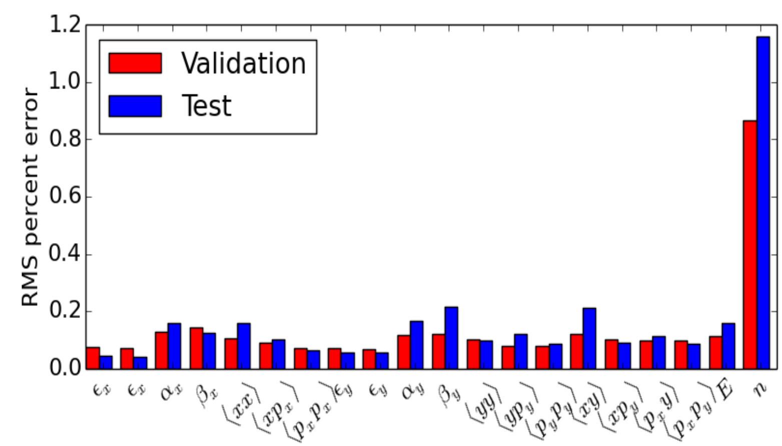
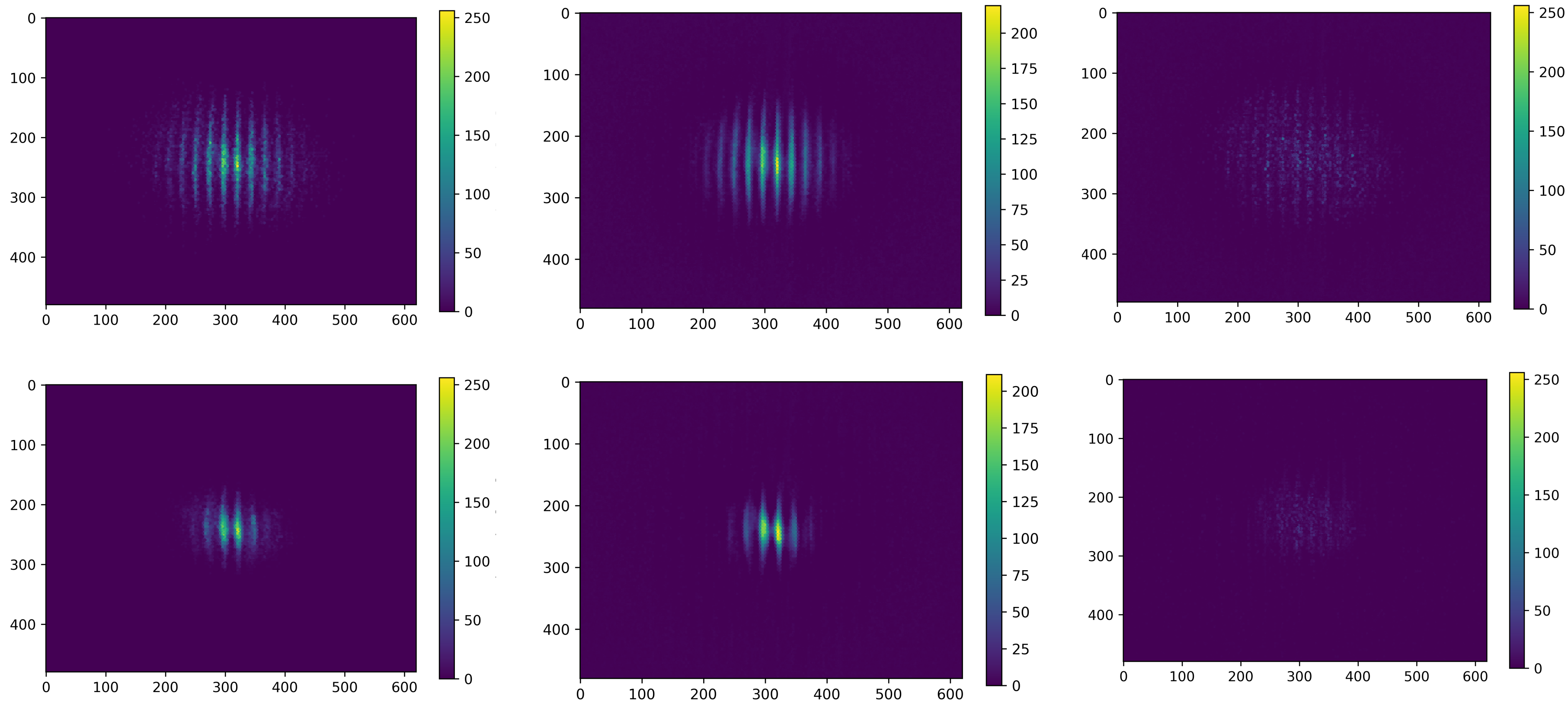


Image predictions

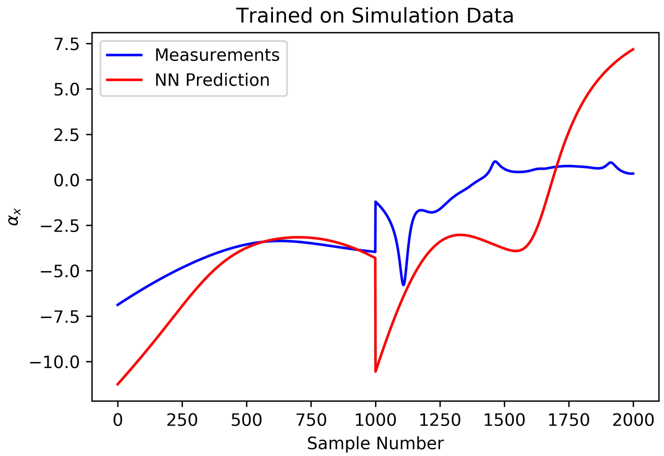
A. L. Edelen, et al. IPAC18, WEPAF040

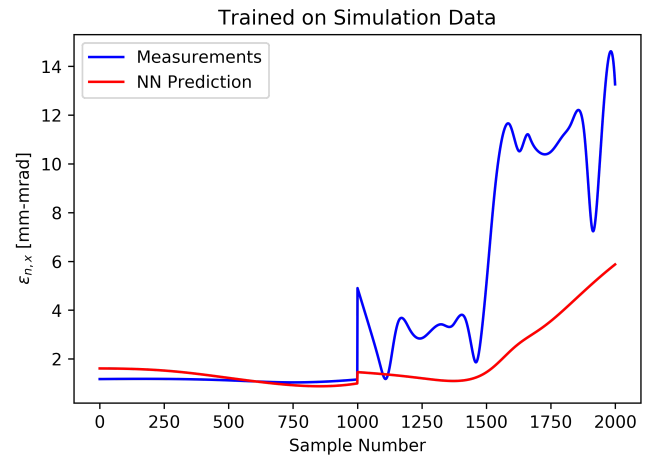


Simulated | NN Predictions | Difference

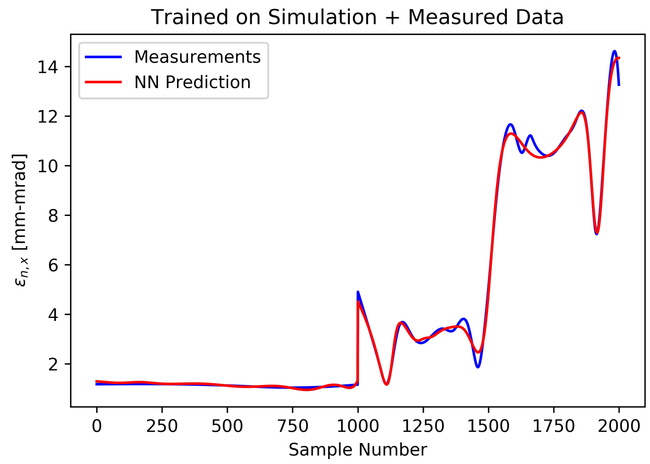
Predicting measurements

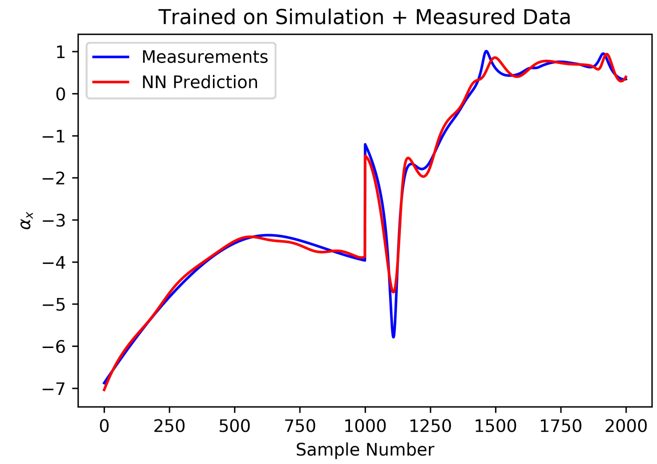
- Predicting measurements with the model trained on simulations
- Prediction is poor:
  - *Note this model was trained on rms parameters from simulations, not the simulated multi-slit measurement*



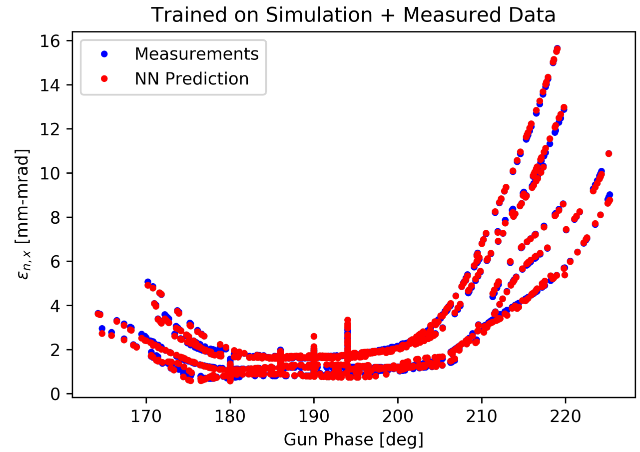


Updating with measurements





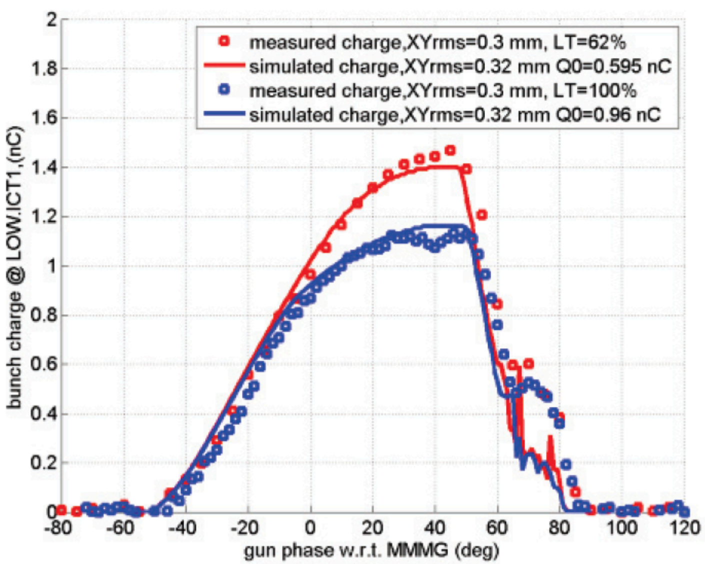
- Updating with measurements
  - *Top Left: Normalized emittance as a function of sample number for updated dataset*
  - *Top Right: Alpha as a function of sample number for updated dataset*
- Network retains the information from the simulations
  - *Right: comparison of network prediction for phase scan data from before and after updating with measurements*



Why bother with simulation at all? → Rough initial solution facilitates training with measured data

Next steps

- Continue to improve simulations of the machine
  - *Include beam offsets and correctors*
  - ***Include Schottky effect in emission model (gun phase calibration)***
    - Good results from the PITZ gun presented in 2012



EMISSION STUDIES OF PHOTOCATHODE RF GUN AT PITZ

J. Li*+, G. Asova‡, I.V. Isaev, M. Groß, L. Hakobyan, Y. Ivanisenko, M. Khojoyan‡+,G. Klemz, G. Kourkafas, M. Krasilnikov, K. Kusoljariyakul‡‡, M. Mahgoub, D. Malyutin, B. Marchetti, A.Oppelt, B. Petrosyan, S. Rimjaem‡‡, A. Shapovalov, F. Stephan, G. Vashchenko, DESY, 15738 Zeuthen, Germany
G. Feng, DESY, 22607 Hamburg, Germany
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Next steps

- Continue to improve simulations of the machine
  - *Include beam offsets and correctors*
  - *Include Schottky effect in emission model (gun phase calibration)*

- Next run
  - *Take more measurements: at different gun voltages, CC1 phase, and CC2 phase*
  - *Deploy prototype virtual diagnostic*
- Long term
  - *Develop and test phase-space controller*