

# **Adaptive LiTrack at LCLS**

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Alex Scheinker, Los Alamos National Laboratory

Jovan Nelson, Science Undergraduate Laboratory Internship Program

## Outline

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Motivation

LiTrack Upgrades & Description

Extremum Seeking

MD Plan & Future Work

Neural Networks

Scheme for a Virtual Diagnostic

## Motivation

This project has grown out of conversations that started with TTO for Two Bunch Two Color Experiment

Develop a online simulator with a useful set of tools that might provide the following:

- Optimization
- Virtual Diagnostics: e.g. feedback

Explore using a Machine Learning and/or ES algorithms at LCLS

- Using a Neural Network to provide a virtual diagnostic

# LiTrack & Recent Changes

Initialization  
  
☐ Extremum Seeking Mode 100 # of

(beamline legend)

<input checked="" type="radio"/> plot	1	0.003	90	0.104969	5	6.1
<input type="radio"/> plot	1	0.0585003	0	0.104969	5	3.05
<input type="radio"/> plot	1	0.135365	-2.5	0.104969	0	3.05
<input type="radio"/> plot	1	0.0001	0.14	0.135	0	0
<input type="radio"/> plot	1	0.0063	0.14	0.135365	0	8.78
<input type="radio"/> plot	10	0.238883	-22.5307	0.104969	5	8.78
<input type="radio"/> plot	10	0.220073	-160	0.026242	6	0.6
<input checked="" type="radio"/> plot	7	-0.0454703	0.220073	0	5	329.1
<input type="radio"/> plot	1	0.2	0.094	1	5	329.1
<input type="radio"/> plot	1	0	0	0	0	0
<input type="radio"/> plot	10	3.00205	-35.5105	0.104969	5	329.1
<input checked="" type="radio"/> plot	7	-0.027999	3.00005	0	0	0
<input type="radio"/> plot	17	0.54	0.0346	1	0	0
<input type="radio"/> plot	10	4.002	0	0.104969	5	552.9
<input type="radio"/> plot	15	0.0125	76	76	5e-15	0
<input type="radio"/> plot	6	0.000133	0.0063	4	8e-15	1
<input type="radio"/> plot	1	2.62	0.0087	4	8e-15	NaN
<input type="radio"/> plot	15	0.0125	275	3.8e+07	8e-15	0
<input type="radio"/> plot	99	1.32e-05	0	0	0	0
<input type="radio"/> plot	99	0.0025	130	3.8e+07	8e-15	1
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0

Initial Bunch Parameters  
 Bunch popul. (1E10): 0.093633  
 Initial energy (GeV): 0.135  
 z-offset (mm): 0  
 dE/E-offset (%): 0

Wakefield Parameters  
 Number of z-bins: 200  
 /home/physics/dbohler/LiTrackES-32717/Wakefile  
 1. SlacL.dat  
 2. Zwake\_CERN\_Trieste.dat  
 3. Zwake\_SOAB\_Trieste.dat  
 4. Zwake\_SLS7\_Trieste.dat  
 5. slac.dat  
 6. slacx.dat  
 7. tesla.dat  
 8. tesla\_3900.dat  
 (choose file index for 'wakeON' column)

Save/Restore Files  
 /home/physics/dbohler/LiTrackES-32717/SaveFile  
 Long\_SDM.mat  
 Medium1.mat  
 PV\_history.mat  
 PV\_history2.mat  
 Ryan.mat  
 ScriptGenerated.mat  
 bline\_bypass.mat  
 bline\_new.mat  
 dufis.mat  
 (double click to load file)  
 PV\_history.mat

Input Particles from  
☐ Internal source  
☒ External file

Particles from File  
 /home/physics/dbohler/LiTrackES-32717/Particles  
 YAGS5am.zd  
 YAGS7am.zd  
 testData2.zd  
 sigZ scalar: 1  
 Use every other N: 1

Plotting Control  
☐ Small Plots  
☐ Gaussian Z-fit  
☐ Gaussian dE/E-fit  
☒ Color contour image  
 1 Particle fraction to plot

Comment:  
 Generated by script...  
 04/01/2015 13:09:48    
 Loaded from: PV\_history.mat

## Longitudinal Phase Space Tracking Code

- Faster / simpler than 6D codes
- A lot of physics dominated by longitudinal phase space
- Easier integration

# LiTrack & Recent Changes

Initialization:    ☐ Extremum Seeking Mode  # of

(beamline legend)

<input checked="" type="radio"/> plot	1	0.003	90	0.104969	5	6.1
<input type="radio"/> plot	1	0.0585003	0	0.104969	5	3.05
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<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0
<input type="radio"/> plot	99	0	0	0	0	0

Initial bunch Parameters

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Initial energy (GeV): 0.135  
z-offset (mm): 0  
dE/E-offset (%): 0

Wakefield Parameters

Number of z-bins: 200

/home/physics/dbohler/LiTrackES-32717/Wakefile

1. SlacL.dat
2. Zwake\_CERN\_Trieste.dat
3. Zwake\_S0AB\_Trieste.dat
4. Zwake\_S1S7\_Trieste.dat
5. slacx.dat
6. slacx.dat
7. tesla.dat
8. tesla\_3900.dat

(choose file index for 'wakeON' column)

Save/Restore Files

/home/physics/dbohler/LiTrackES-32717/SaveFile

Long\_SDM.mat  
Medium1.mat  
PV\_history.mat  
PV\_history2.mat  
Ryan.mat  
ScriptGenerated.mat  
blin\_bypass.mat  
blin\_new.mat  
dufis.mat

(double click to load file)

PV\_history.mat

Comment:  
Generated by script...

04/01/2015 13:09:48

Loaded from: PV\_history.mat

Input Particles from

☐ Internal source  
☒ External file

Particles from File

/home/physics/dbohler/LiTrackES-32717/Particles

YAGS5am.zd  
YAGS7am.zd  
testData2.zd

sigZ scalar: 1  
Use every other N: 1

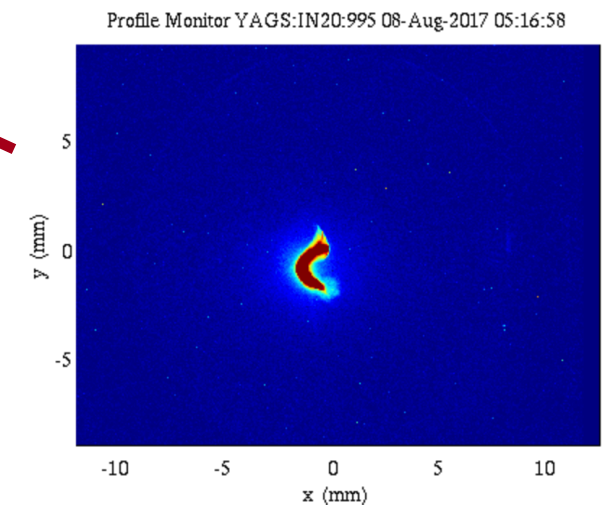
Plotting Control

☐ Small Plots  
☐ Gaussian Z-fit  
☐ Gaussian dE/E-fit  
☒ Color contour image

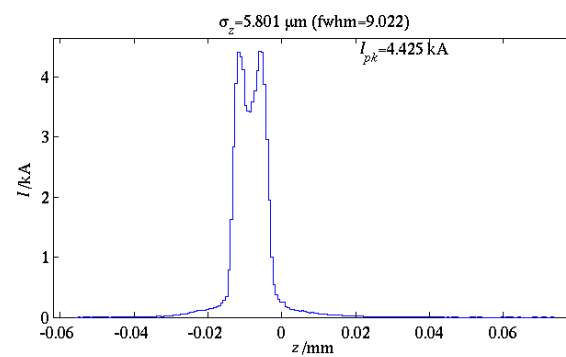
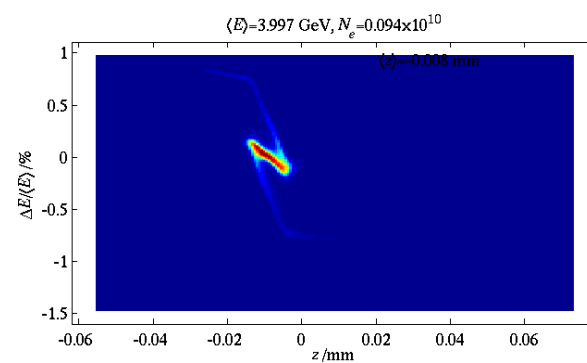
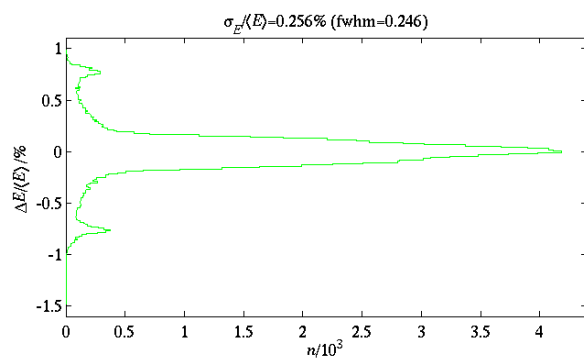
1 Particle fraction to plot

## New Features:

- Input dist. from YAGS2
- Load Machine Parameters
- Extremum Seeking Mode



# LiTrack Output



	opt1	opt2	opt3	opt4	opt5	opt6	opt7	opt8	opt9	opt10
Do Nothing	0.0030	<input type="checkbox"/>	[0,0]	90	<input type="checkbox"/>	[0,0]	0.1050	<input type="checkbox"/>	[0,0]	5
Do Nothing	0.0575	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[-6:6]	0.1050	<input type="checkbox"/>	[0,0]	5
Do Nothing	1.9794e-04	<input type="checkbox"/>	[0,0]	-2.5000	<input type="checkbox"/>	[-6:6]	0.1050	<input type="checkbox"/>	[0,0]	0
Do Nothing	1.0000e-04	<input type="checkbox"/>	[0,0]	0.1400	<input type="checkbox"/>	[0,0]	0.1350	<input type="checkbox"/>	[0,0]	0
Do Nothing	0.0063	<input type="checkbox"/>	[0,0]	0.1400	<input type="checkbox"/>	[0,0]	1.9794e-04	<input type="checkbox"/>	[124,145]	0
L1S Linac	0.2354	<input type="checkbox"/>	[0,0]	-28.5743	<input checked="" type="checkbox"/>	[-45.5:5.5]	0.1050	<input type="checkbox"/>	[0,0]	5
L1X Linac	0.2182	<input type="checkbox"/>	[0,0]	-160	<input checked="" type="checkbox"/>	[-170:-150]	0.0262	<input type="checkbox"/>	[0,0]	6
BC1 Chicane	-0.0463	<input type="checkbox"/>	[0,0]	0.2182	<input checked="" type="checkbox"/>	[0.200:0.01:0...	0	<input type="checkbox"/>	[0,0]	5
Do Nothing	0.2000	<input type="checkbox"/>	[0,0]	0.0940	<input type="checkbox"/>	[0,0]	1	<input type="checkbox"/>	[0,0]	5
Do Nothing	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0
L2 Linac	5.0021	<input type="checkbox"/>	[0,0]	-34.4345	<input checked="" type="checkbox"/>	[-45:-23]	0.1050	<input type="checkbox"/>	[0,0]	5
BC2 Chicane	-0.0280	<input type="checkbox"/>	[0,0]	5.0001	<input checked="" type="checkbox"/>	[3:0.3:5.5]	0	<input type="checkbox"/>	[0,0]	0
CSR	0.5400	<input type="checkbox"/>	[0,0]	0.0346	<input type="checkbox"/>	[0,0]	1	<input type="checkbox"/>	[0,0]	0
L3 Linac	13.9120	<input type="checkbox"/>	[0,0]	-13	<input checked="" type="checkbox"/>	[-30:0]	0.1050	<input type="checkbox"/>	[0,0]	5
Resistive-wall wakefield	0.0125	<input type="checkbox"/>	[0,0]	76	<input type="checkbox"/>	[0,0]	76	<input type="checkbox"/>	[0,0]	5.0000e-15
DL2 Compressor	1.3300e-04	<input type="checkbox"/>	[0,0]	0.0063	<input type="checkbox"/>	[0,0]	13.9100	<input type="checkbox"/>	[0,0]	8.0000e-15
Do Nothing	2.6200	<input type="checkbox"/>	[0,0]	0.0087	<input type="checkbox"/>	[0,0]	4	<input type="checkbox"/>	[0,0]	8.0000e-15
Resistive-wall wakefield	0.0125	<input type="checkbox"/>	[0,0]	275	<input type="checkbox"/>	[0,0]	38000000	<input type="checkbox"/>	[0,0]	8.0000e-15
End of Beamline	1.3200e-05	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0
End of Beamline	0.0025	<input type="checkbox"/>	[0,0]	130	<input type="checkbox"/>	[0,0]	38000000	<input type="checkbox"/>	[0,0]	8.0000e-15
End of Beamline	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0
End of Beamline	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0
End of Beamline	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0
End of Beamline	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0
End of Beamline	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0	<input type="checkbox"/>	[0,0]	0

## Extremum Seeking Example

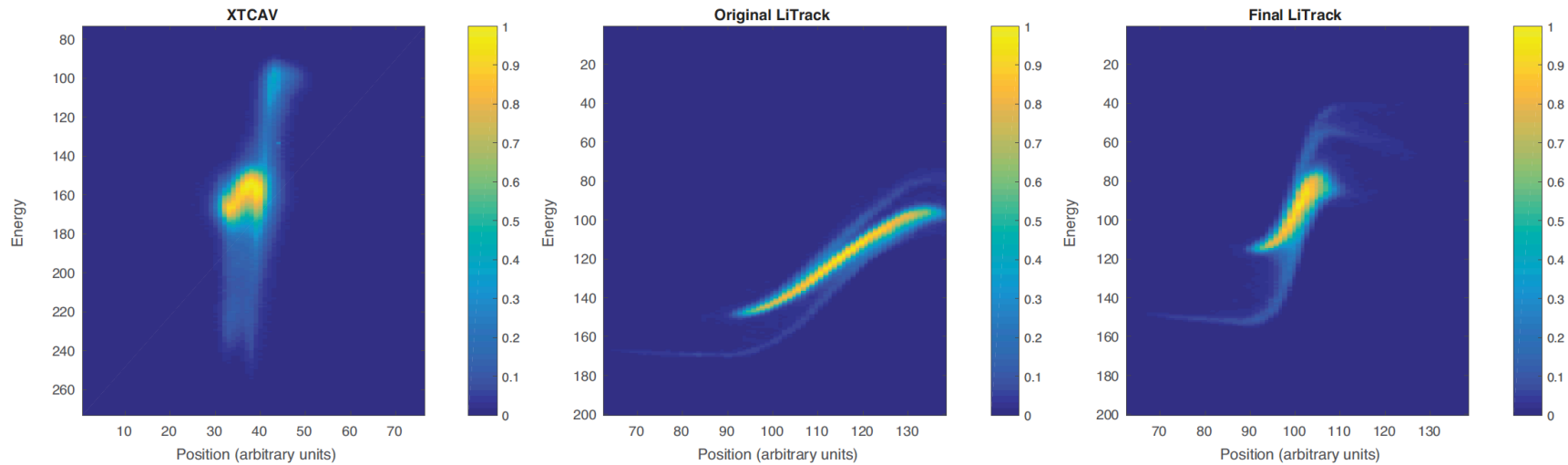


Figure 2: Measured XTCAV, original LiTrack and final, converged LiTrack energy vs position phases space of the electron bunch shown.

### ES advantages

- 1) Multiple parameters tuned simultaneously by dithering at independent frequencies, thereby creating orthogonality in Hilbert space, and extracting the influence of each parameter in real time.
- 2) Robustness to system and parameter time variation and measurement noise – safe.



# Iterative Extremum Seeking Algorithm (Obs.)

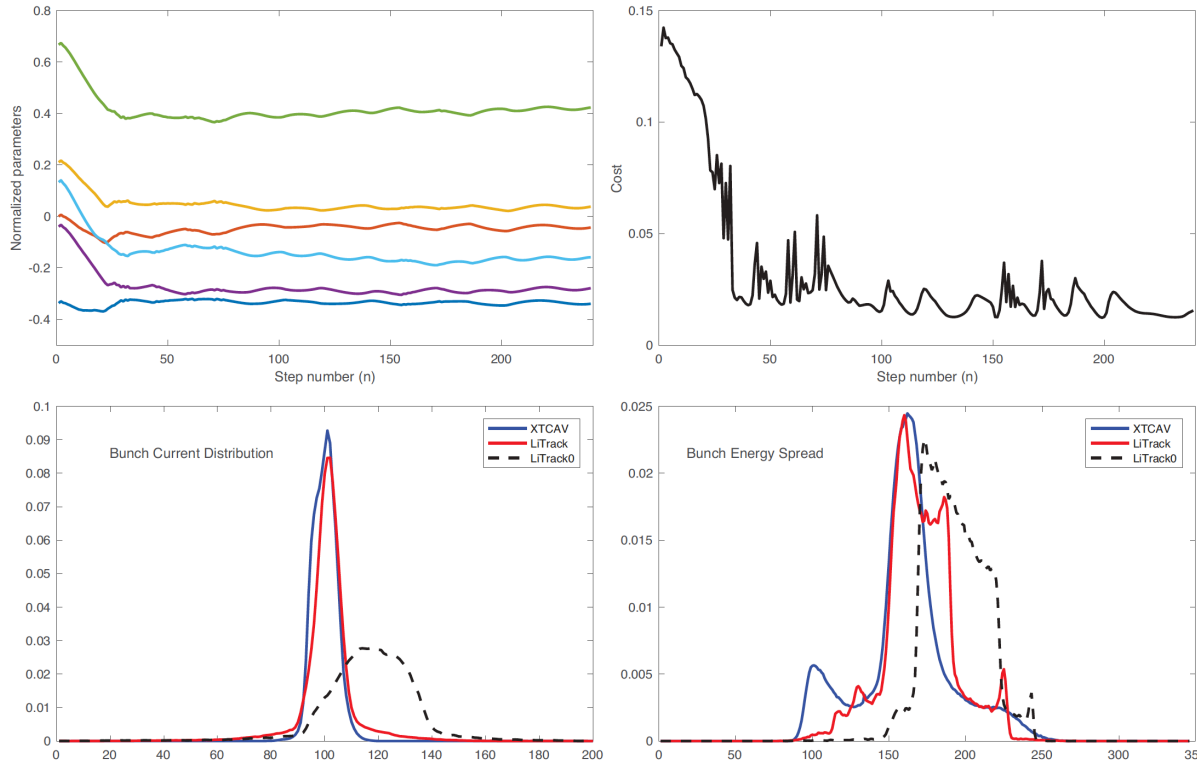


Figure 1: Parameter convergence and cost minimization for matching desired bunch length and energy spread profiles.

XTCAV measured :  $\rho_{\text{TCAV}}(\Delta E, \Delta z)$ ,

LiTrack simulated :  $\rho_{\text{LiTrack}}(\Delta E, \Delta z)$ .

integrated along projections:  
1D energy and charge distrs.

$$\rho_{E,\text{TCAV}}(\Delta E), \quad \rho_{z,\text{TCAV}}(\Delta z),$$

$$\rho_{E,\text{LiTrack}}(\Delta E), \quad \rho_{z,\text{LiTrack}}(\Delta z).$$

$$C_E = \int [\rho_{E,\text{TCAV}}(\Delta E) - \rho_{E,\text{LiTrack}}(\Delta E)]^2 d\Delta E, (1)$$

$$C_z = \int [\rho_{z,\text{TCAV}}(\Delta z) - \rho_{z,\text{LiTrack}}(\Delta z)]^2 d\Delta z, (2)$$

E and z spread distributions were compared to create cost values:

$$C = w_E C_E + w_z C_z.$$

## Iterative Extremum Seeking Algorithm (Updated)



$$Cost = \sum [\rho_{XTCAV} - \rho_{LiTrack}]^2$$

ES performed via finite difference approximation

$$\frac{\mathbf{p}(t + dt) - \mathbf{p}(t)}{dt} \approx \frac{d\mathbf{p}}{dt} = \sqrt{\alpha\omega} \cos(\omega t + kC(\mathbf{p}, t)),$$

by updating LiTrack model parameters

$$p_j(n + 1) = p_j(n) + \Delta \sqrt{\alpha\omega_j} \cos(\omega_j n \Delta + kC(n)),$$

where the previous step's cost is based on the previous simulation's parameter settings

$$C(n) = C(\mathbf{p}(n)).$$

Parameters must be tuned to optimize performance of ES

$\alpha$  - dithering amplitudes

$\omega$  - dithering frequencies

$k$  - feedback gains

$$dt = \frac{(2\pi)}{\max(\omega)}$$

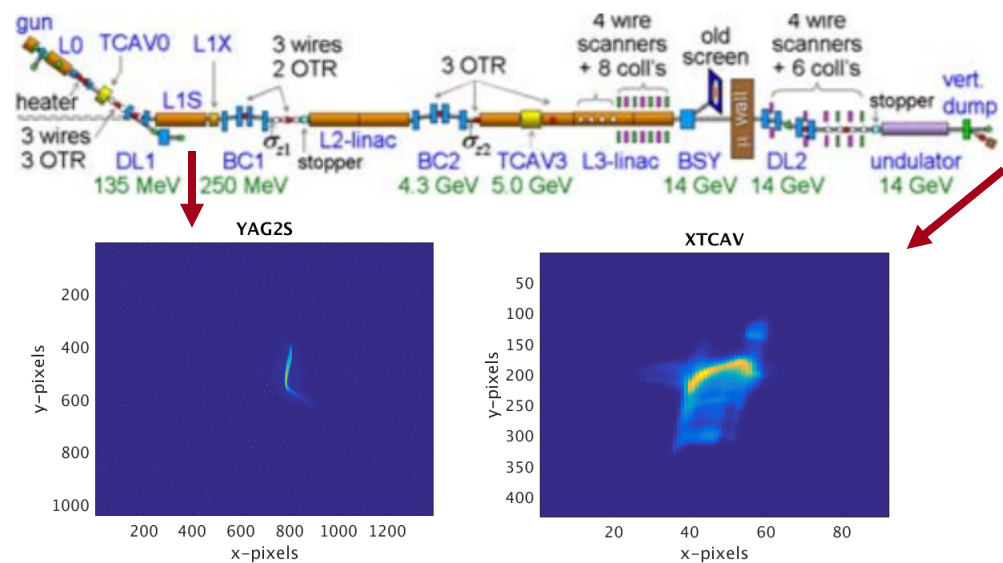
Benefits of ES:

(1) Robust for time varying system

## Previous Shift Plan/Results of Shift – 8/8/17

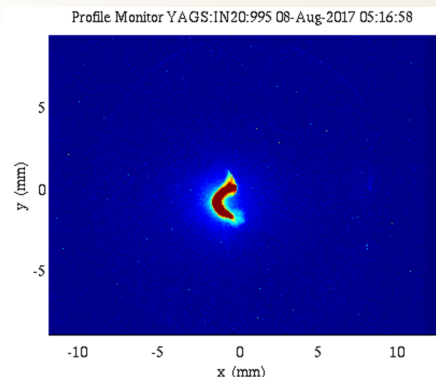
SLAC

- Not much corresponding YAGS2/XTCAV Data
- Goal to obtain more complete data sets
- Take YAGS2 data w/ bunch length calibrations
- Take XTCAV data at various energies
  - 9.5 KeV, 6 KeV, 4 KeV
  - 550 eV, 700 eV, 900 eV

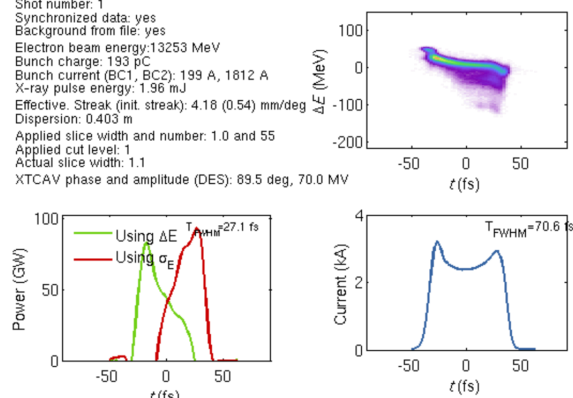


# Some Shift Data

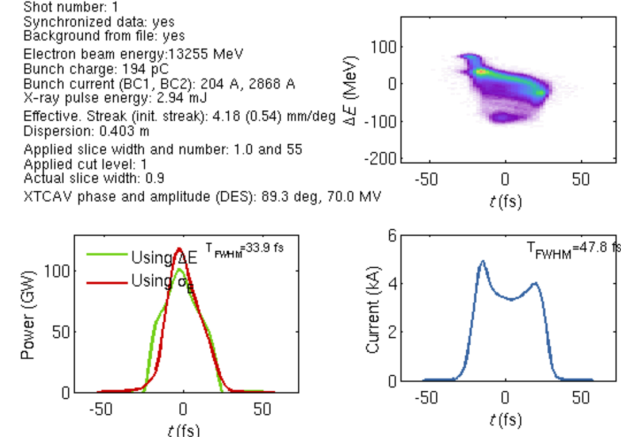
SLAC



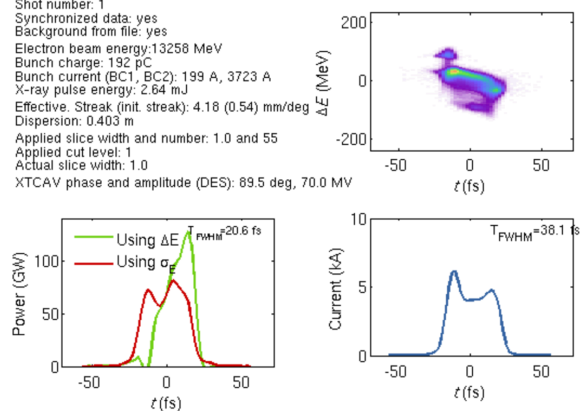
Date and time: 2017-08-08-060915  
 Shot number: 1  
 Synchronized data: yes  
 Background from file: yes  
 Electron beam energy: 13253 MeV  
 Bunch charge: 193 pC  
 Bunch current (BC1, BC2): 199 A, 1812 A  
 X-ray pulse energy: 1.96 mJ  
 Effective. Streak (init. streak): 4.18 (0.54) mm/deg  
 Dispersion: 0.403 m  
 Applied slice width and number: 1.0 and 55  
 Applied cut level: 1  
 Actual slice width: 1.1  
 XTCAV phase and amplitude (DES): 89.5 deg, 70.0 MV



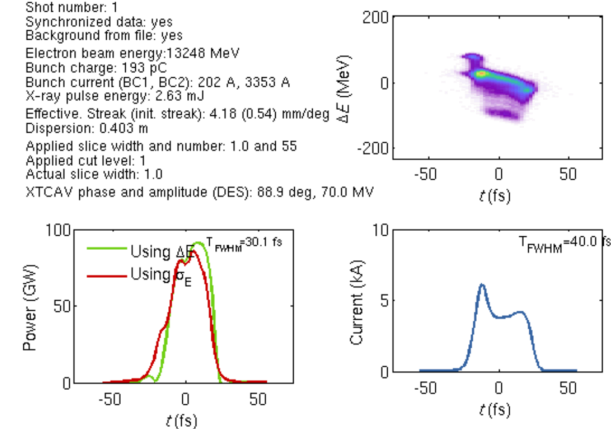
Date and time: 2017-08-08-060859  
 Shot number: 1  
 Synchronized data: yes  
 Background from file: yes  
 Electron beam energy: 13255 MeV  
 Bunch charge: 194 pC  
 Bunch current (BC1, BC2): 204 A, 2868 A  
 X-ray pulse energy: 2.94 mJ  
 Effective. Streak (init. streak): 4.18 (0.54) mm/deg  
 Dispersion: 0.403 m  
 Applied slice width and number: 1.0 and 55  
 Applied cut level: 1  
 Actual slice width: 0.9  
 XTCAV phase and amplitude (DES): 89.3 deg, 70.0 MV



Date and time: 2017-08-08-060837  
 Shot number: 1  
 Synchronized data: yes  
 Background from file: yes  
 Electron beam energy: 13258 MeV  
 Bunch charge: 192 pC  
 Bunch current (BC1, BC2): 199 A, 3723 A  
 X-ray pulse energy: 2.64 mJ  
 Effective. Streak (init. streak): 4.18 (0.54) mm/deg  
 Dispersion: 0.403 m  
 Applied slice width and number: 1.0 and 55  
 Applied cut level: 1  
 Actual slice width: 1.0  
 XTCAV phase and amplitude (DES): 89.5 deg, 70.0 MV



Date and time: 2017-08-08-060805  
 Shot number: 1  
 Synchronized data: yes  
 Background from file: yes  
 Electron beam energy: 13248 MeV  
 Bunch charge: 193 pC  
 Bunch current (BC1, BC2): 202 A, 3353 A  
 X-ray pulse energy: 2.63 mJ  
 Effective. Streak (init. streak): 4.18 (0.54) mm/deg  
 Dispersion: 0.403 m  
 Applied slice width and number: 1.0 and 55  
 Applied cut level: 1  
 Actual slice width: 1.0  
 XTCAV phase and amplitude (DES): 88.9 deg, 70.0 MV



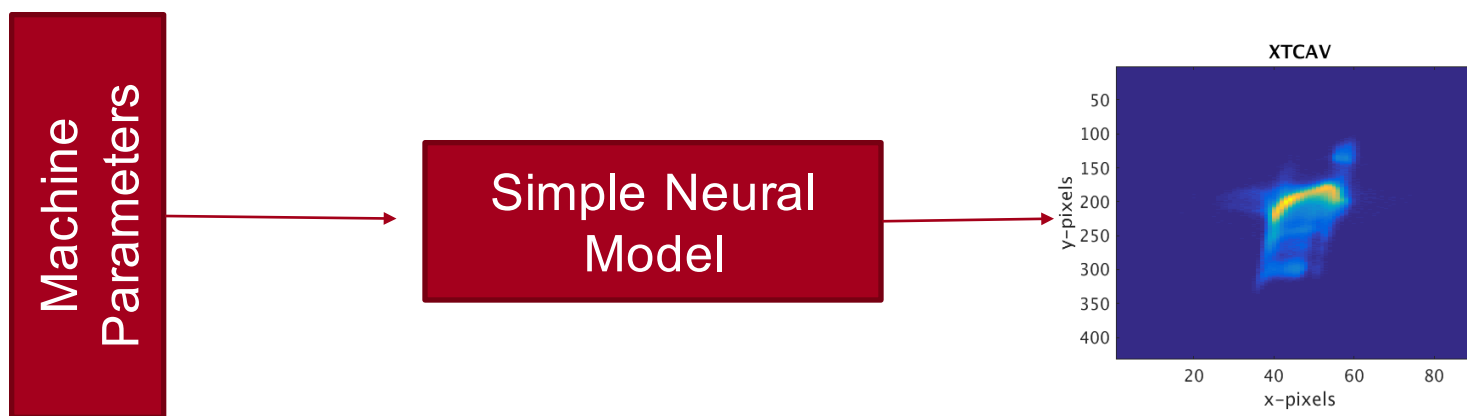
## Future Plan



### Future Work

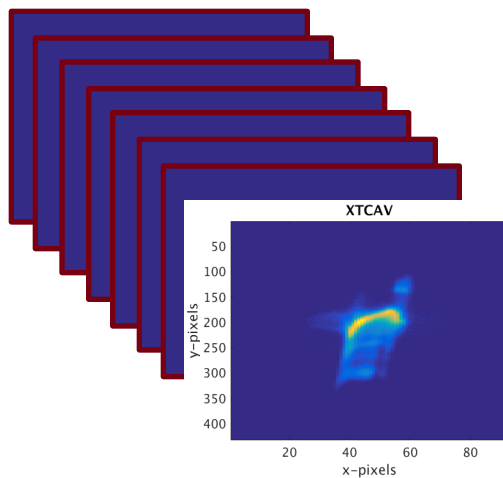
- Verify / study how well the simulator is working and identify the limits of the simulation
- Look at how each input changes wrt small changes and make sure model is consistent
- Build catalog for standard injector setups for SAB Data?
- Compare LiTrack output to more diagnostics (e.g. Blen monitors, OTR )
- Compare Optimization Algorithms ES, GD, GA for convergence, speed, robustness...

# Exploring Neural Networks

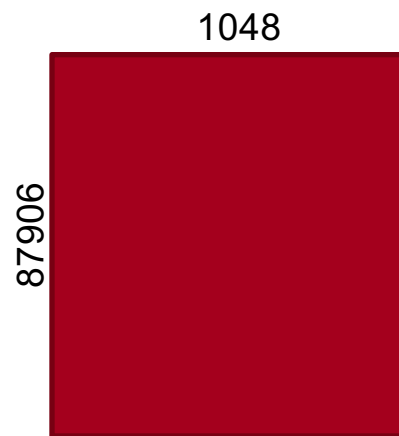


# Principle Component Analysis

1048 XTCAV Images 2014-16



Size of images: 294 x 299



Reduce  
Dimensionality  
Using PCA



Represent data  
using  
1000 components



PCA Inverse Transform



## Description of PCA

Three main steps:

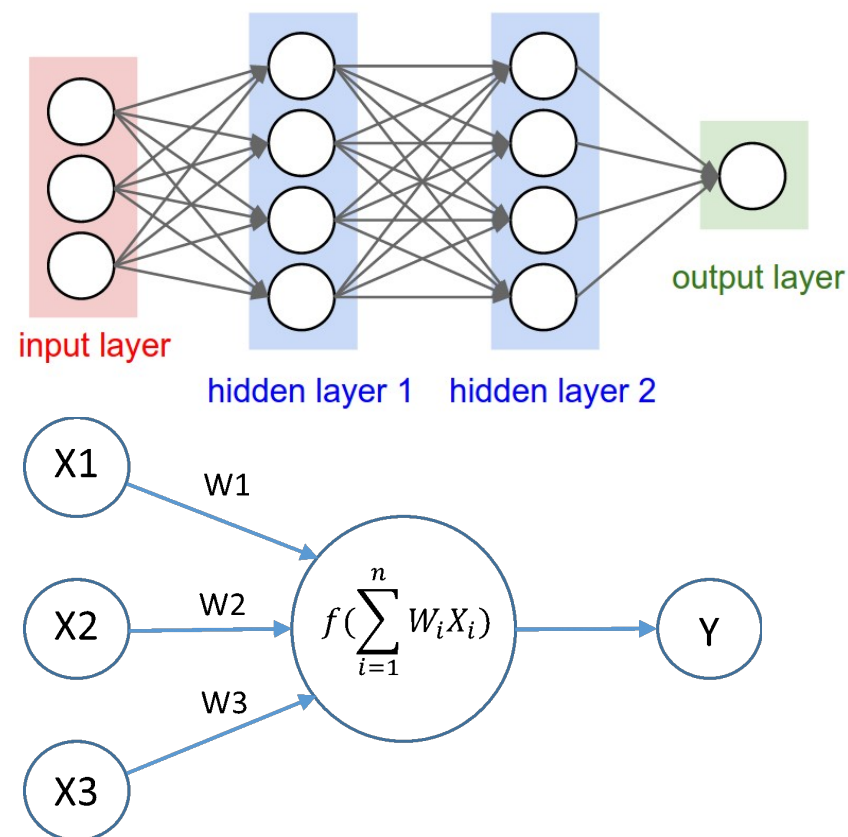
- Eigen decomposition
- Selecting Principal Components by sorting the eigenpairs
- Projection onto a new feature space



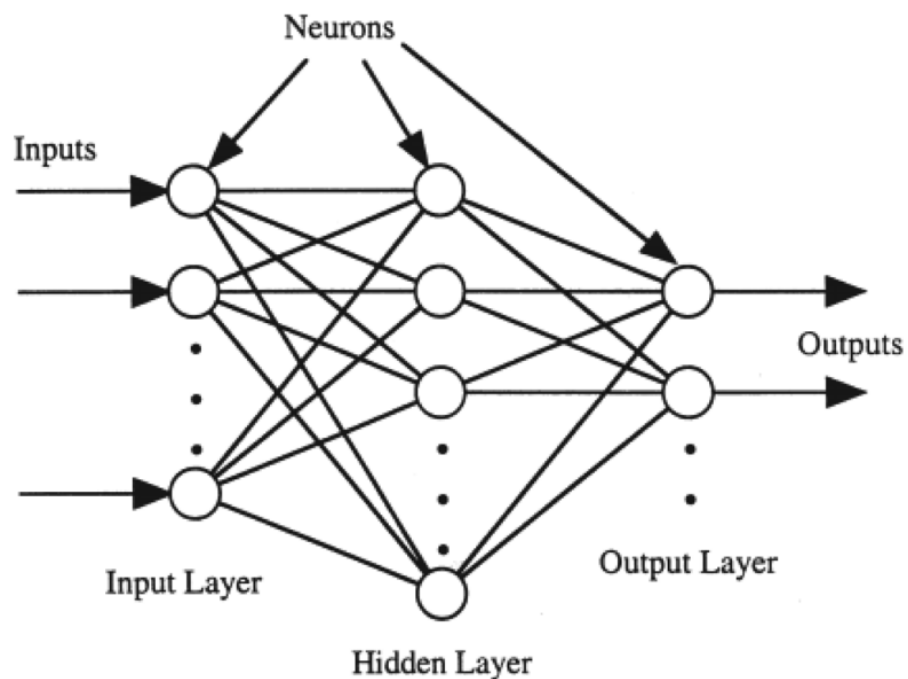
## Modeling Accelerators: Artificial Neural Networks

Has artificial neurons that mimic the human brain to learn about data

- A type of machine learning:
  - Supervised
- Use training data to generate weights that are then used to predict the data you're interested in.
- Activation functions can be used at each layer of neurons to learn nonlinear trends in the data



## Graphic of Network

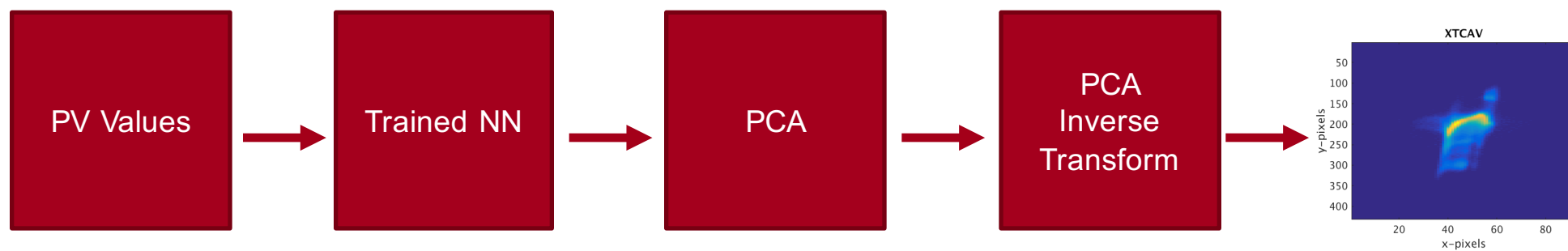


11 PVs

1500 nodes

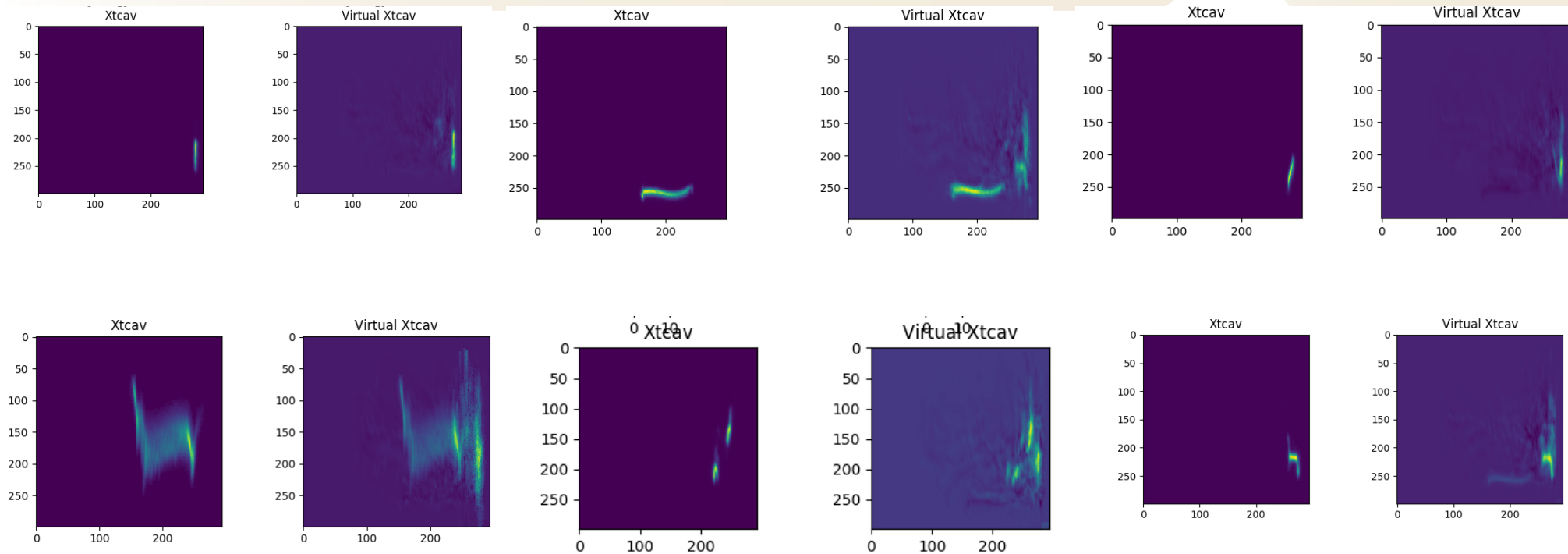
1000 PCA features

L1SE (GeV)	L1Sphi (deg)	L1XE (GeV)	BC1 R56	BC1E (GeV)	L2E (GeV)	L2phi (deg)	BC2E (GeV)	L3E (GeV)	L3phi (deg)	DL2E (GeV)
---------------	-----------------	---------------	------------	---------------	--------------	----------------	---------------	--------------	----------------	---------------

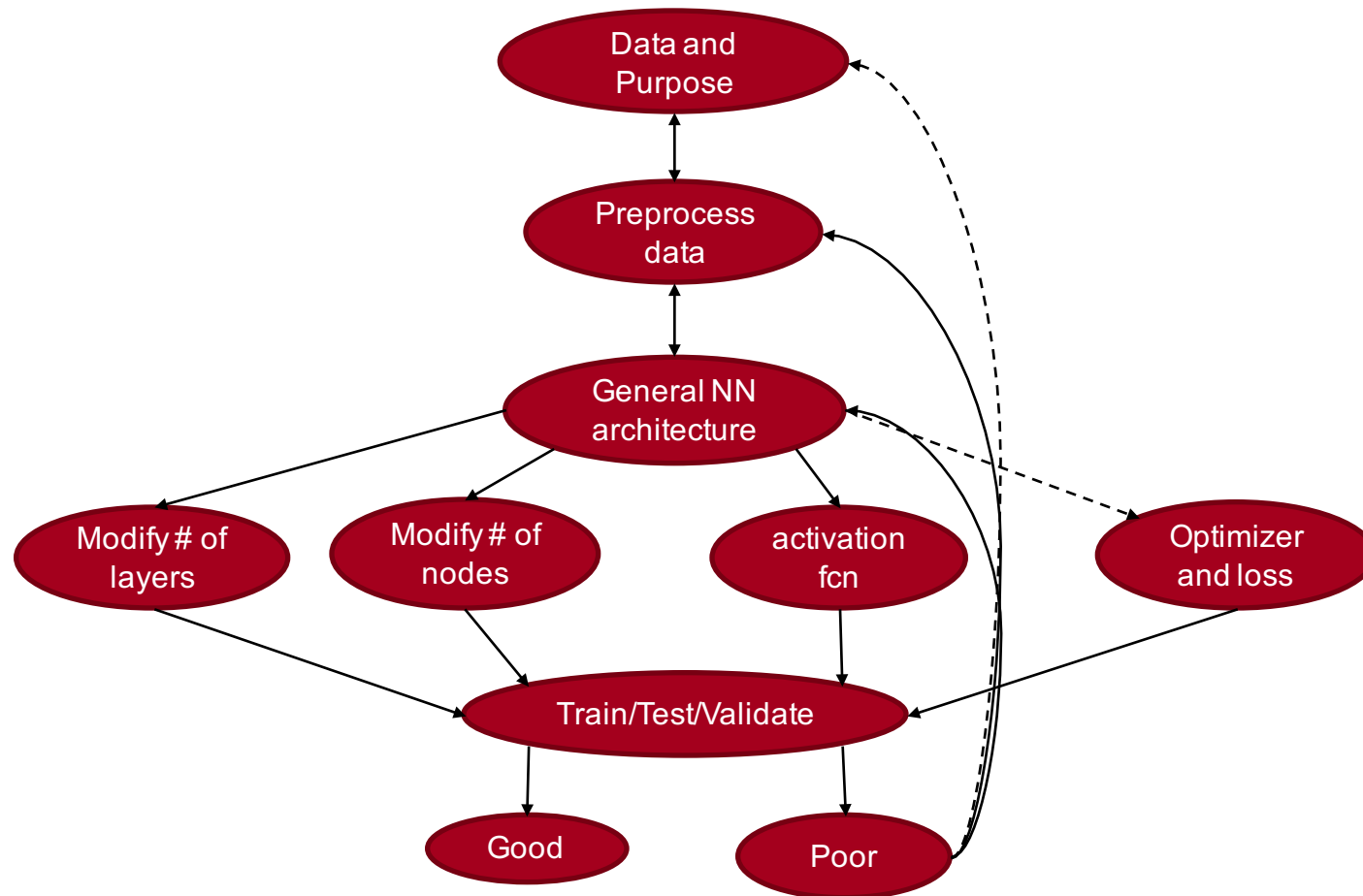


# Preliminary Data

SLAC



## Next Steps ...

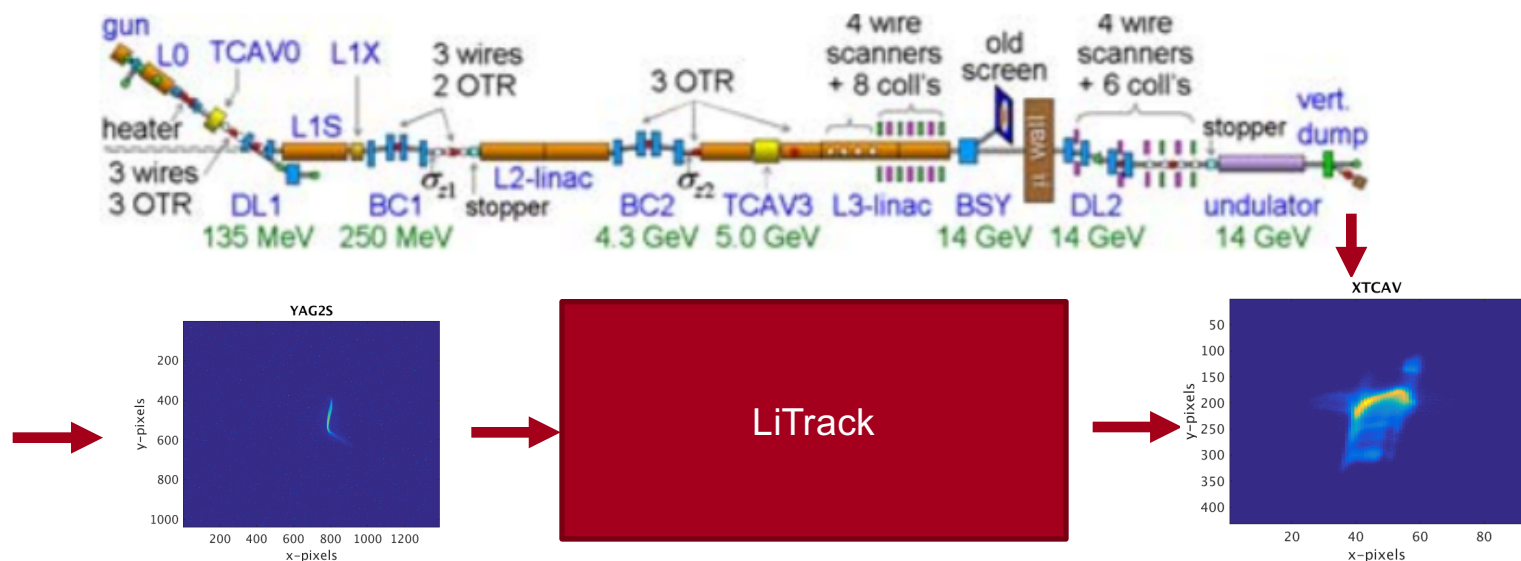


## Scheme for a virtual diagnostic?

Trained NN

Inj long  
profile /  
pulse  
stacker

Injector  
PV Values



Virtual Diagnostic = Neural Networks may be use to predict longitudinal distribution before L1S which serves as an input into LiTrack or other physics models. Using the Extremum Seeking (or other optimization) routine we can then feedback back on the XTCV output. Using a back calculation feature would allow us to compute the Longitudinal distribution anywhere in the machine. Could add many tuning automation tools to this framework.

Feedback with XTCV