An integrated scheme for online correction of laser focal position

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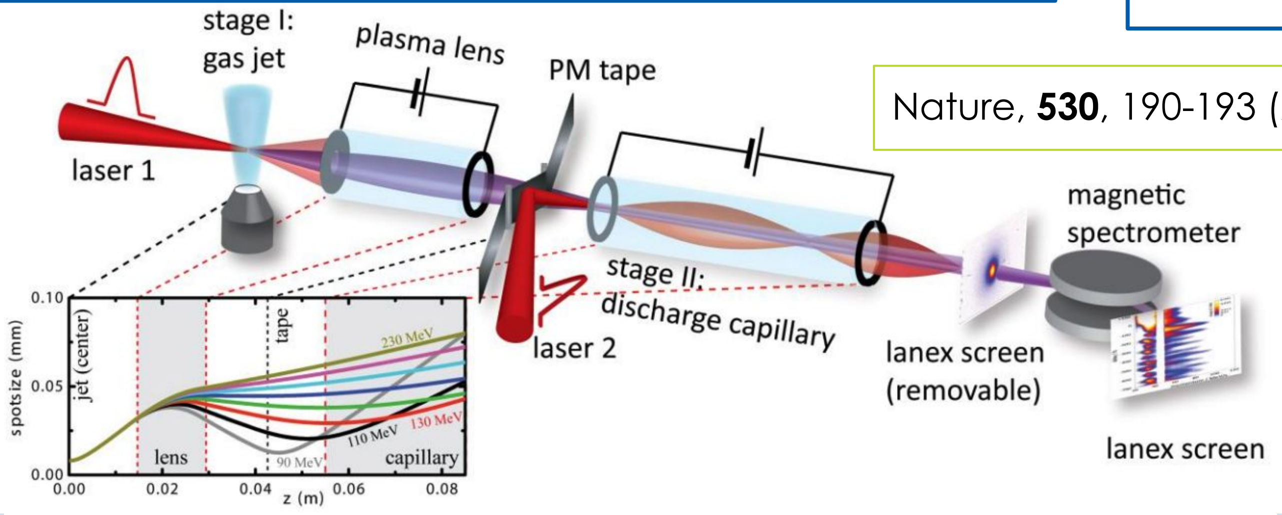
Motivation: High Average Power Lasers for Next Generation Accelerators

High intensity lasers are a critical technology for present-day and future accelerators

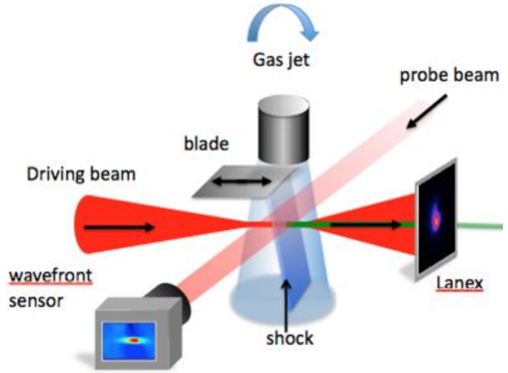
- Electron and proton beam-sources leverage these lasers for ionization, capture, and acceleration
  - Laser plasma accelerators (LPAs) may generate GeV-scale electron beams from cm-scale accelerators
  - Laser-driven ion acceleration schemes rely on careful control of intensity profile and laser/target alignment

New technologies permit real time assessments

- Machine Learning
  - Data from imaging sensors can be inputs to a convolutional neural network for QA
  - Neural networks can be trained to produce corrective adjustments as outputs
- FPGAs
  - Neural networks can be burned-in to chips and then function with low latency
  - Updating/upgrading is possible using the same hardware



Nature, **530**, 190-193 (2016)



Laser Focal Position is a critical figure of merit for experiments

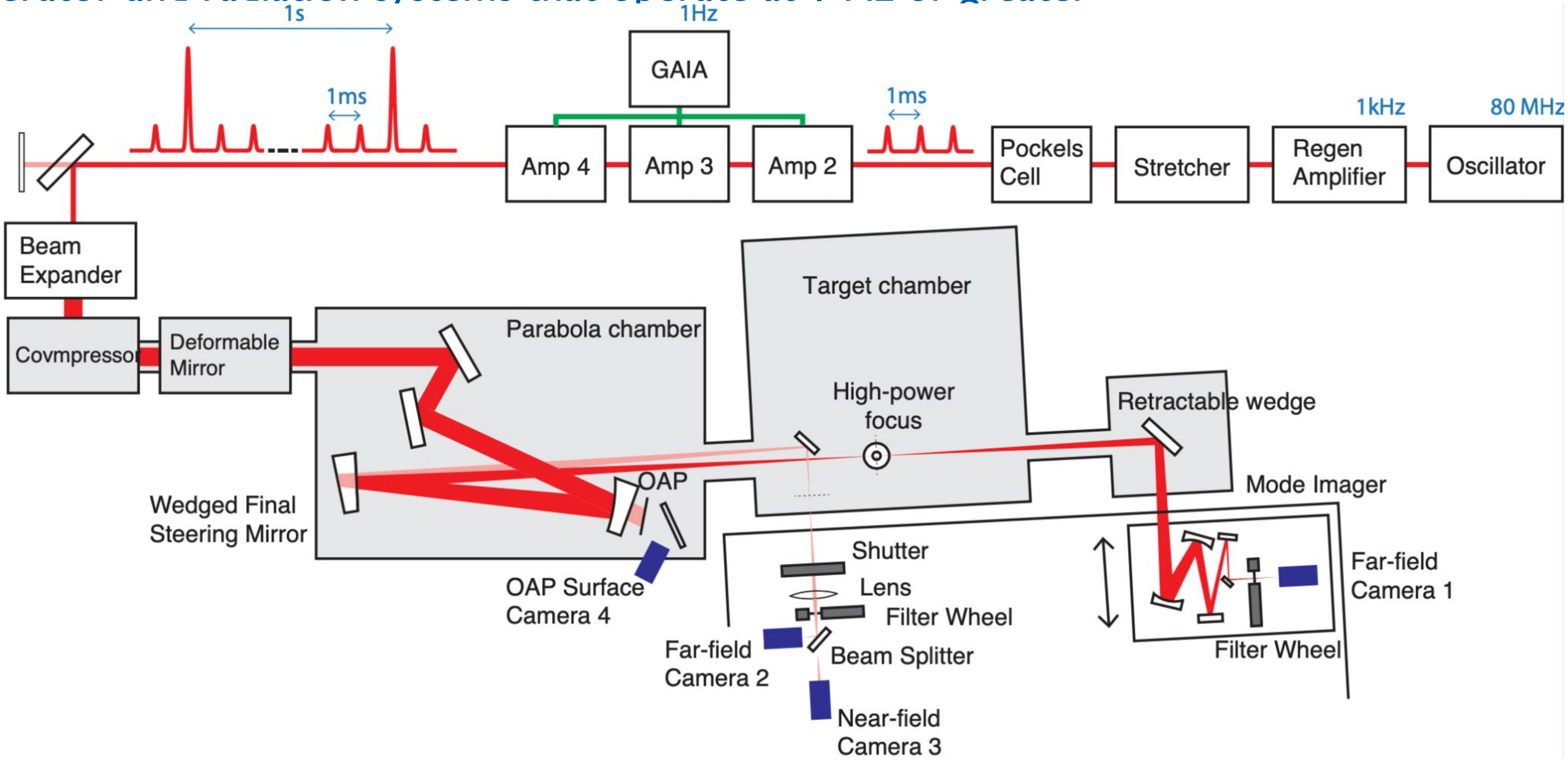
- Focal position is critical for LPA schemes
  - Plasma stages are spatially configured to capture and guide the incident laser wavefront, preserving mode quality and beam intensity throughout the accelerating region
  - Variations in focal position reduce injection physics, capture efficiency, accelerating gradient, and subsequent beam quality

- Focal position is sensitive to many environmental and beamline factors
  - Optical vibrations, alignment, pointing stability, and temperature fluctuations can influence the wavefront
  - These variations couple nonlinearly to interactions with amplifiers, stretchers, compressors, and adaptive optics (AO) systems
  - Many of these fluctuations occur with frequencies >1 Hz, requiring fast identification and correction

- Correction schemes should address deviations as closely to interaction-point as possible
  - Machine protection requirements and optical tolerances limit the use of correction schemes upstream of the final focus
  - Adaptive optics can be used, but may introduce unwanted coupling that risks pointing stability and other control schemes

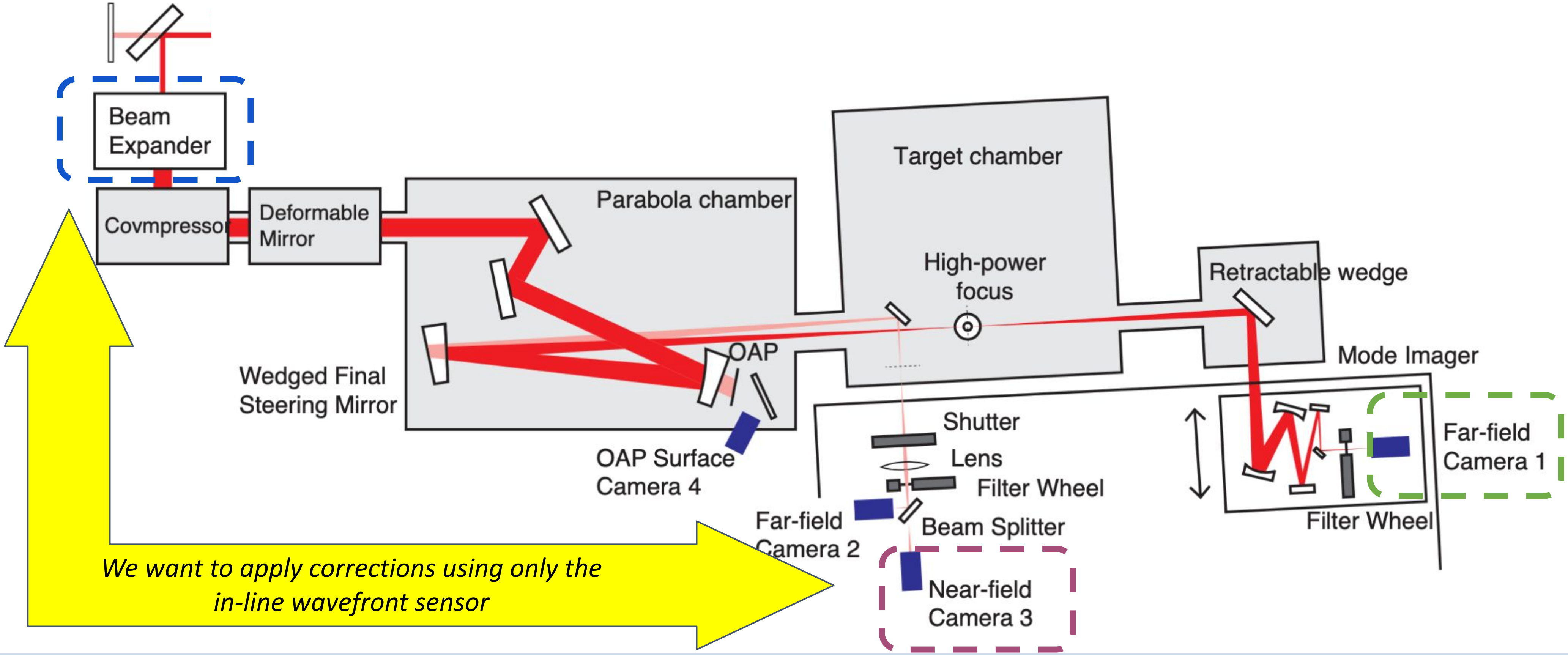
High Power Laser Systems at the BELLA Center

- The BELLA Center at LBL hosts a number of TW- & PW-scale laser systems for prototyping accelerator and radiation systems that operate at 1 Hz or greater



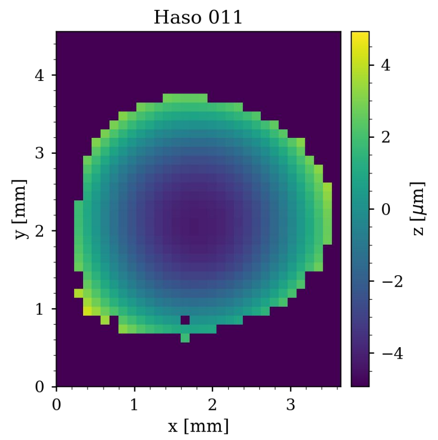
A fast and simple scheme for laser focal position correction

Destructive wavefront sensor (HASO WFS)
Non-destructive wavefront sensor (Thorlabs WFS)
Adjustment Position (Beam Expander)



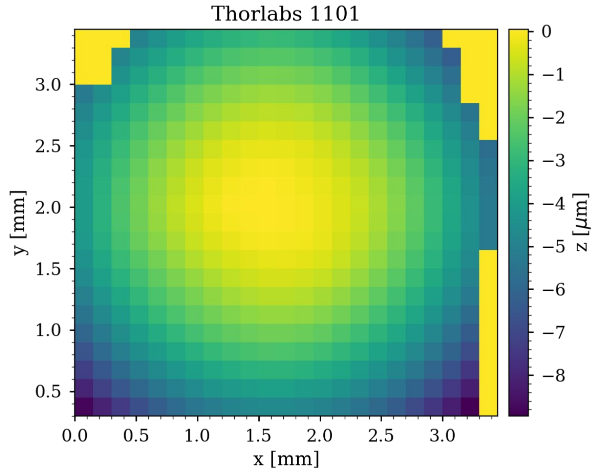
Fast capture and dataset generation

HASO Wavefront Sensor



- Perturbative measurement in beamline
- Hardware produces Zernike fits to go along with images
  - 50%-100% pupil
- 110µm pixel pitch
- 100Hz Read Frequency

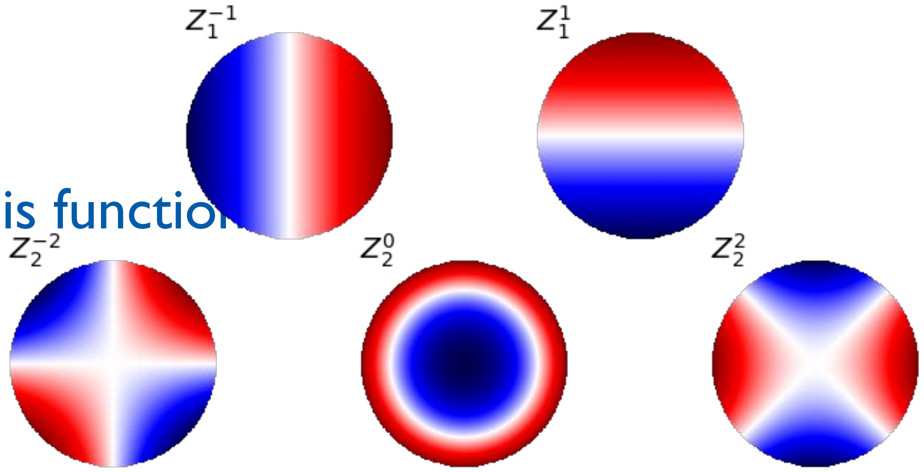
Thorlabs WFS20-7AR Wavefront Sensor



- Non-perturbative measurement
- 150µm pixel pitch
- <u>1 kHz Read Frequency</u>

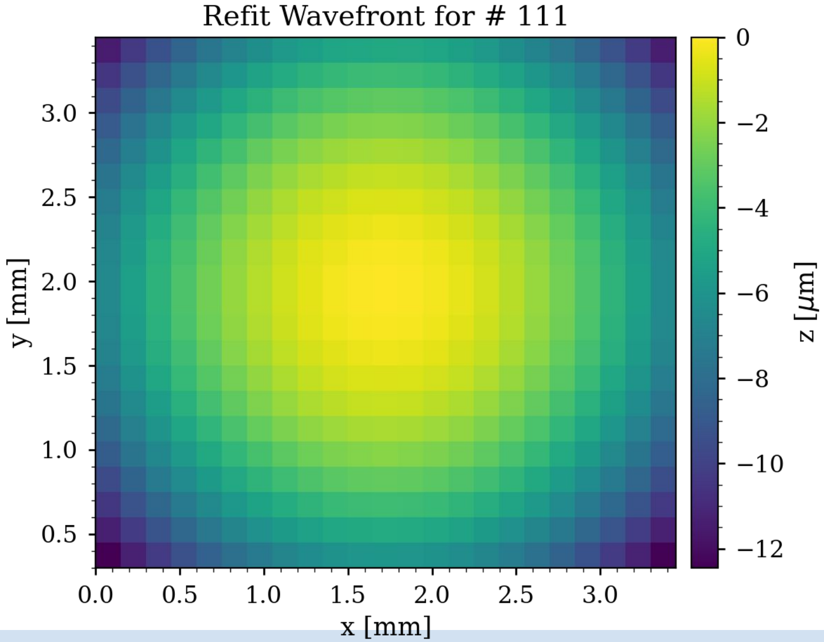
Dataset pre-processing

- Masking noisy or low-information pixels
- Fit Thorlabs wavefront sensor with Zernike polynomial basis functio
  - Starting with lower-order terms

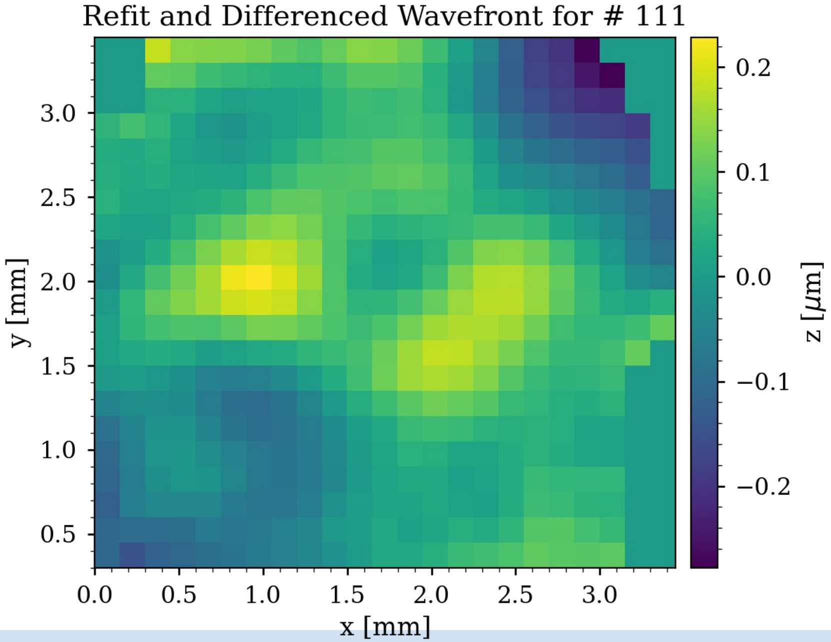


$$Z_1^{-1} = 2z_1\rho\sin(\theta) \quad Z_2^0 = z_3\sqrt{3}(2\rho^2 - 1)$$

- Subtract out top 3 terms:



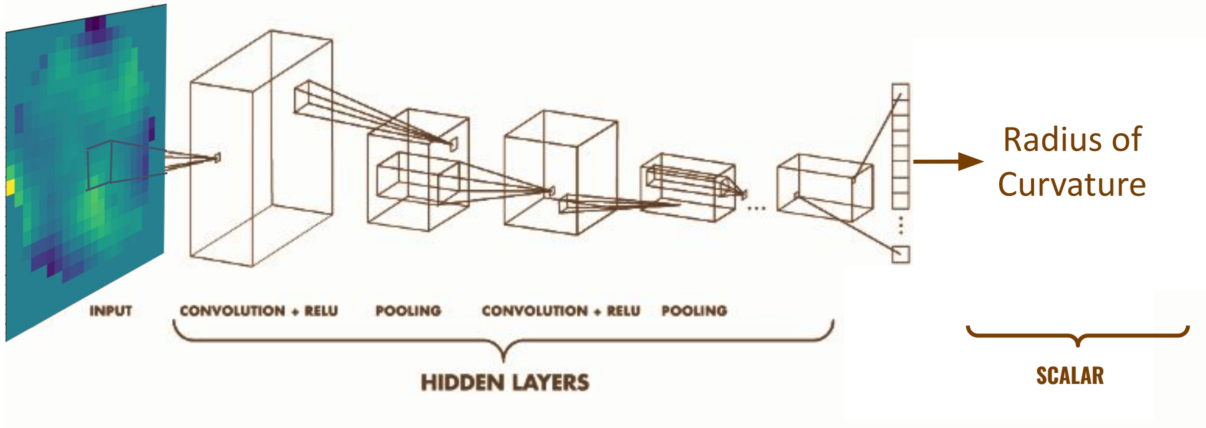
$$- (Z_1^1 + Z_1^{-1} + Z_2^0) =$$



Neural network and initial correlations

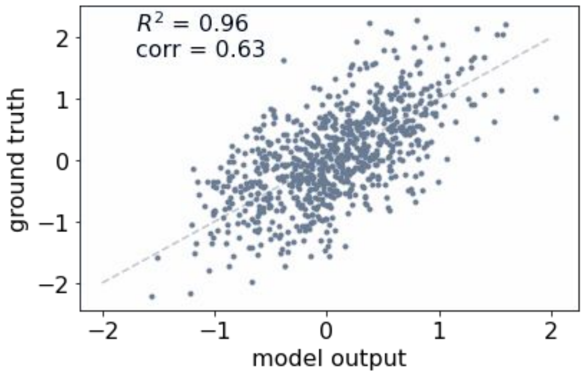
- Investigating convolutional neural networks and feed-forward neural networks for mapping

Convolutional Neural Network



Use differenced images from Thorlabs WFS to learn relationship to the HASO WFS

Exploring architectures with 2 convolutional layers



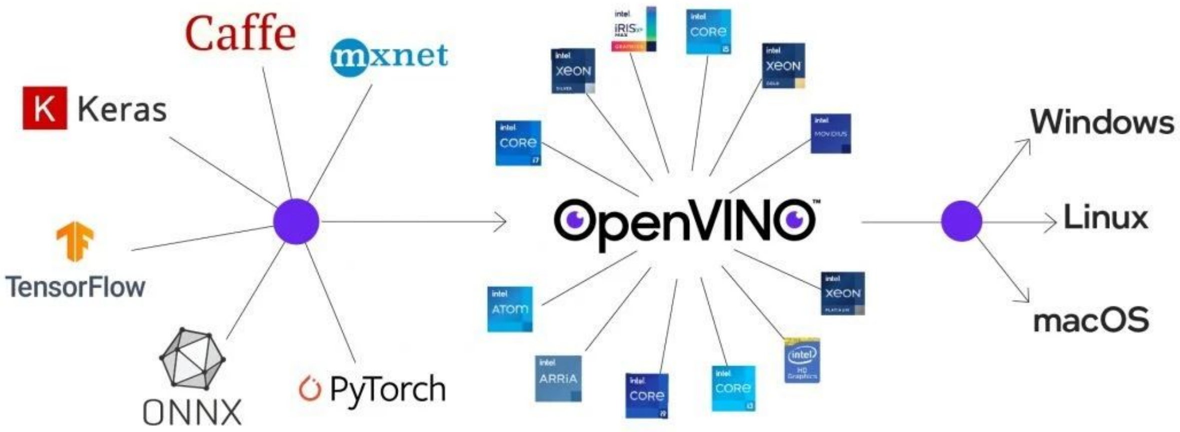
Feed-forward Neural Network

Since focal point errors may not be correlated between cameras, FFNN may be better at learning relationships

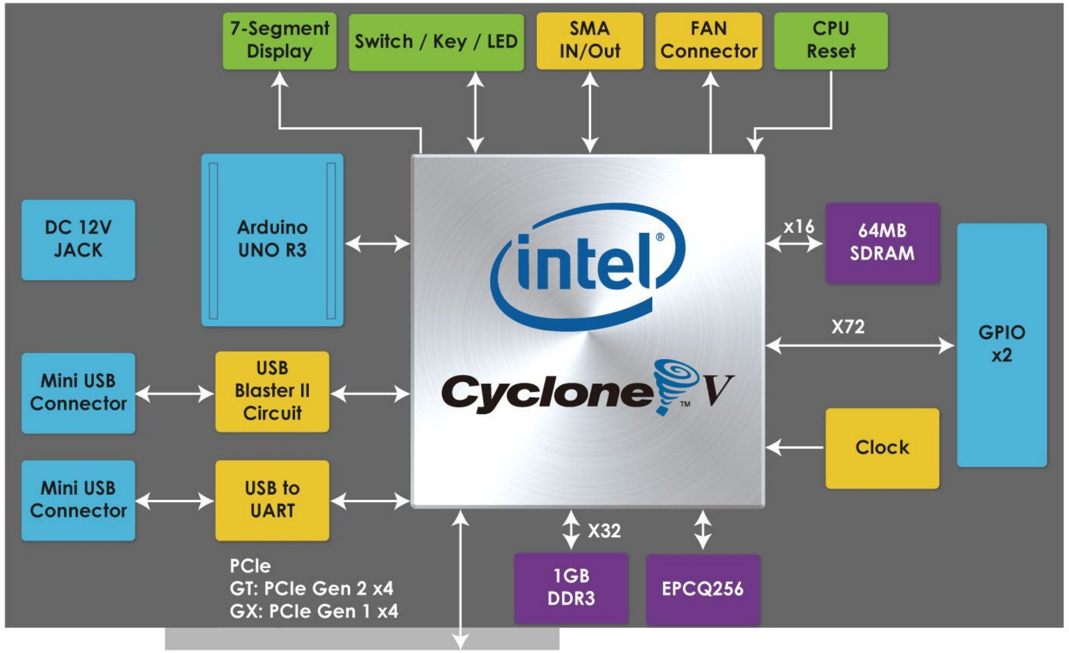
Augment inputs to NN by including Thorlabs hardware scalar outputs

In development - additional data cleaning required

FPGA Deployment Scheme



- Cyclone V GT OpenVINO platform
  - High Level Synthesis
  - Flexibility with TensorFlow/Keras software
  - 125 MHz clock frequency
  - 72 GPIO pins
  - Arduino headers



Conclusion

- High intensity lasers are a critical technology for present-day and future accelerators
  - Electron and proton beam-sources leverage these lasers for ionization, capture, and acceleration
    - e.g. laser plasma accelerators (LPAs) may generate GeV-scale electron beams from cm-scale accelerators
- New technologies permit real time assessments
  - ML - for inference of beam positioning
  - FPGAs - for deployment of ML for real-time corrections
- We are leveraging these technologies to prototype real-time correction schemes for the focal position of high power lasers at > 1 Hz operation