FACET-II
Facility for Advanced Accelerator Experimental Tests

Novel diagnostics and beam phase space recovery

C. Emma
FACET-II Science Workshop, SLAC
October 2017

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Presentation Outline

1. Introduction and motivation
   1.1. FACET- Bunch profile prediction

2. FACET-II advanced diagnostics upgrades

3. Schematic software learning workflow

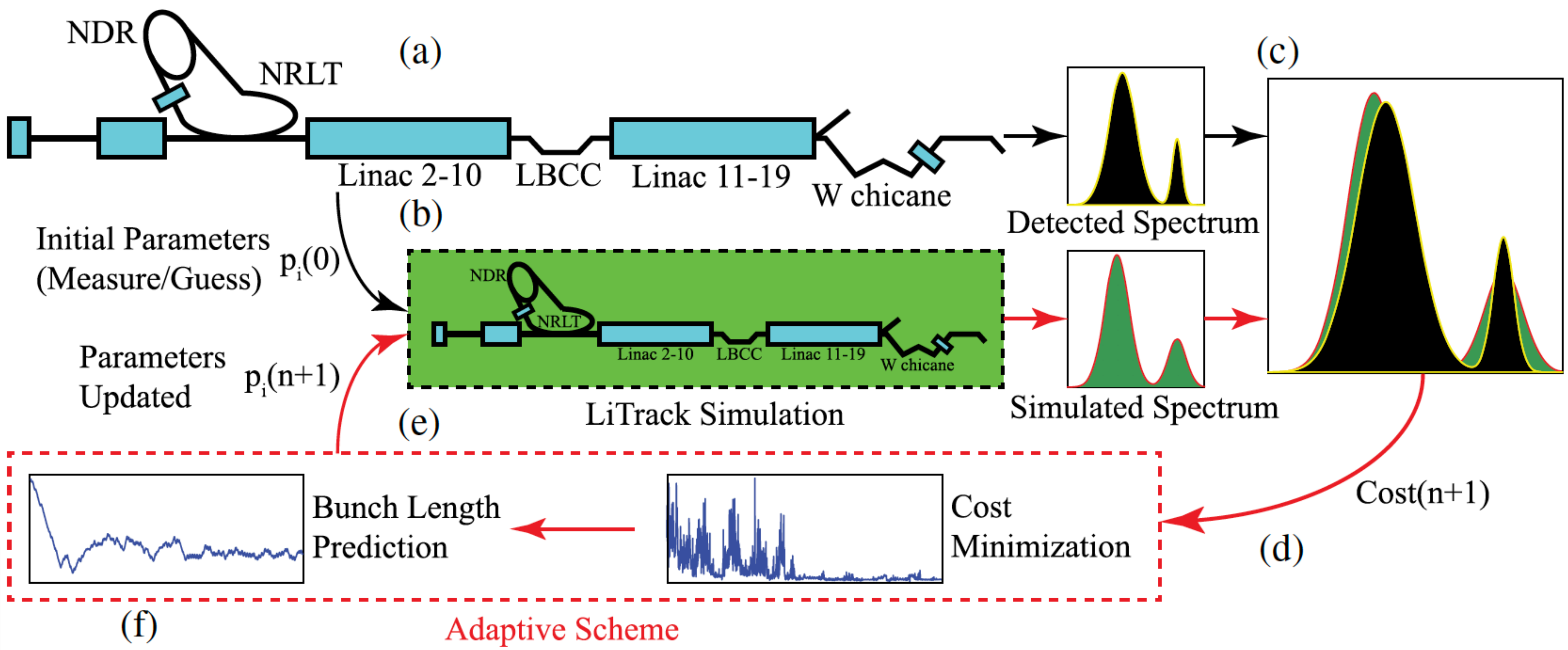
   3.1. Example optimization LCLS undulator taper

4. First steps: working plan for FACET-II

5. Conclusions

Example - Bunch profile prediction at FACET

Guess machine parameters and simulate with LiTrack



Measure energy spectrum on SYAG

Compare LiTrack spectrum with SYAG

Adapt machine parameters to minimize difference

With “correct” machine parameters estimate longitudinal bunch profile based on LiTrack output LPS

Scheinker, Gessner, PRSTAB **18** 102801 (2015)

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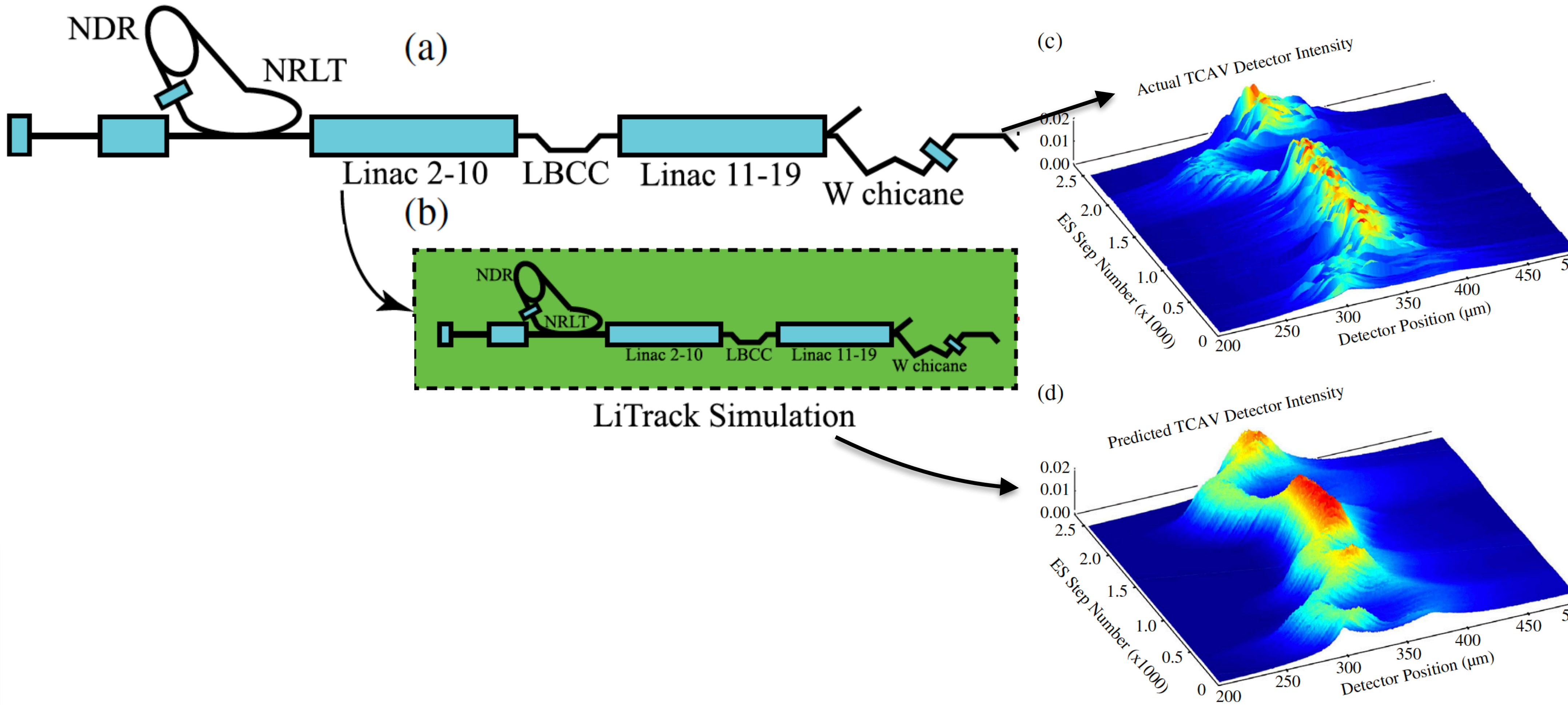

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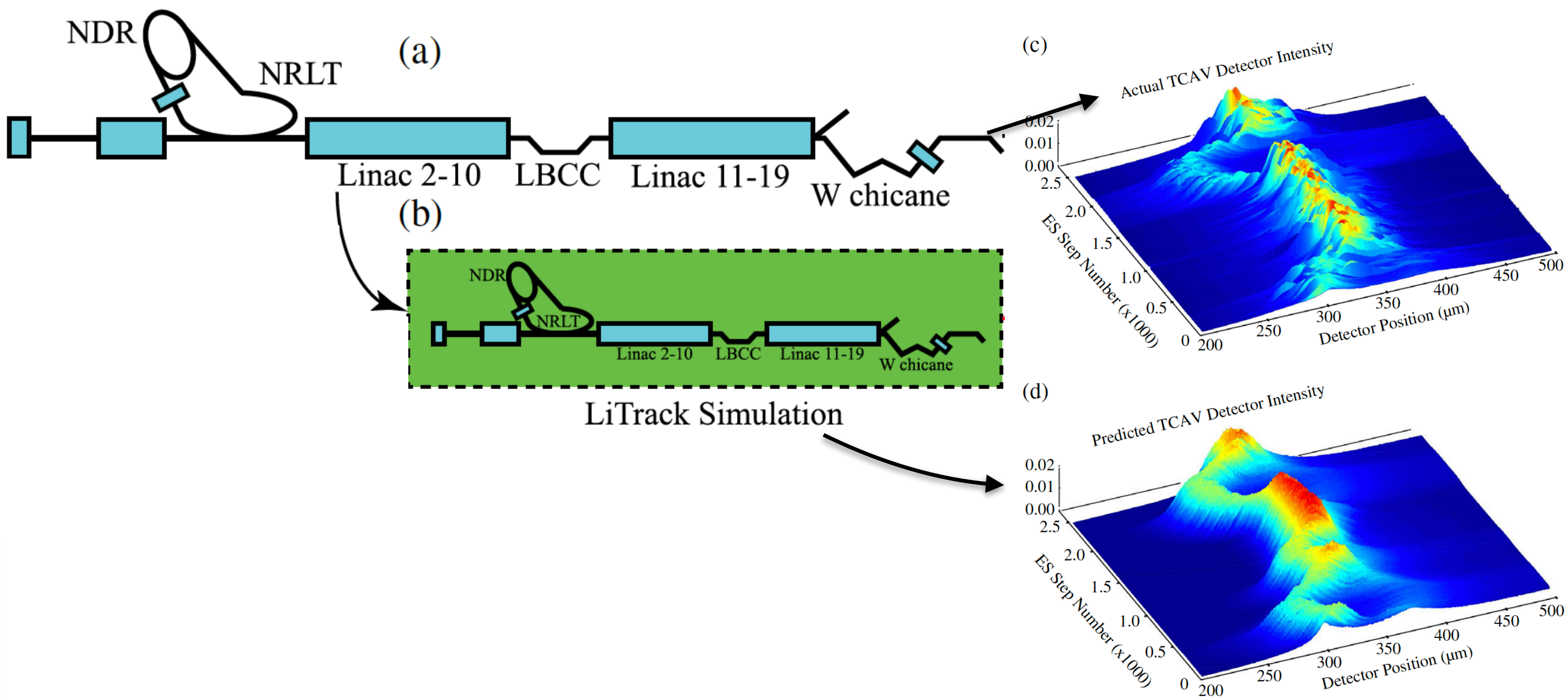


Measure energy spectrum on SYAG

Compare LiTrack spectrum with SYAG

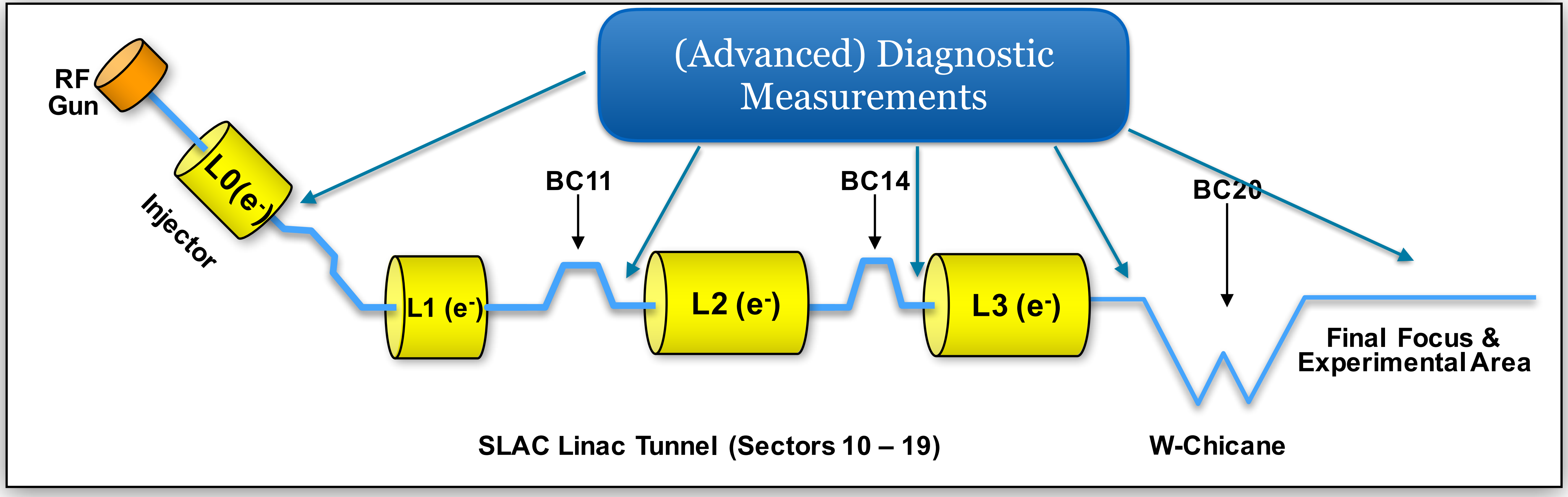
Adapt machine parameters to minimize difference

With "correct" machine parameters estimate longitudinal bunch profile based on LiTrack output LPS

Convergence rate and accuracy is sensitive to the initial parameter guess

Furthermore, we hope to one day utilize LiTrackES as an actual feedback to the machine settings in order to tune for desired electron beam properties.

Motivation for FACET-II work



FACET-II will deliver beams with *exciting* characteristics:

- 10 GeV, 100 kA, $\delta\gamma/\gamma$~1 %, ε_n~1 μm, $\sigma_\perp$ ~10 μm

Software Modeling

(1) Can we meet the challenge of measuring such intense beams by using:

- Advanced non-destructive diagnostics
- Interplay between experiment and (real-time) simulations

to recover the beam phase space on a shot-by-shot basis?

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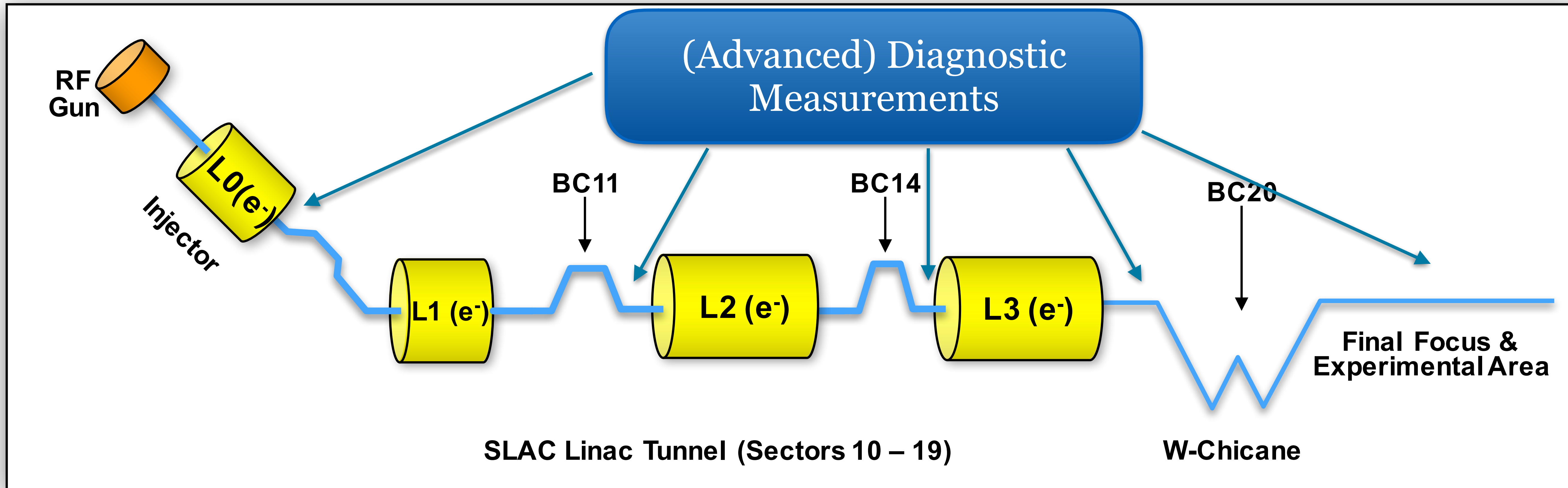

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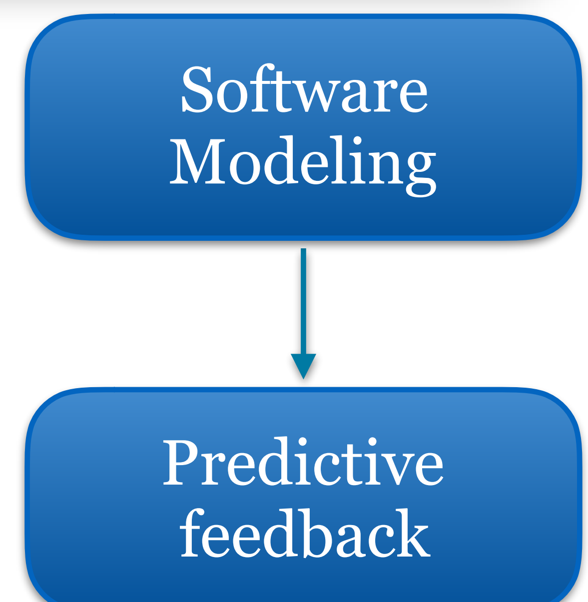
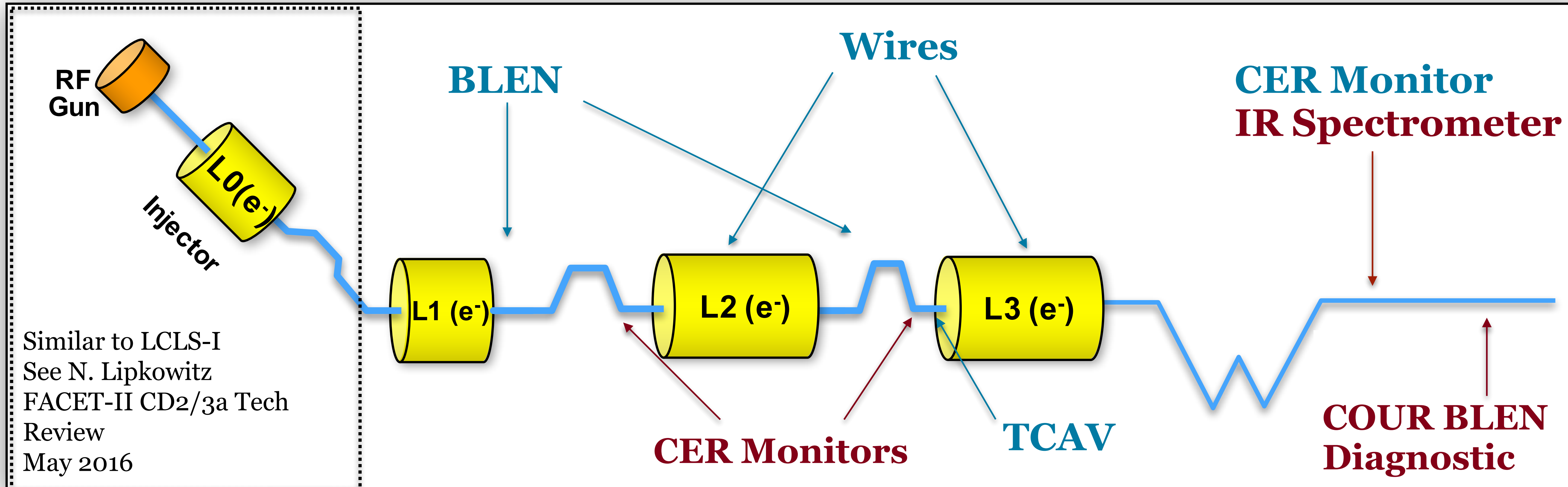
(2) Can we use the predictive properties of (1) to feedback on the machine and produce the phase space we want?



FACET-II Diagnostic improvements

SLAC



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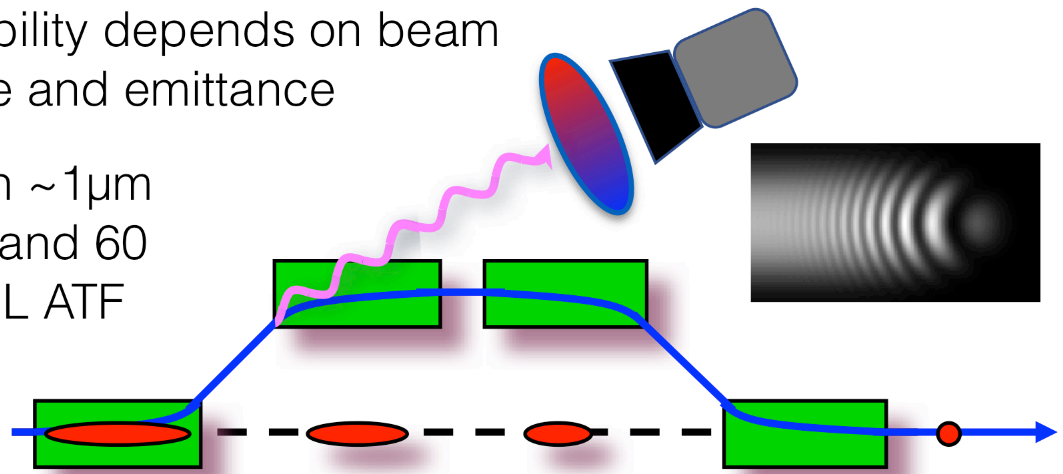
New non-interceptive diagnostics can constrain the model parameters improve convergence and prediction

(2) Can we use the predictive properties of (1) to feedback on the machine and produce the phase space we want?

Concepts for Novel Beam Diagnostics at FACET-II

Interference of Dipole Edge Radiation – Monitor for Beam Divergence

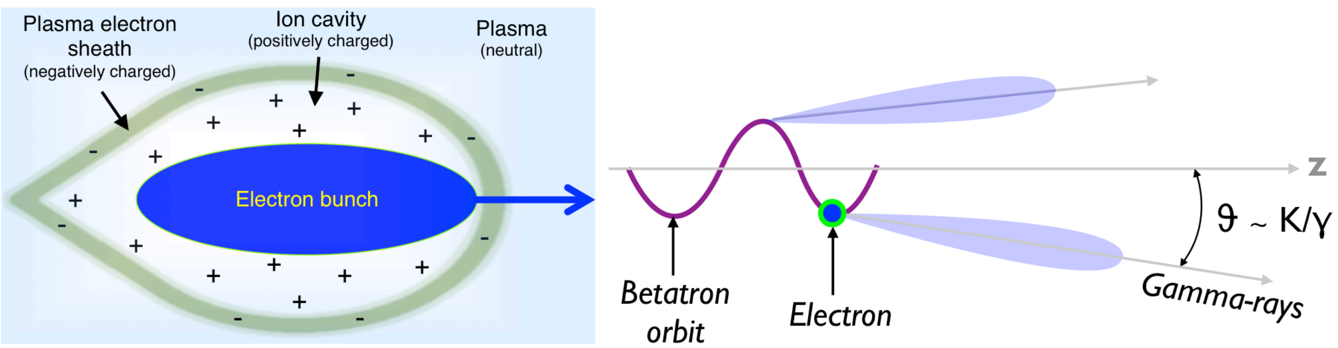
- Fringe visibility depends on beam divergence and emittance
- Tested with ~1μm emittance and 60 MeV at BNL ATF



O. Chubar PhD thesis 1990

Betatron Radiation for Measuring Ultra-low Emittance

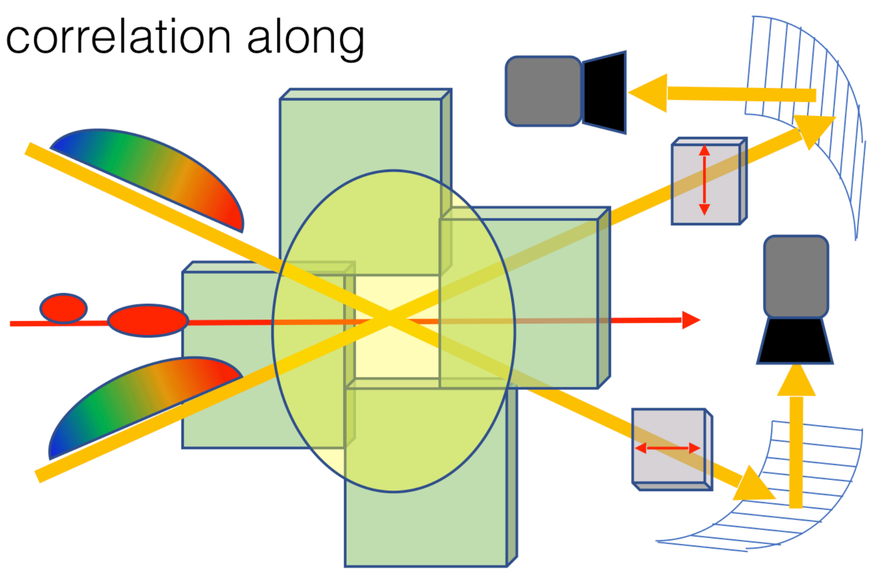
- Central betatron wavelength proportional to beam energy
- Linewidth of the radiation proportional to beam emittance



J. Rosenzweig, 2016 FACET-II Science Workshop

Quadrant EOS to Measure r-t Beam Correlations

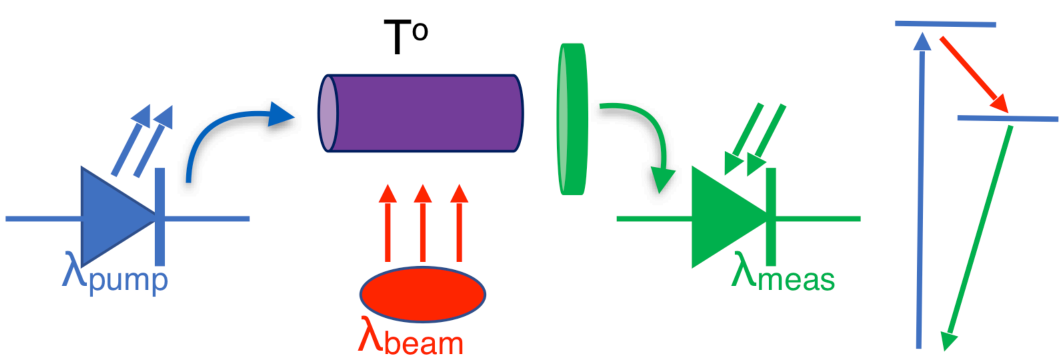
- Goal is to measure correlation along ~1ps long bunch
- Spectrally encoded EOS with imaging spectrometer enable non-destructive measurement of correlations



V. Yakimenko, Private comm.

Bunch Length Monitor for 3-30fs Long Bunches

- Laser light resonantly pumps gas to excited state
- Relaxation to intermediate state triggered by beam field
- Emission rate from intermediate to ground state depends on temporal spectrum of the beam field



M. Zolotorev, Private comm.

Unprecedented beams at FACET-II provide exciting diagnostic challenges

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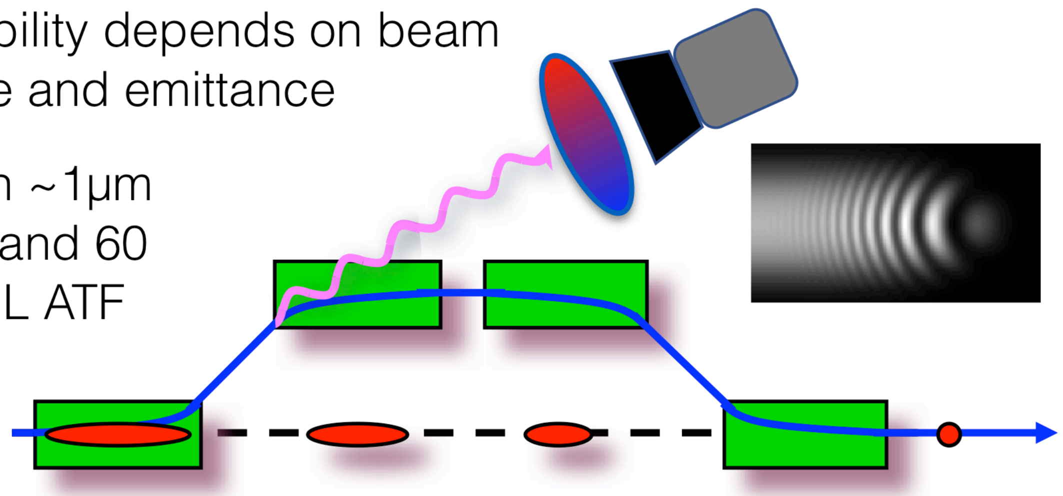

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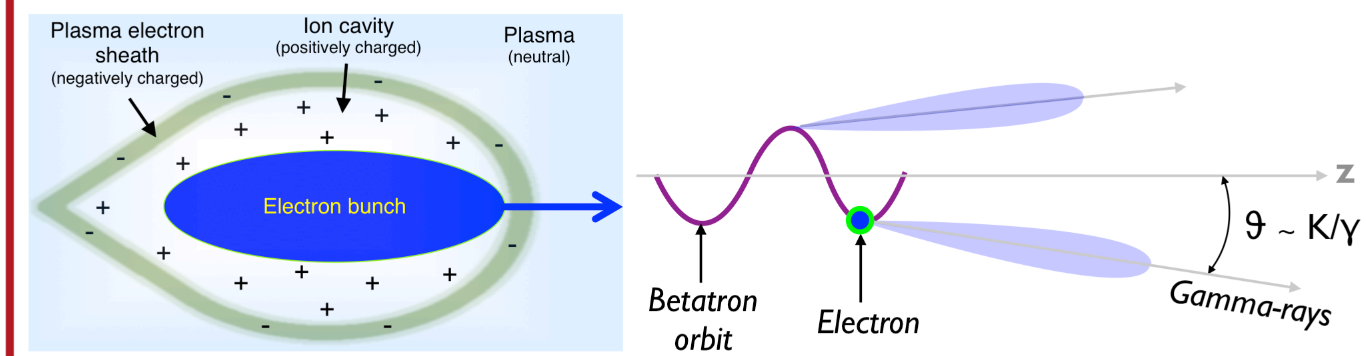

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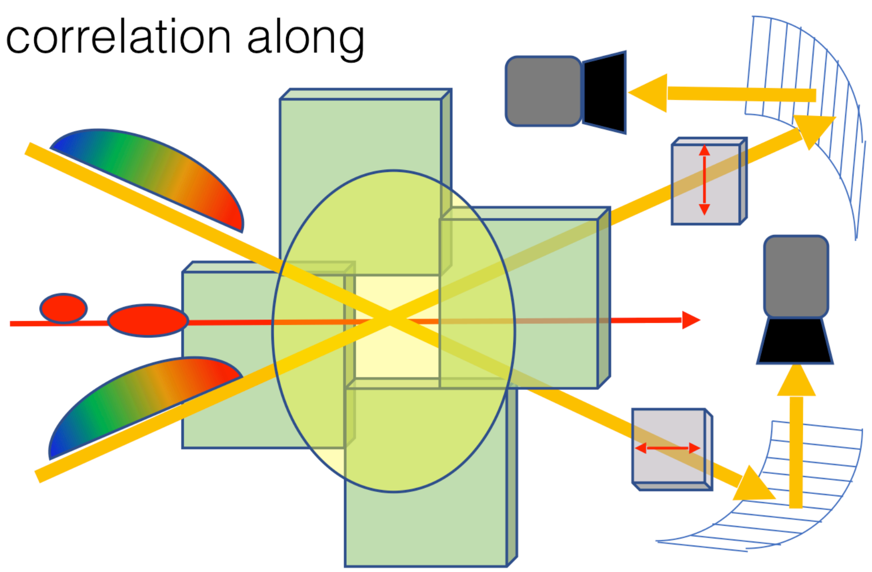
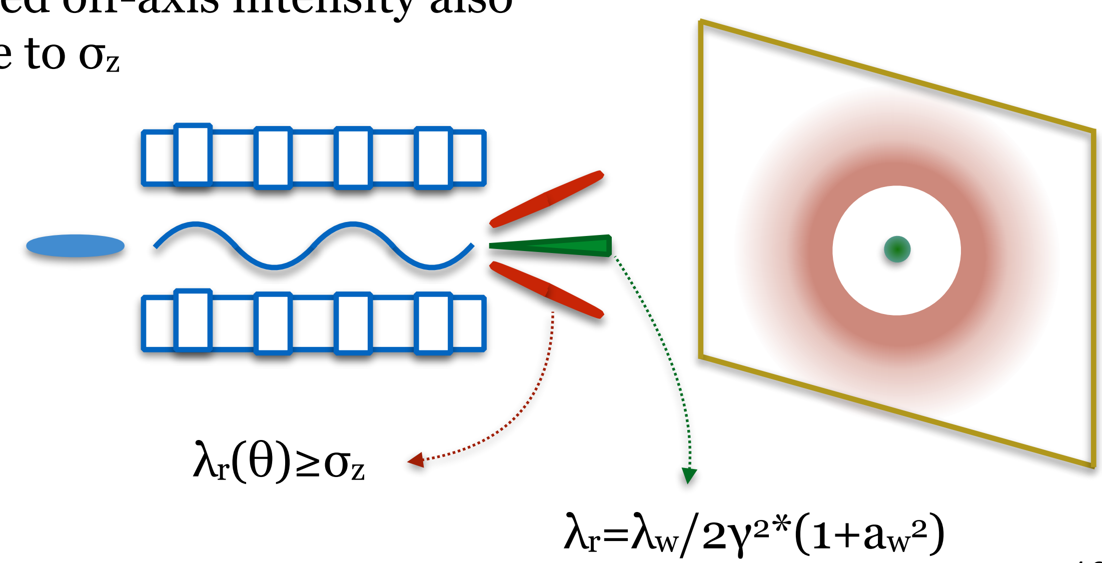


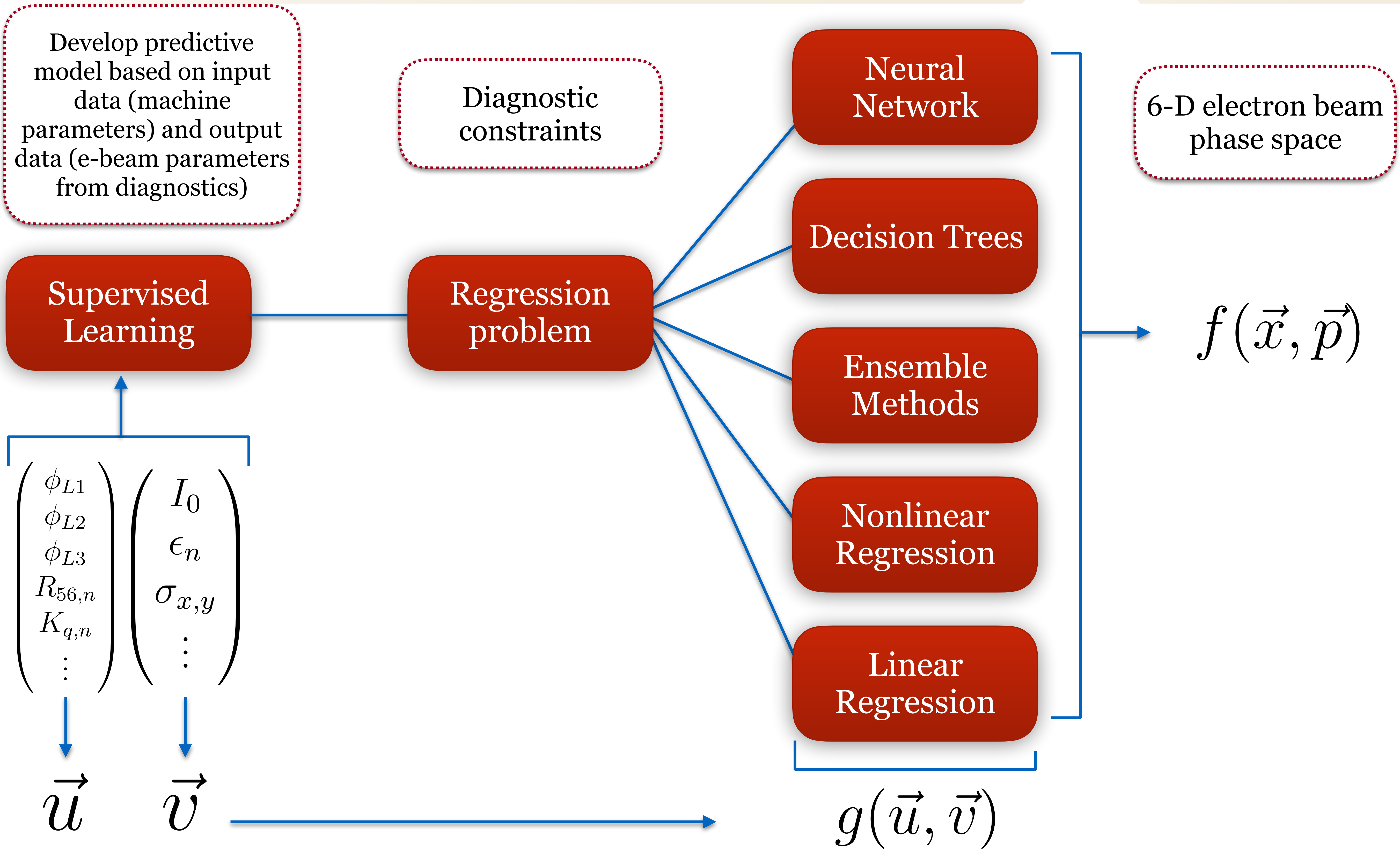
V. Yakimenko, Private comm.

Coherent undulator radiation bunch length monitor

- Off-axis intensity peak angle depends on bunch length
- Coherent emission at long wavelengths $\lambda \geq \sigma_z$
- Integrated off-axis intensity also sensitive to σ_z



Schematic software learning workflow



Inverse problem - model driven feedback

Desired 6-D electron beam phase space

Change machine parameters

Inverse mapping from training data

Undesirable 6-D electron beam phase space

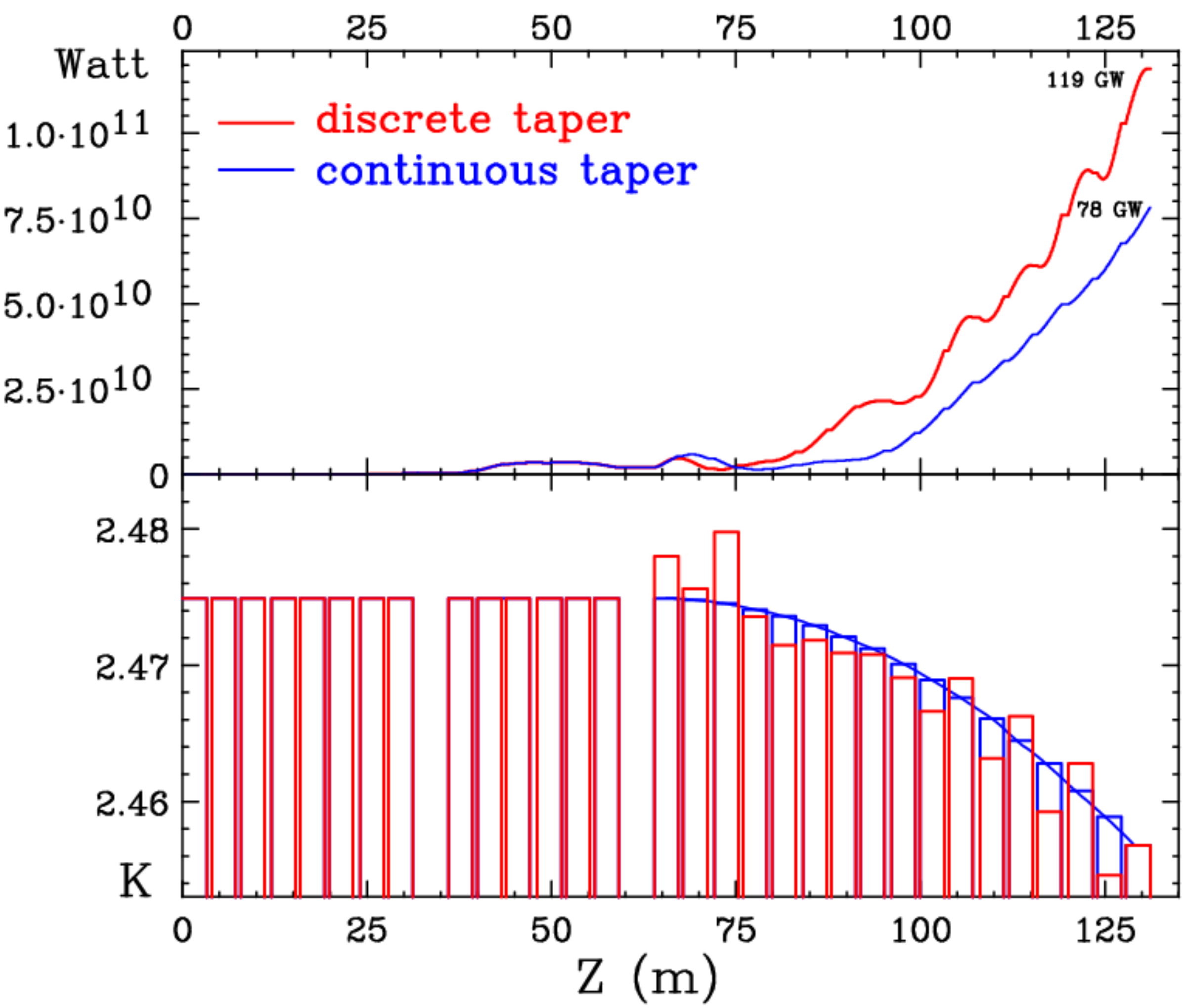
$$\left[\begin{matrix} f^*(\vec{x},\vec{p}) \\ \begin{pmatrix} I_0 \\ \epsilon_n \\ \sigma_{x,y} \\ \vdots \end{pmatrix} \\ \vec{v}^* \end{matrix} \right] \leftarrow \begin{matrix} \begin{pmatrix} \phi_{L1} \\ \phi_{L2} \\ \phi_{L3} \\ R_{56,n} \\ K_{q,n} \\ \vdots \end{pmatrix} \\ \vec{u}^* \end{matrix} \leftarrow g^{-1}(\vec{u},\vec{v}) \leftarrow \left[\begin{matrix} f(\vec{x},\vec{p}) & \\ \begin{pmatrix} I_0 \\ \epsilon_n \\ \sigma_{x,y} \\ \vdots \end{pmatrix} & \begin{pmatrix} \phi_{L1} \\ \phi_{L2} \\ \phi_{L3} \\ R_{56,n} \\ K_{q,n} \\ \vdots \end{pmatrix} \\ \vec{v} & \vec{u} \end{matrix} \right]$$

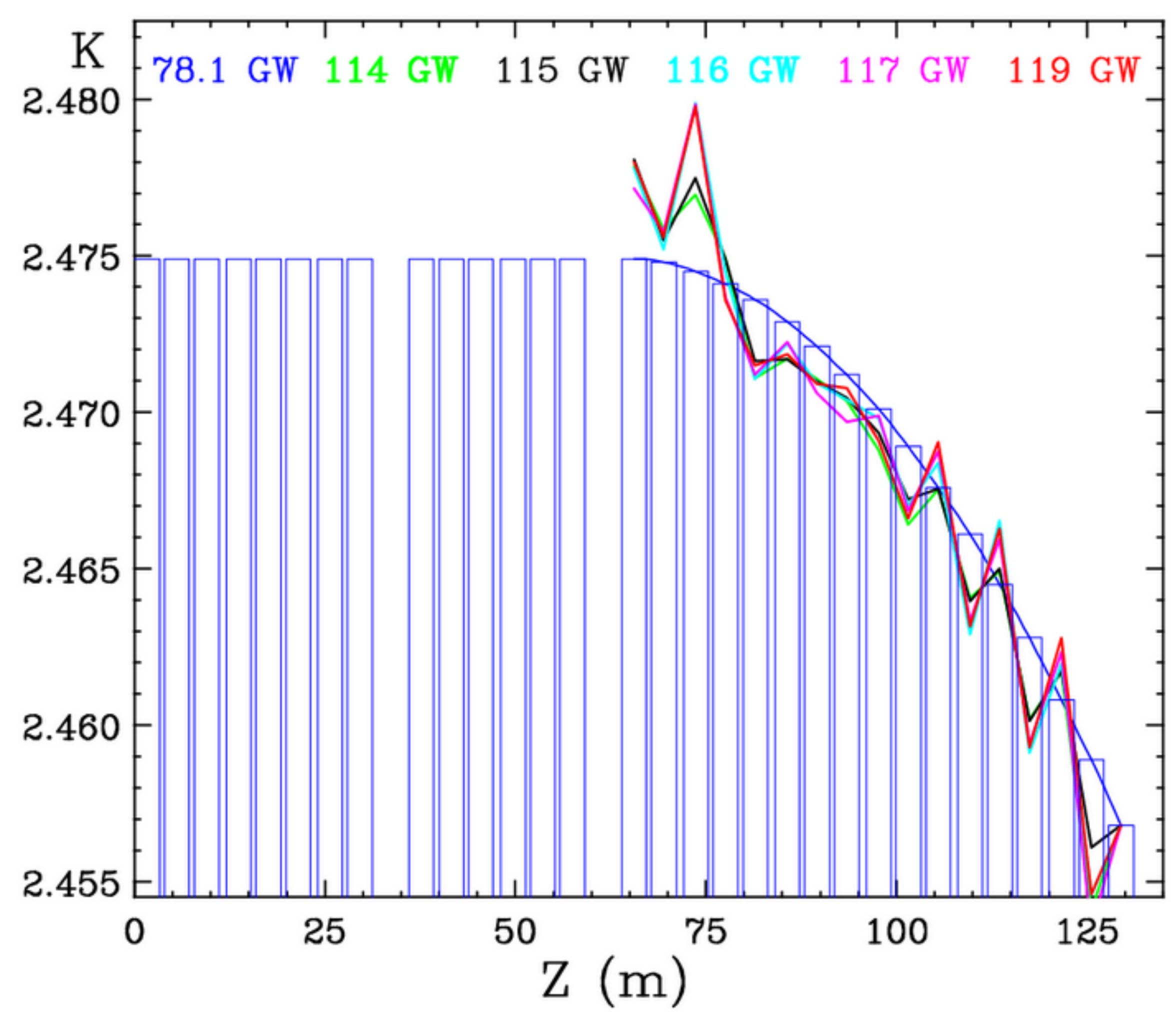
LCLS example - machine learning optimization of FEL

- Learned from Start-to-end simulation data: **Zig zag** > 50% increase over **continuous** profile

Taper profile

- Taper optimizer:





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Courtesy J. Wu

First steps before the accelerator is on

Lucretia - GPU operation/speedup

Using Lucretia output as “training data” for AI model.

Open Questions:

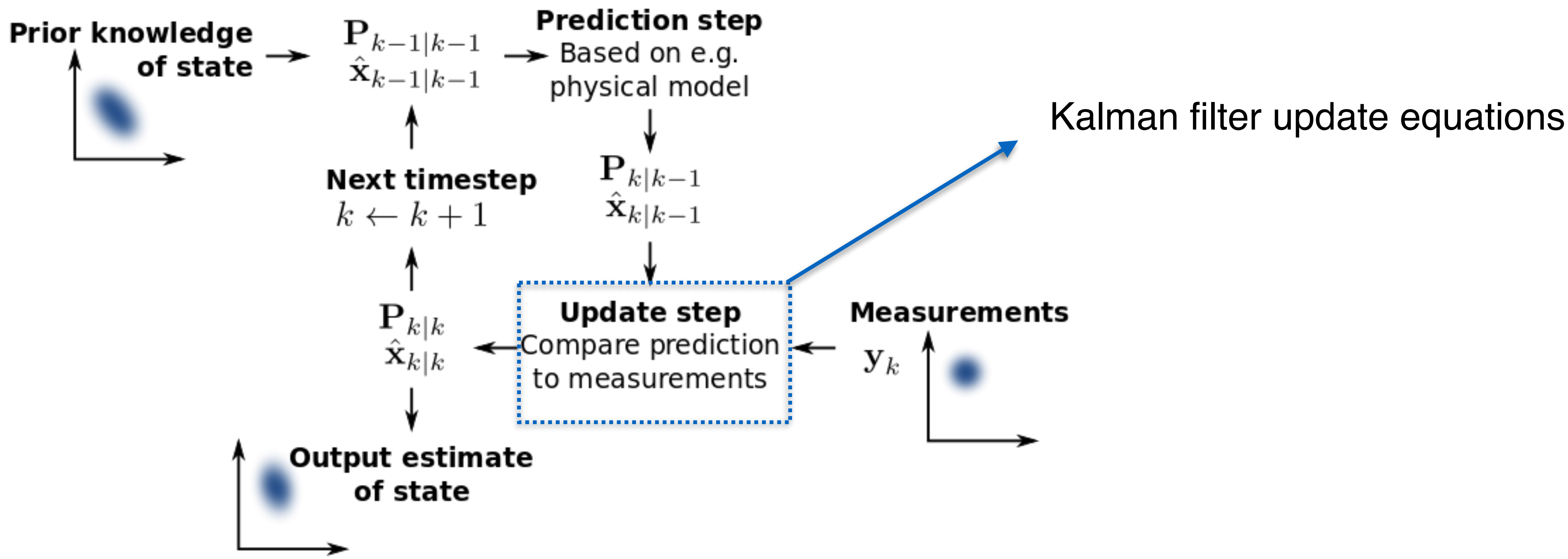
- Where do we put what advanced diagnostics?
- What diagnostics are most important to constrain the model?
- Can we use the simulation to tell us which parameters the fit is most sensitive to?
- Small team of people working on it (B. O’Shea, G. White, N. Lipkowitz…) more collaborators/useful ideas are welcome!

Conclusions

- We are planning on using AI techniques to *predict* and *correct* 6d phase space on a shot-by-shot basis at FACET-II
- Confidence and motivation comes from successes of previous AI schemes for prediction/feedback (LCLS, FACET, DESY, LANL…)
- The task is challenging due to intense beam parameters requiring advanced non-destructive diagnostics.
- Significant effort in using simulations as "training data" may improve convergence rate of model by constraining parameters
- Fast model-based predictions can allow for real-time virtual experiments to accompany routine machine operation with significant benefit for users

Additional slides

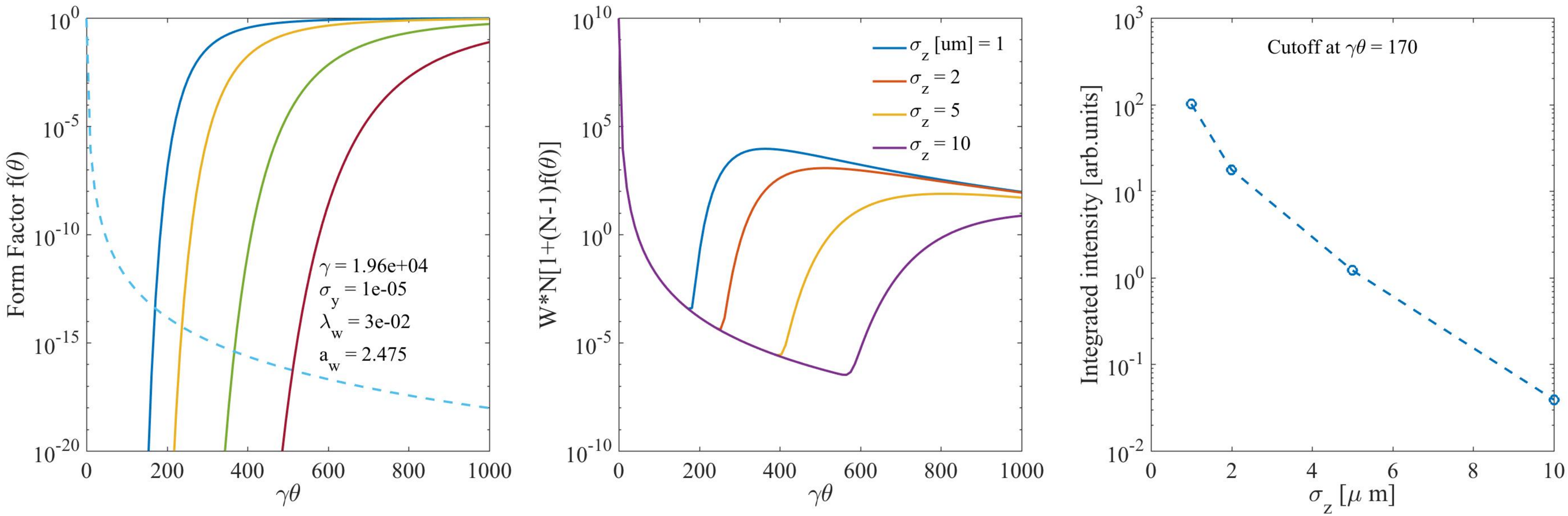
Example from meteorology - Data assimilation



- Can we improve the dependence of the model's accuracy on the initial guess?
- "Data Assimilation (DA) is a class of methods that combines uncertain models with uncertain data to provide the best estimate of the system state at a given point in time"
- Useful for weather forecasting models very sensitive to initial conditions - the "butterfly effect"
- Measurements of the system are combined with numerical models to gain a global view of the system

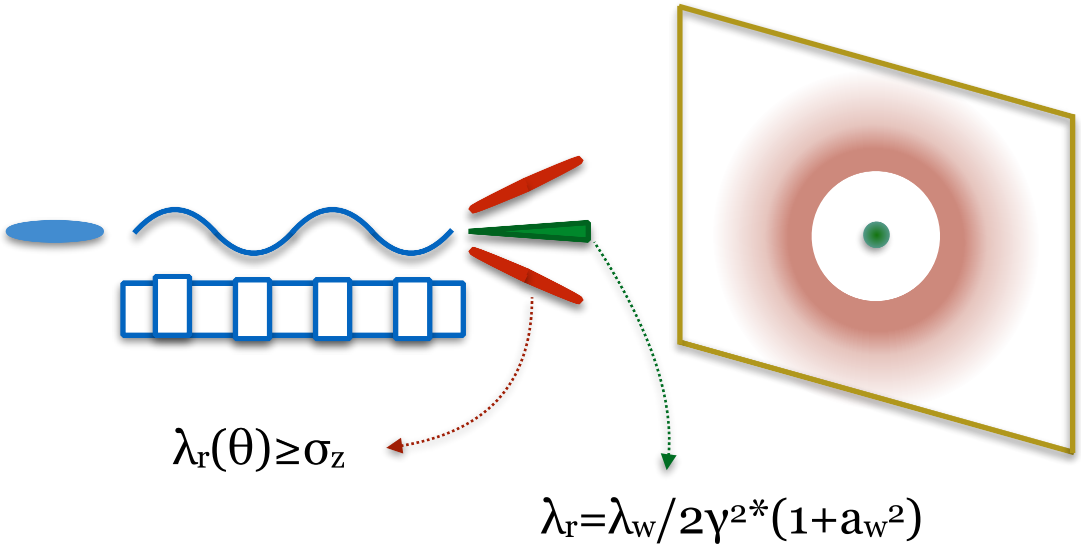
J. Sousa, C. Gorle, "Improving urban wind flow predictions through data assimilation" Stanford University

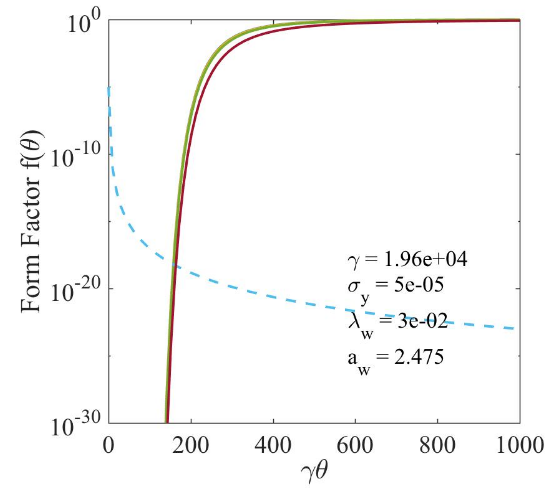
COUR bunch length diagnostic

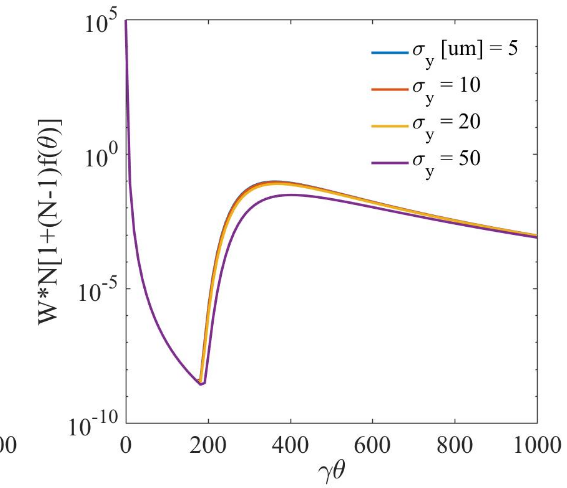


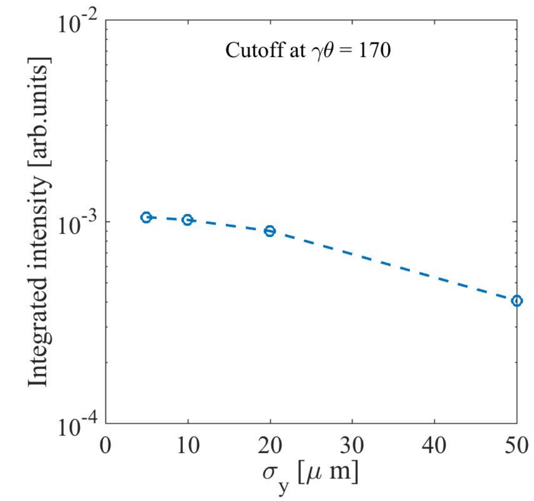
- Measuring change in total integrated intensity (cutting off small angle contribution) gives changes in bunch length. Off-axis intensity should be on the order of on-axis power ~ O(1) nJ for 10 periods, can be detected with bolometer (1 pJ resolution at BNL)
- Total intensity can be calibrated against TCAV to give absolute measurements (right plot), and extrapolated beyond TCAV resolution (~1 um at high energy?)
- Movements of the peak of the distribution also give changes in the bunch length but these are small at high energy ($\gamma\theta$~100~5 mrad) so may be more difficult to detect.
- **Note:** $f(\theta)$ depends on σ_z and σ_y coherent emission requires $k_0\sigma_y\sin\theta<1$ or $\sigma_y/\sigma_z<1/2\pi\theta\sim10$ which should be ok with focused beam. If condition isn't met the change in intensity could be due to changes in beam transverse size.
- **Note 2:** calculation is in the "single frequency" limit which is strictly true for $N_u\rightarrow\infty$, have to do the total integration over frequencies for exact result.

COUR bunch length diagnostic - transverse coherence









- Measuring change in total integrated intensity (cutting off small angle contribution) gives changes in bunch length. Off-axis intensity should be on the order of on-axis power ~ O(10) uJ, can be detected with e.g. gas detector

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