Application of Artificial Neural Network in the APS Linac Bunch Charge Transmission Efficiency

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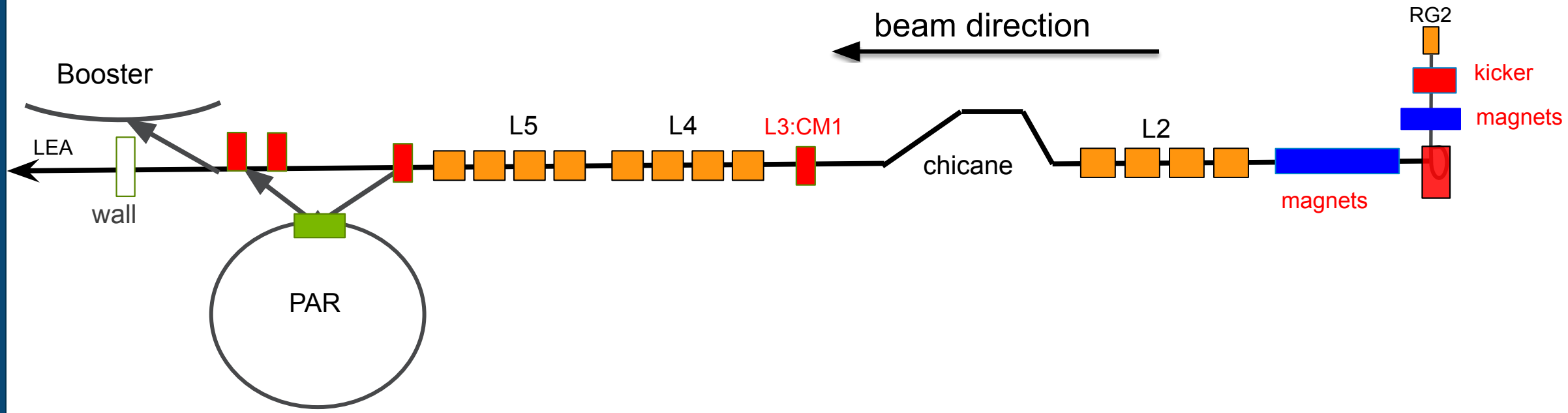
Introduction

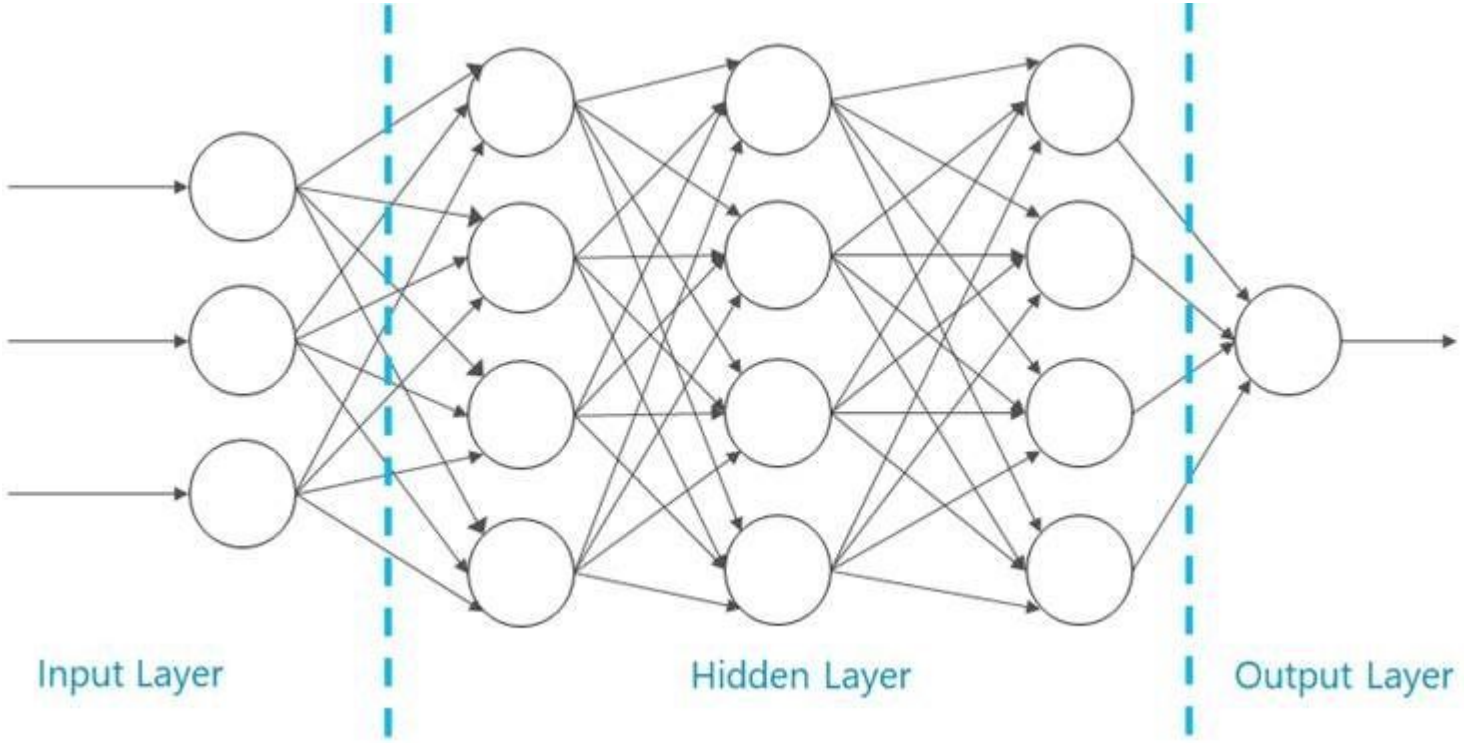


- APS linac charge transportation is maximized by:
  - A simplex optimizer to maximize charge (L3:CM1 charge) with gun front end quadrupoles and steering magnets (16 magnets) (kicker voltage is fixed)
  - A steering controllaw to adjust the linac trajectory (15 magnets in each plane)

As the first step of testing ML at APS linac, we'd like to speed up the optimization process which took about half an hour before (will take much longer now).

Artificial Neural Network Model

- Input Layer: 28 magnets
- Output layer: L3:CM1 charge
- 3 hidden layers model
  - 128, 256, 256 nodes (NNN)
  - 64, 64, 64 nodes (NNN64)
- 2 hidden layers model
  - 64, 64 nodes (NN64)



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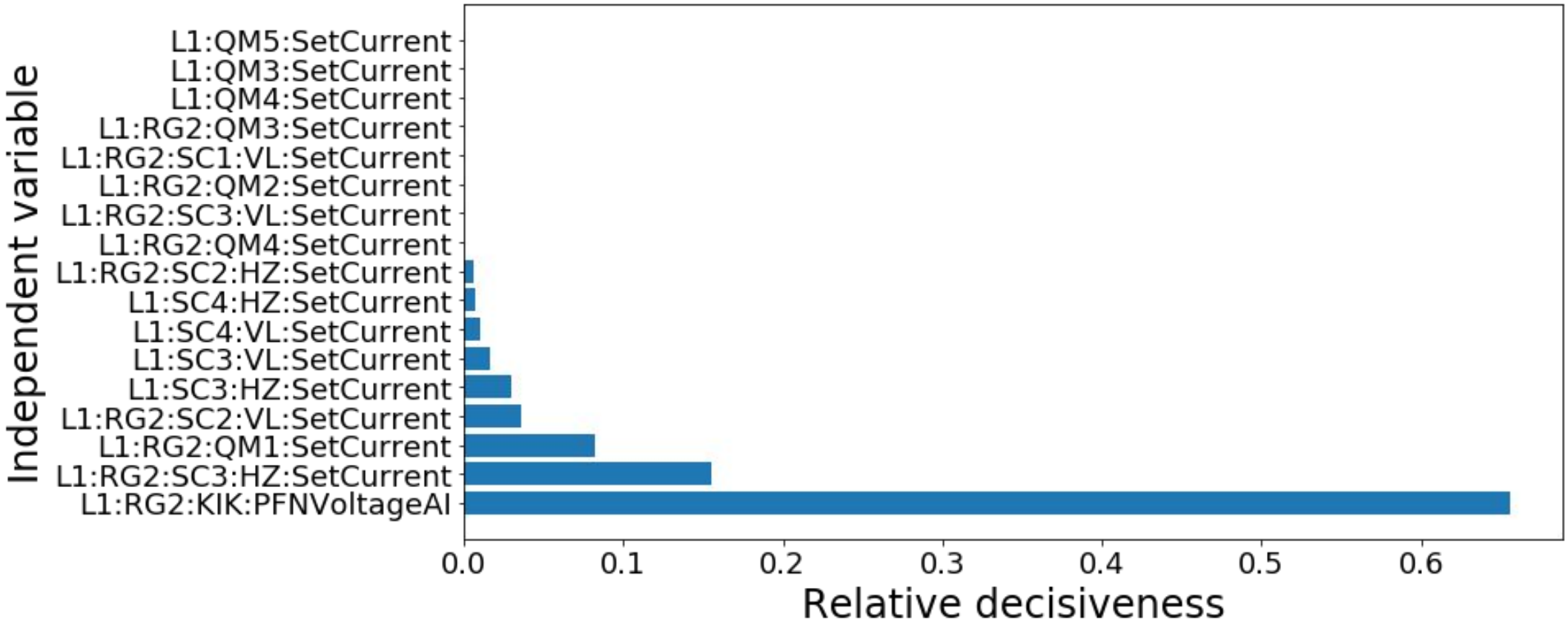
28 128 256 256 1

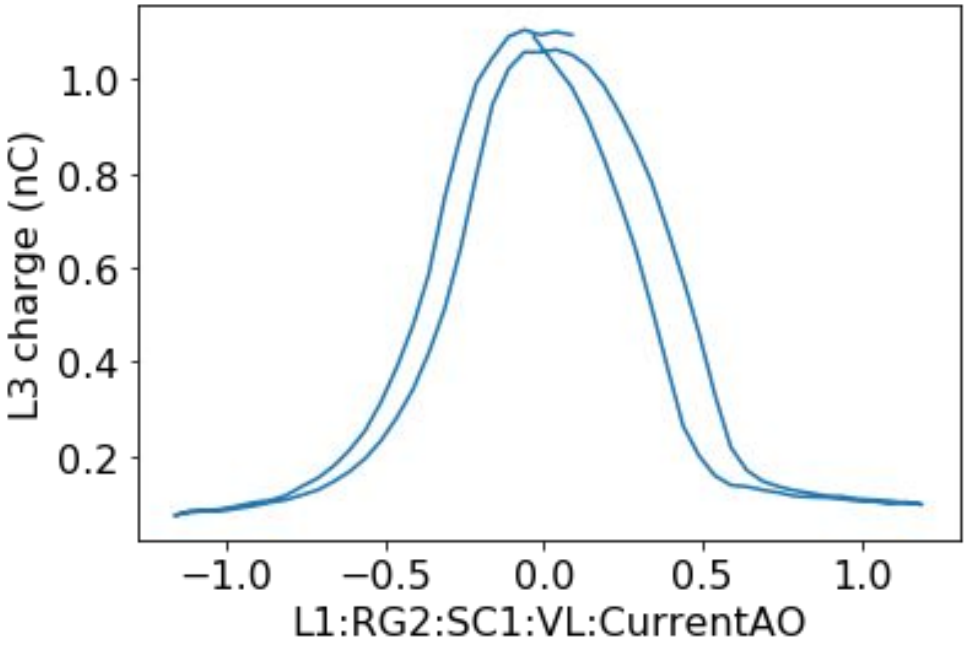
Feature Importances study

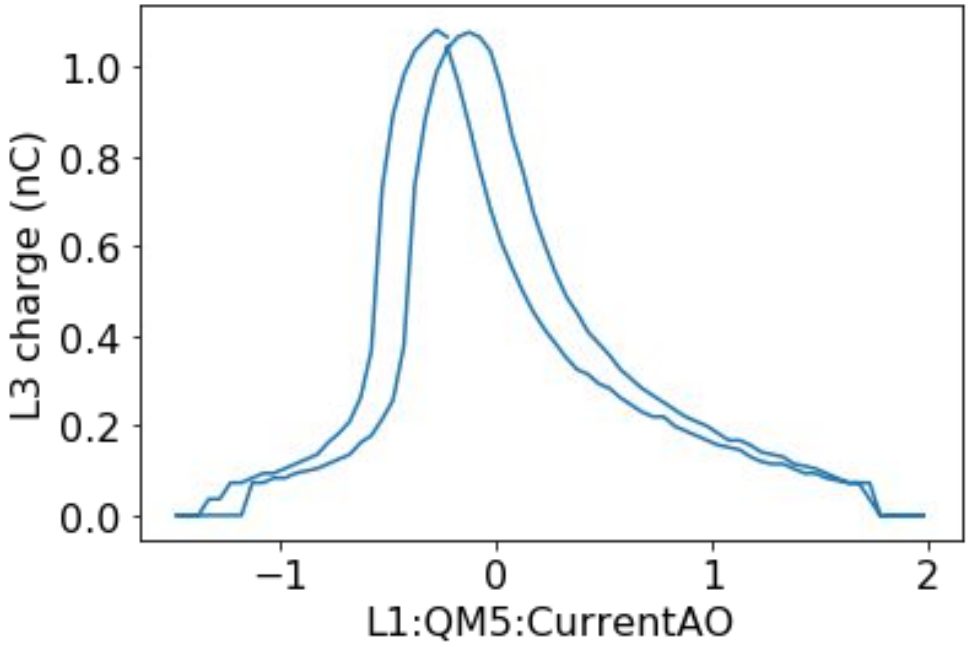
- Feature importances study shows that Kicker voltage impacts L3:CM1 the most
- (RandomforestRegressor -- data fit not good)



Problems

- Magnet response time -- it takes long time for magnet current to reach the setpoint when change is big (during optimization) (check the readback and setpoint difference to fix it)
- Magnet hysteresis: (use smaller step size to reduce it)





Due to these two problems, the L3:CM1 charge sometimes could not reach the best value the optimizer found after setting the the magnets to their best positions -- had to manually adjust some knobs. After improving the optimizer to avoid the above problems, the optimization will take much longer than half an hour (before). ML is needed!

Data Improvement

- Fix kicker voltage (e.g. 13.5kV) (readback 13.2 to 13.4kV)
- Include other steering magnets (before L3:CM1) that change L3:CM1 charge:

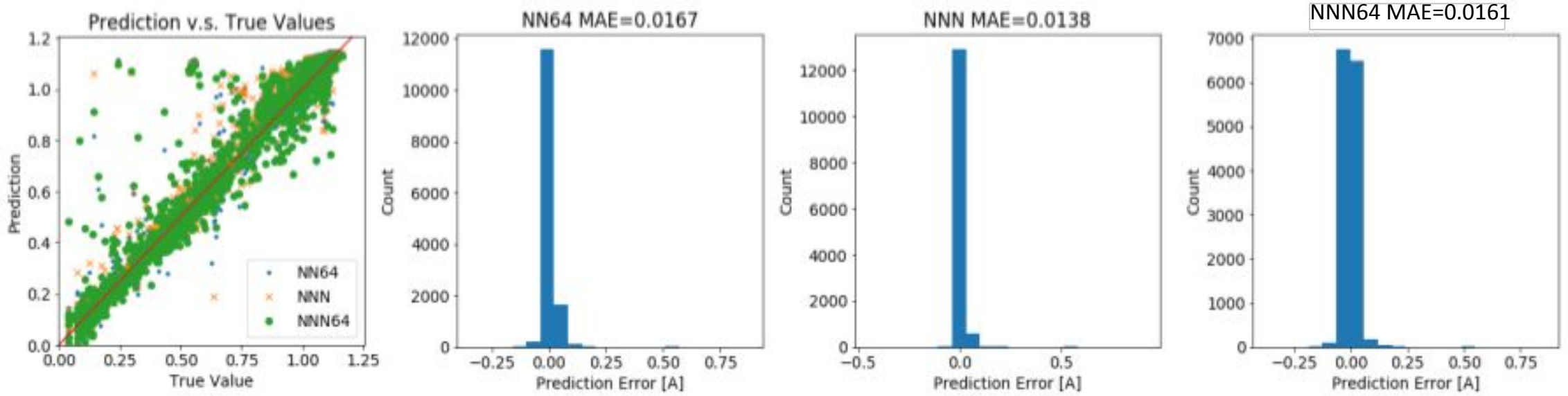
  16 input variables (used in optimization) → 28 input variables
- Remove the data where the setpoint and readback of the magnets do not agree.
- After the above processes, the input data has 13644 samples

Neural Network Fitting on Improved Data

(kicker voltage 13.5kV, magnet setpoint == readback, 16334 samples, train:validate:test 60%:20%:20%)

- NN64 → two hidden layers (64, 64 nodes)
- NNN → three hidden layers (128, 256, 256 nodes)
- NNN64 → three hidden layers (64, 64, 64 nodes)
- MAE → mean absolute error

True values (measurement) v.s Predictions (for all samples) and the prediction error histograms

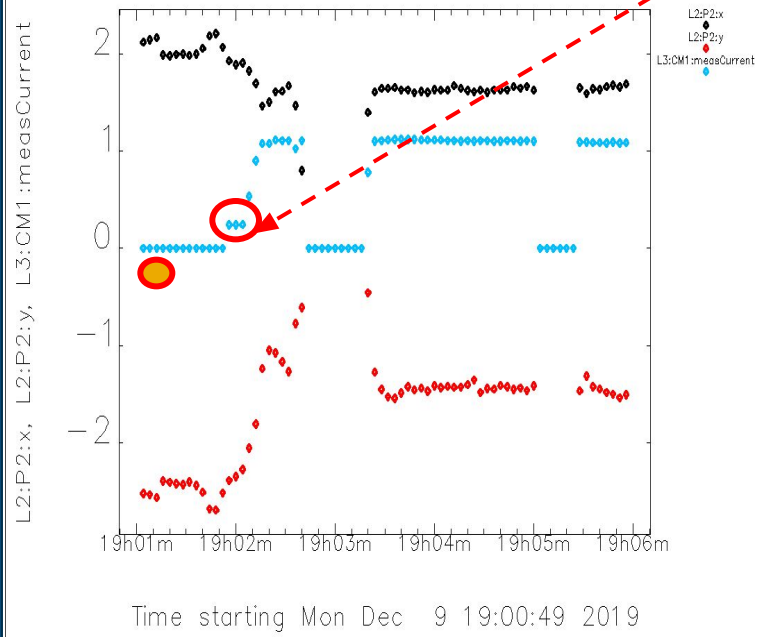


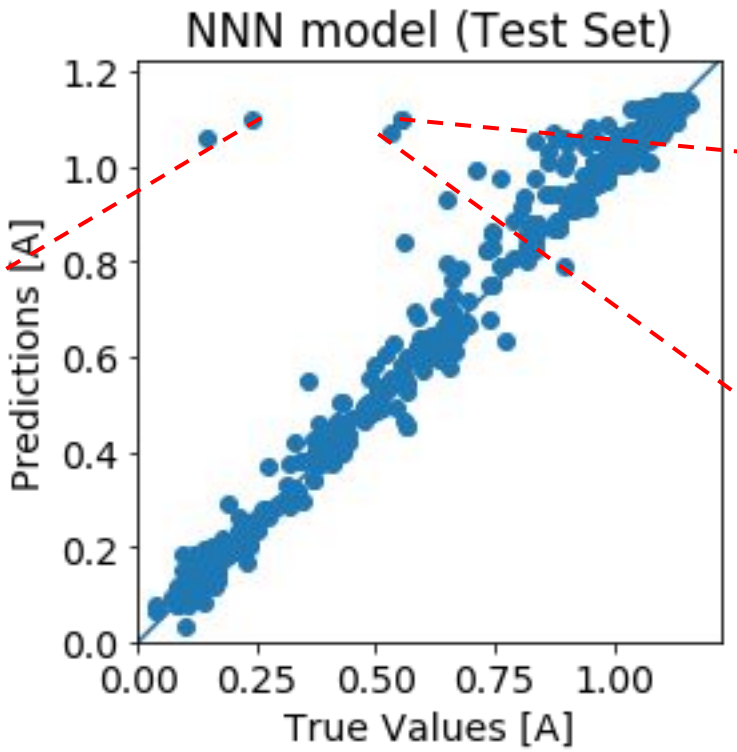
3-layer (128, 256, 256) model is the best

Machine and Trajectory Error Detection

Does not affect the fitting because most of data was collected with close to zero trajectory error (steering controllaw converged)

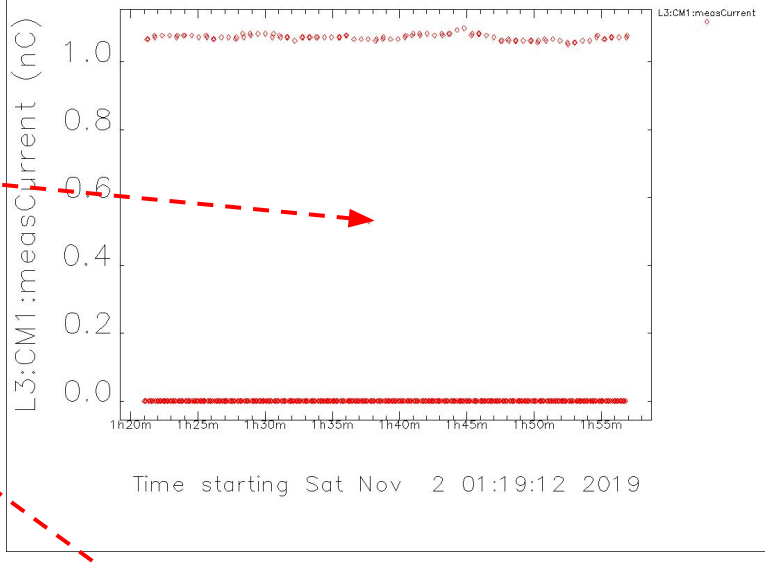
Trajectory Error

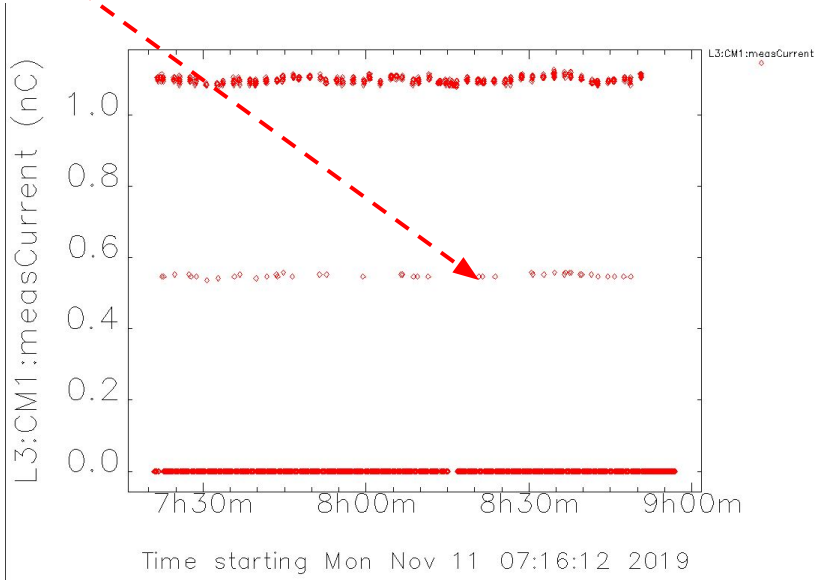




L3:CM1 charge is averaged over the last 2 samples in IOC.

Machine Error

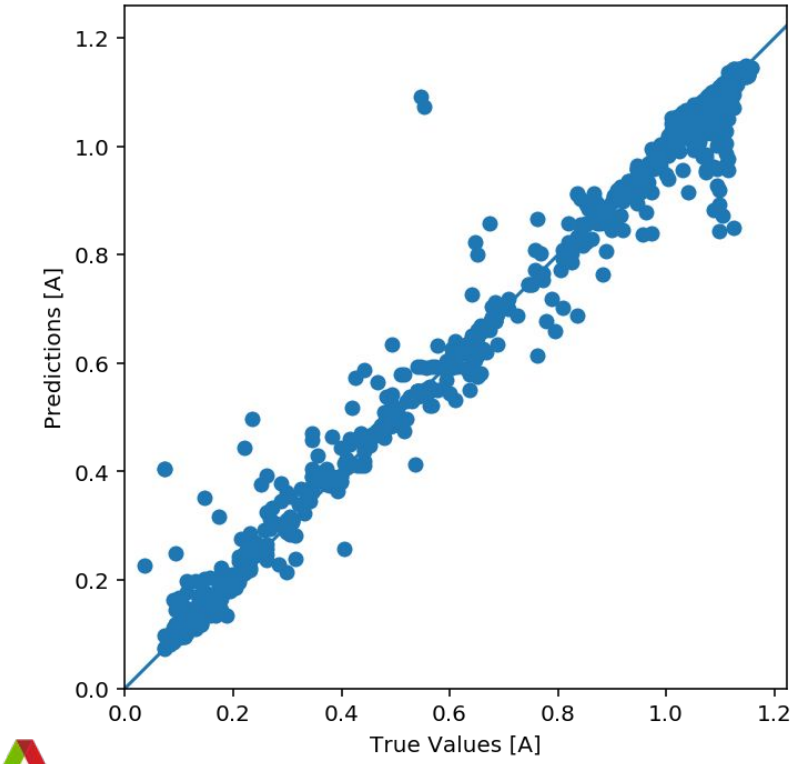


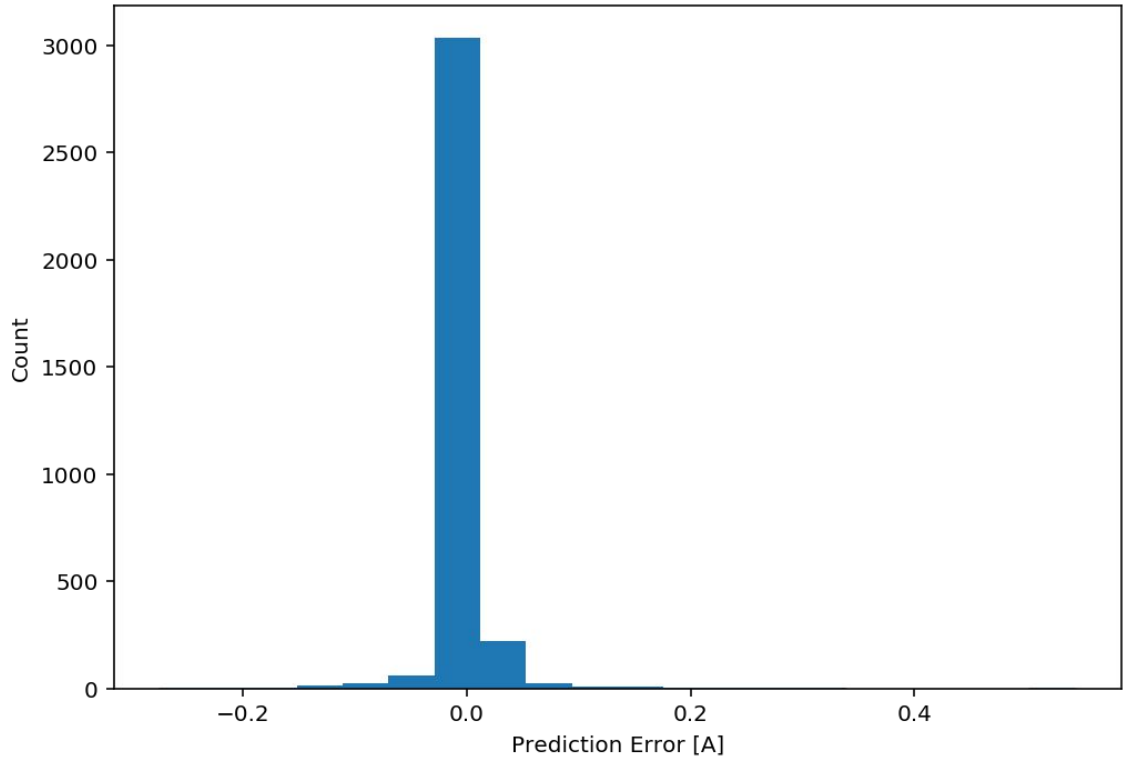


Machine Learning Model Optimization

- DeepHyper in ALCF: 3-layer NN model (75 nodes) (~2000, non-filtered data)
  - Need to run in super computer
  - The model is good enough
  - Data processing, data analysis and underline physics are more important in this application
- TPOT (thanks to Tianzhe Xu provide example of using TPOT): (run overnight on personal computer)

  Find the best model -- 2-order PolynomialFeatures (MAE=0.0108)





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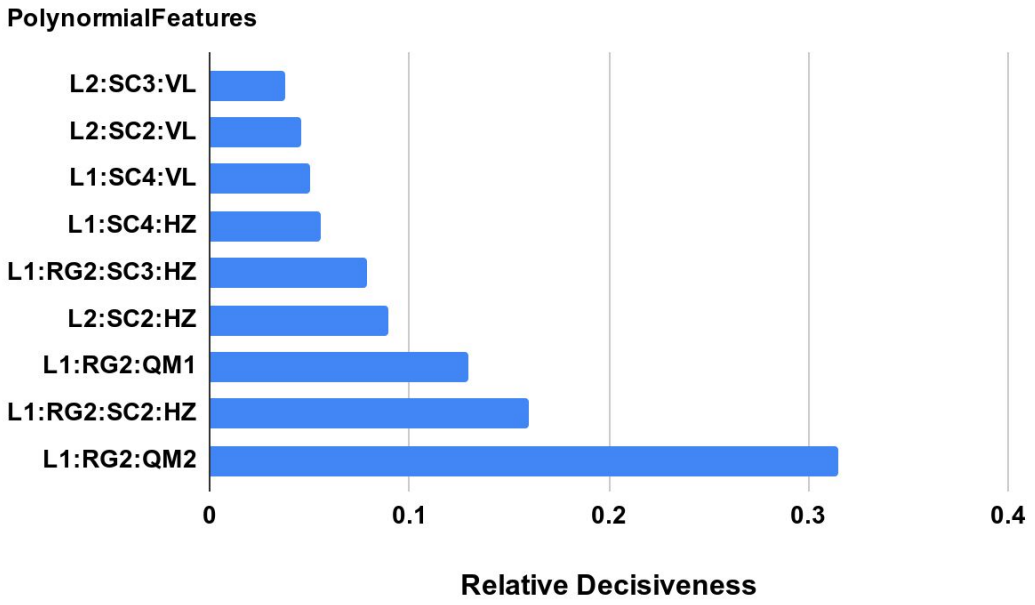
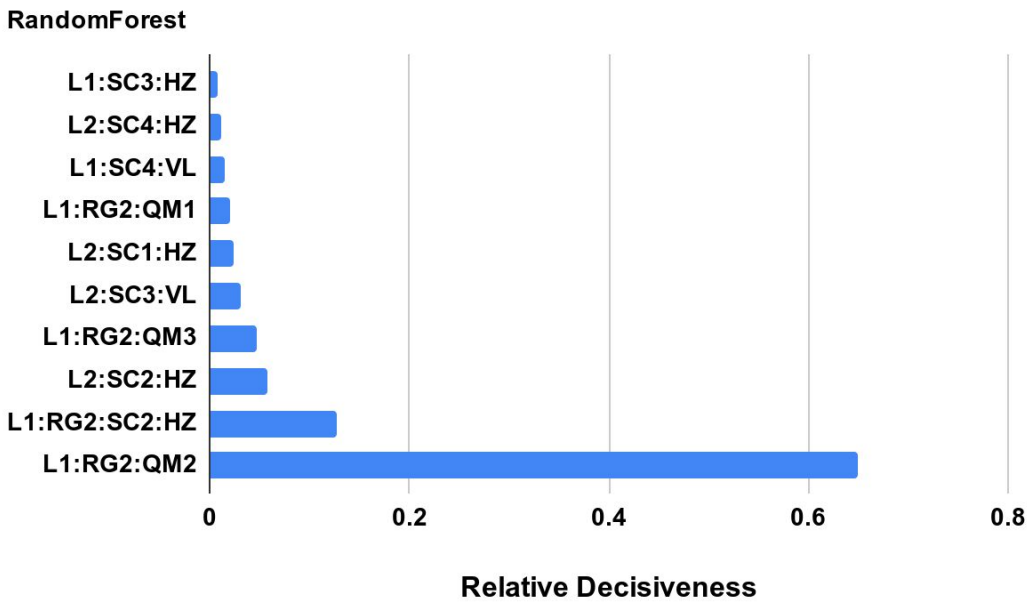
Feature Importances on New Processed Data





PolyNomialFeatures: fit well -- feature importances not accurate (second order)
RandomForest: importances analysis more reliable, does not fit well to the data

L1:RG2:QM2 and L1:RG2:SC2:HZ are the two most sensitive knobs in controlling beam lattice and trajectory , their settings strongly impact L3:CM1 charge, so they should be placed first in the optimizer.

Summary

- Both ANN model and PolynomialFeatures regression model are able to predict the L3:CM1 charge (~1% error) from magnets settings
- Detected the machine error (could remove these bad data before fitting)
- Feature importances analysis provides the order of the input variables in the optimizer → speed up the optimization