Karlsruhe Institute of Technology

Institute for Beam Physics and Technology (IBPT)

Surrogate Modelling of the FLUTE Low-Energy Section

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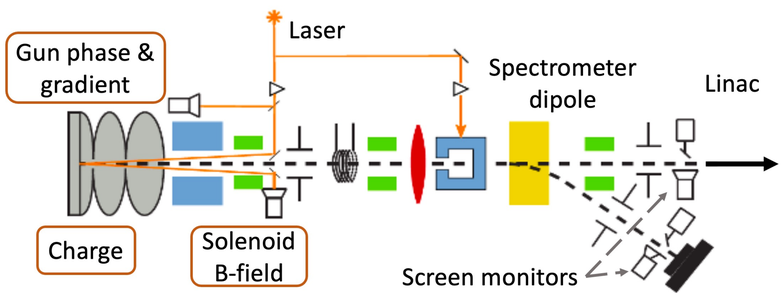
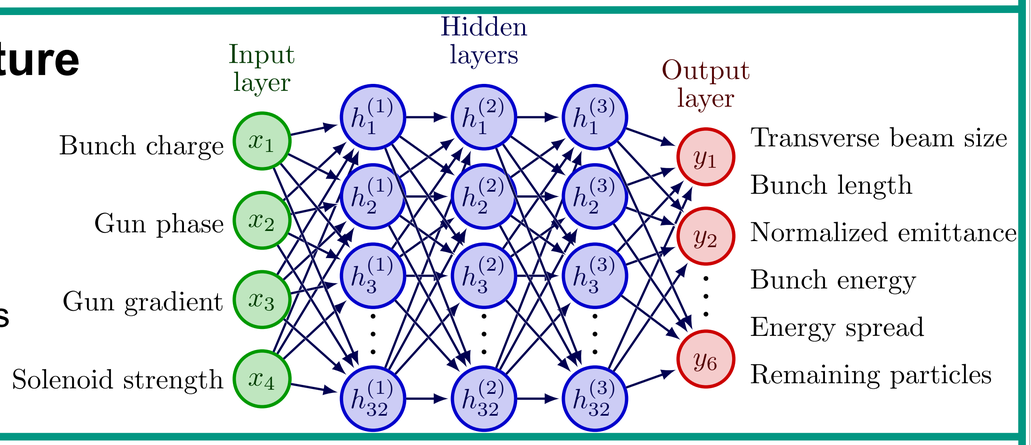
*Numerical beam dynamics simulations are essential tools for particle accelerators but also very time consuming. Surrogate model trained on the accelerator structure can provide **fast** and **accurate** predictions of beam properties.*

FLUTE Low-energy Section Layout



Neural Network Architecture

Fully-connected neural network (**NN**) as surrogate model
- 4 inputs, 6 outputs
- 3 hidden layers, each 32 neurons
- Tanh activation function



NN Model Training

Training data: 10,000 ASTRA simulations with random parameter settings

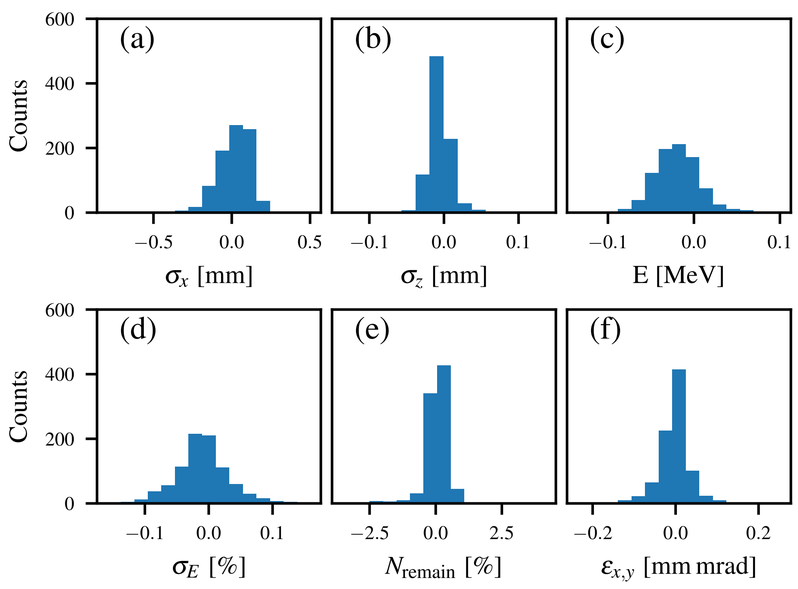
Input Parameters	Range	Unit
Charge	1 to 30	pC
Gun phase	175 to 235	deg
Gun gradient	50 to 100	MV/m
Solenoid B-field	0.08 to 0.2	T

Training procedure
- Min-max normalization of input & output
- Mean squared error loss function
- Adam optimizer, batch size = 64, learning rate = 10^{-3}
- 200 epochs

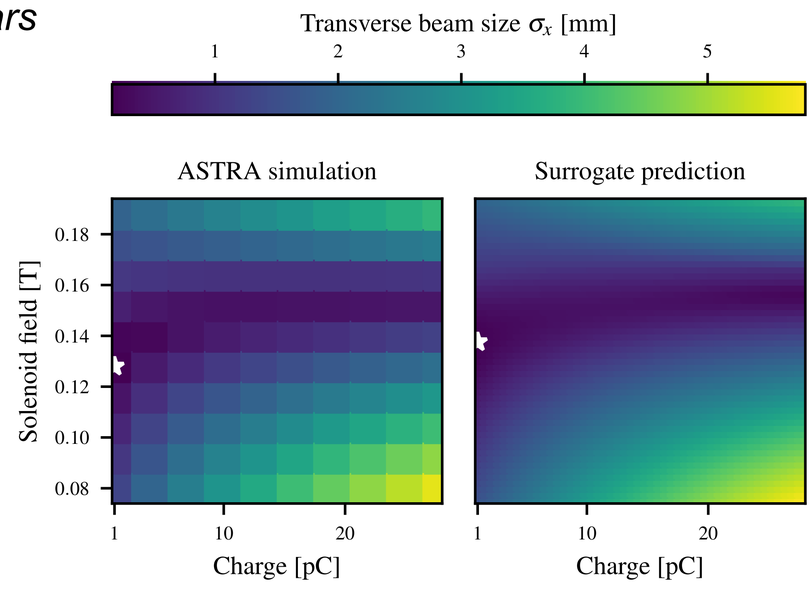
Performance on Validation Data

1,000 random settings not seen in training process

NN outputs agree well with the ASTRA simulation results for all predicted properties



Example: *2D subspace with fixed gun RF phase and gradient, with minimal beam sizes marked as white stars*

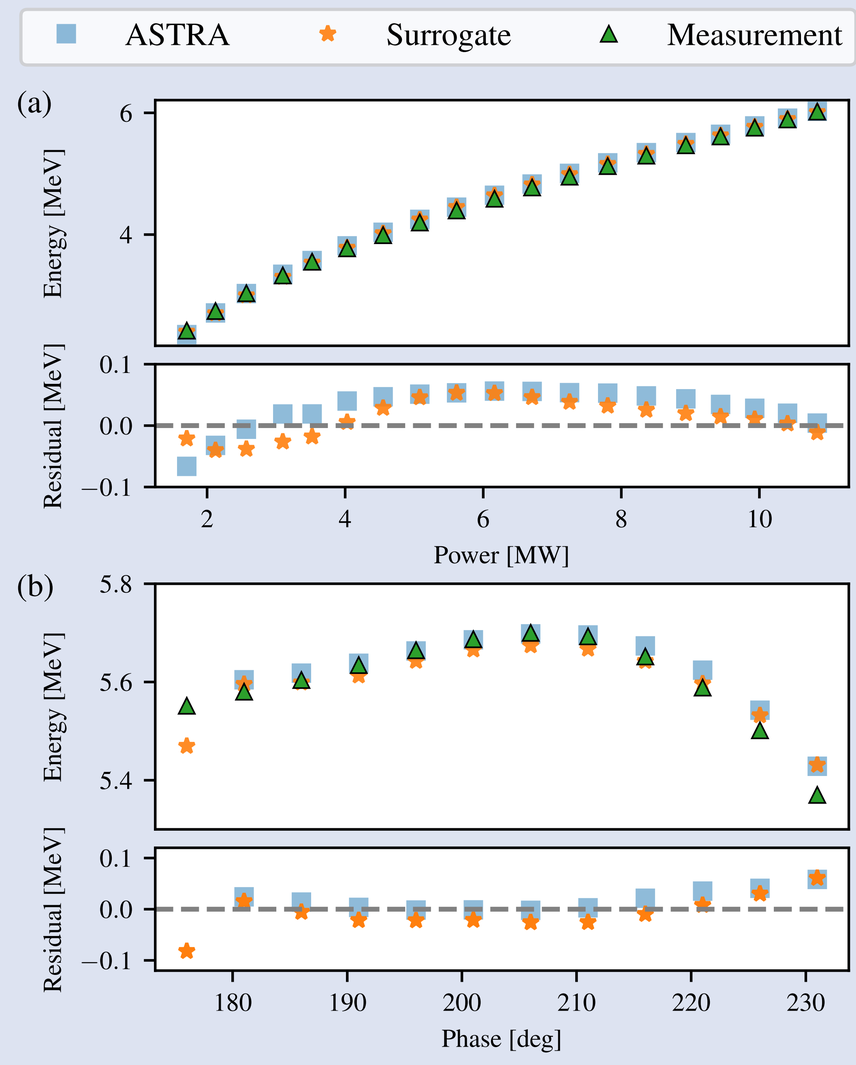


Left:
10*10 ASTRA grid scans
computation time **~5 h**
min. $\sigma_x = 0.166$ mm

Right:
50*50 NN model prediction
computation time **~1 ms**
min. $\sigma_x = 0.164$ mm

Comparison to Measurements

Energy measured at FLUTE with gun RF power and phase scans using spectrometer dipole .
NN surrogate predictions show deviation $\boldsymbol{\Delta E < 0.1\ \mathrm{MeV}}$



Application of the Surrogate Model:

- **Virtual diagnostics**: online beam properties prediction during operation
- Training environment for **reinforcement learning** (RL) applications
- Speed up parameter optimizations for new operation mode by **constraining the search space**

Outlook:

- Integrate into control system to be a **daily tool** for operators
- Add inputs & outputs; full **phase-space image prediction**
- Train surrogate model for high-energy section; connect models for start-to-end prediction

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