Optimization of high-intensity laser-solid interactions using gaussian process regression.

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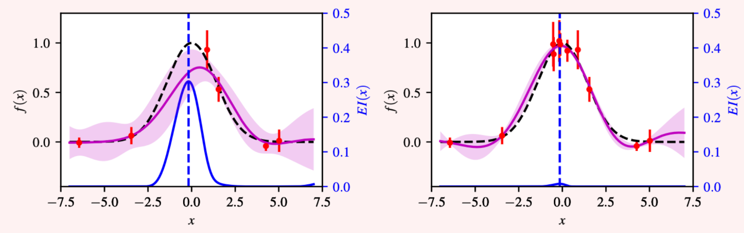
A Bayesian optimizer (BO) using Gaussian processes regression (GPR) provides an efficient way to map a multi-dimensional parameter space focusing on regions of parameter space with desirable properties. Unlike alternative methods of optimization such as genetic algorithms, the BO incorporates all data into the construction of the parameter space model and provides a record of uncertainties.

Plots to the right demonstrate how a model (pink line) is built to represent the parameter space (blue dashed line) from discrete data points (red) and how the expectation value (blue solid line) guides the data acquisition to efficiently map the maxima.

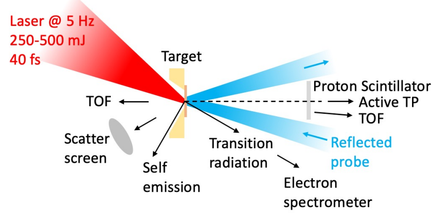
Bayesian Optimization:

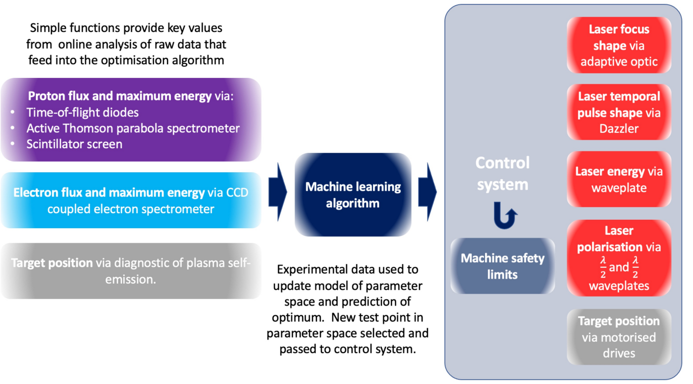


Automated high-repetition rate laser-solid experiment @ GEMINI TA2, CLF:

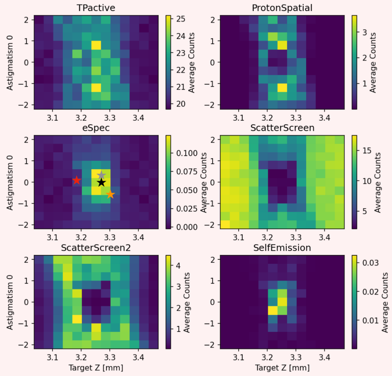
We incorporated control and online feedback through a BO into a high-intensity laser solid interaction at 5 Hz. A schematic of the system (right) highlights the automated hardware and online diagnostics that were utilized for automated optimization of experimental outputs.

Targets were either a tape-drive with positional stability < 5 um, or micron-scale liquid sheet. Target position was diagnosed on-shot using plasma self-emission.





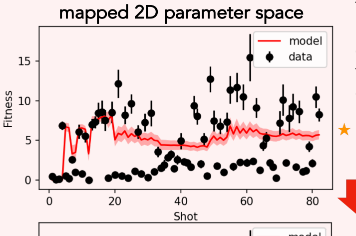
The importance of providing the optimization with accurate measurements:



Slices of parameter space mapped with grid scans provide valuable insight (left: target position vs. astigmatism) but are inefficient for multi-dimensional parameter space.

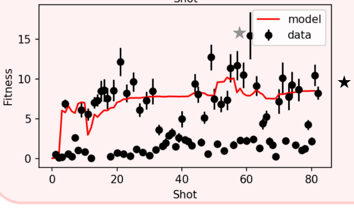
Initial optimizations were performed using the target position readout for target z. For these the algorithm struggled to accept "good data" and incorporate it into the model (see example below). Here, the optimization over the same 2D parameter space failed to finding the brightest electron signal. This was greatly improved by incorporating the measured target position.

Optimization of electron flux in mapped 2D parameter space



(Left) Measured fitness for consecutive bursts with predicted optimum (red) with final value marked by orange star on 2D map above.

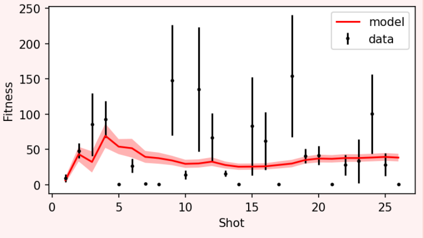
Incorporating the measured target position into the optimization after data collection



(Left) Predicted model optimum (red) significantly closer to mapped optimum marked by black star on 2D map above.

Dealing with model collapse to a diagnostic floor and noisy signal:

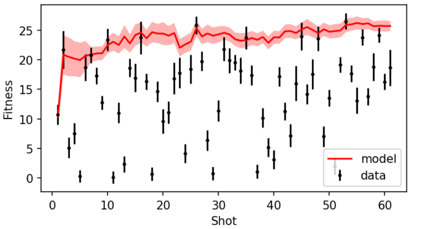
For diagnostics with threshold behavior (i.e. measuring the maximum energy of a spectrometer at the low signal-to-noise threshold) obtaining the measurement error from the standard deviation of measurements will not represent the true error of the measurement. As shown (right) this can result in the GPR model over-trusting these low points and ignoring the measurements that return non-zero values due to their relatively high errors. This can be fixed by including the errors due to the finite sensitivity of the diagnostic.



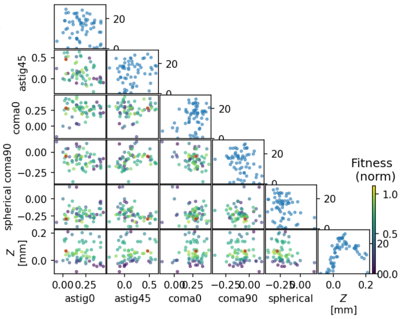
Determining the key interaction drivers through multi-dimensional optimization:

A 5D parameter optimization of laser wavefront and target position, starting from manually optimized focus, showed *a > 2x gain in maximum proton energy* measured by the time-of-flight diodes.

Plot below illustrates measured fitness for consecutive bursts and predicted optimum (model).



The pair plots demonstrate the algorithm explored the parameter space and highlights the *dominant effect of target position on the fitness value.*



Summary:

- A Bayesian optimization based on Gaussian process regression was implemented within a high-repetition rate, high-intensity laser-solid experiment to tune the experimental parameters towards desirable outputs for the first time.
- Optimizations tuned laser wavefront, temporal pulse shape and target position, with on-shot measured target position fed back into the optimization.
- Future developments will look to improve the model performance in sharply varying parameters space and incorporate more powerful adjustor 'knobs'.