Optimization of laser pulse duration using SPIDER and DAZZLER feedback loop

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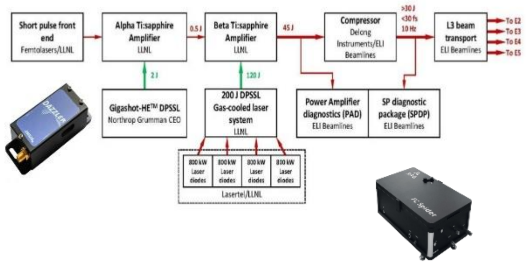
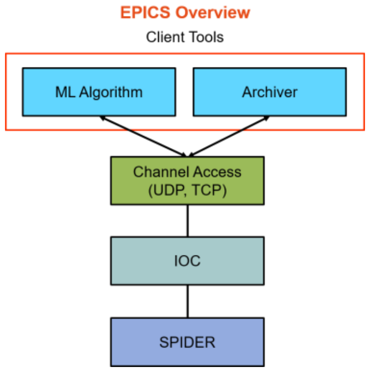
Motivation

Generating high quality plasma accelerated particle beam requires optimization of several laser parameters. One of them is temporal shape of laser pulse. For this purpose L3 HAPLS (The High-Repetition-Rate Advanced Petawatt Laser System) laser system in ELI Beamlines uses Dazzler from Fastlite and FC SPIDER from A.P.E. The purpose of this work is development of control feedback loop between SPIDER and Dazzler that would allow fast and reliable optimization of the laser pulse shape.



Approach

Both SPIDER and Dazzler are already implemented into HAPLS control system. For this purpose new SPIDER software was developed in collaboration with A.P.E. A.P.E provided instrument library for spectrometers and SPIDER algorithm. New SPIDER software enables real-time measurement running on real-time hardware with pulse reconstruction time less than 25ms. SPIDER measurement is published live using EPICS 3.14. This solution uses Channel Access protocol and is linked to an archiver. Data is read and published into EPICS using a custom developed LabVIEW library ((LabIOC - developed in collaboration with Observatory Sciences).

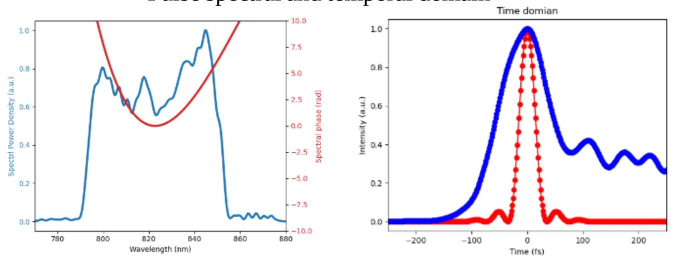


The optimization algorithm is written as a function in Python and then implemented into LabVIEW code through a LabVIEW Python node. Optimization can be done in two ways. First, by changing three DAZZLER phase parameters: GDD, TOD and FOD. Second, to optimize the whole phase function. The second approach allows optimization of higher order terms. New values after the optimization iteration of the aforementioned three parameters or a shape of new phase curve are saved to a text file that is uploaded to DAZZLER. It is very important to keep these parameters in allowed value range to prevent damage in the system.

Optimization Algorithms

- ❑ Choice of Loss Function – Mean Square Error (MSE) :

Pulse spectral and temporal domain



$$J = \frac{1}{N}\sum_{t=1}^{N}\left(I(t) - I_{TL}(t)\right)^2$$

Goal: Finding optimal parameter of the model, θ, for which is obtained minimum of the Loss function J

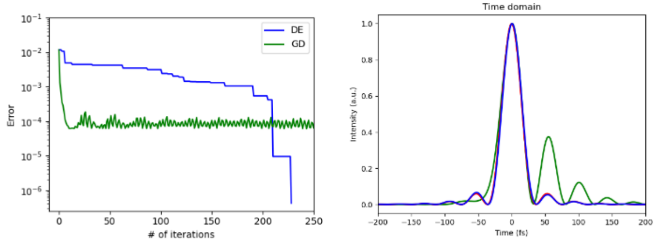
- ❑ Differential Evolution (DE)
  - Black box stochastic and population based evolutionary algorithm
  - Gives good results for global optimization
  - Principle of operation:
    - Generation of Initial population for each parameter within given bounds
    - Loss evaluation for each individual
    - Mutation generation using three different individuals x_1, x_2, x_3 : $x_{mut} = x_1 + F(x_2 - x_3)$
    - Crossover between fourth individual (parent) and x_{mut}.
    - Comparison of loss between parent and mutant and choosing the best for the next generation
    - Procedure is repeated until stopping condition is reached

- ❑ Online Gradient Descent (GD) with adaptive learning rate
  - Most popular first order optimization algorithm
  - Doesn't guarantee to converges to global minimum
  - Parameter update rule:

$$\theta_t^i = \theta_{t-1}^i - \frac{\eta}{\sqrt{\sum_{\tau=1}^{t}\left(g_\tau^i\right)^2}}\, g_\tau^i, \qquad g_\tau^i = \nabla_\theta J\left(\theta_t^i\right)$$

GD algorithm converges very quickly, however it rarely reaches global minimum (dependent on initial phase values). On the other hand DE algorithm finds global minimum but it takes a large number of iteration.

Error and temporal domain of pulse after optimization



Conclusion

Two algorithms are used for optimization of the temporal pulse shape, Differential evolution and Gradient descent. Simulations show that DE requires long time to converge while GD convergence is dependent on initial conditions. Combination of both algorithms converges sufficiently fast. Next steps are possible improvement of GD algorithm, testing of several other algorithms (The Nelder-Mead optimization, Bayesian optimization, Reinforced learning) and full implementation of feedback loop into HAPLS control system.