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High-Efficiency Free Electron Lasers with Pinched Electron Beams

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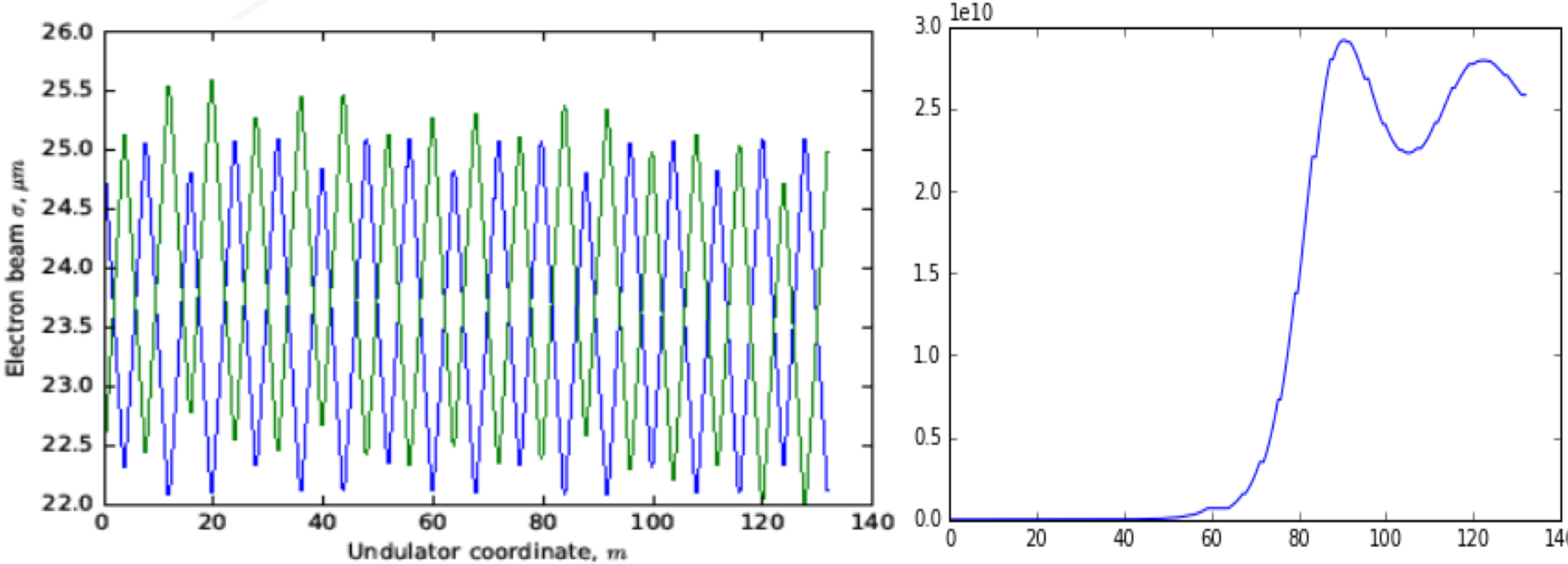
April 13, 2018

LA-UR-18-23463

Outline

- FELs operates with e-beams matched to FODO lattices;
- Extremum Seeking Algorithm;
- Matching e-beam to LCLS layout;
- Pinching e-beam for higher power;
- Finding a taper with the ES algorithm;
- Bringing all together for 10 mJ operation.

FODO matched beam



Beam envelope matched to the LCLS FODO lattice with sections 1, 9 and 16 removed. Input values of $\sigma_x = 25.062\ \mu m$, $\sigma_y = 22.192\ \mu m$, $\alpha_x = 1.083$ ***and*** $\alpha_y = -0.855$ ***have been found with the ES algorithm***

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Optimization with Extremum Seeking Algorithm

- **ES-update rule for cost function** $C(\{p_i\})$

$$p_i^{(n+1)} = p_i^{(n)} + dt\sqrt{\alpha_i \omega_i}\cos\left(\omega_i\, ndt + kC\left(\{p_i^{(n)}\}\right)\right)$$

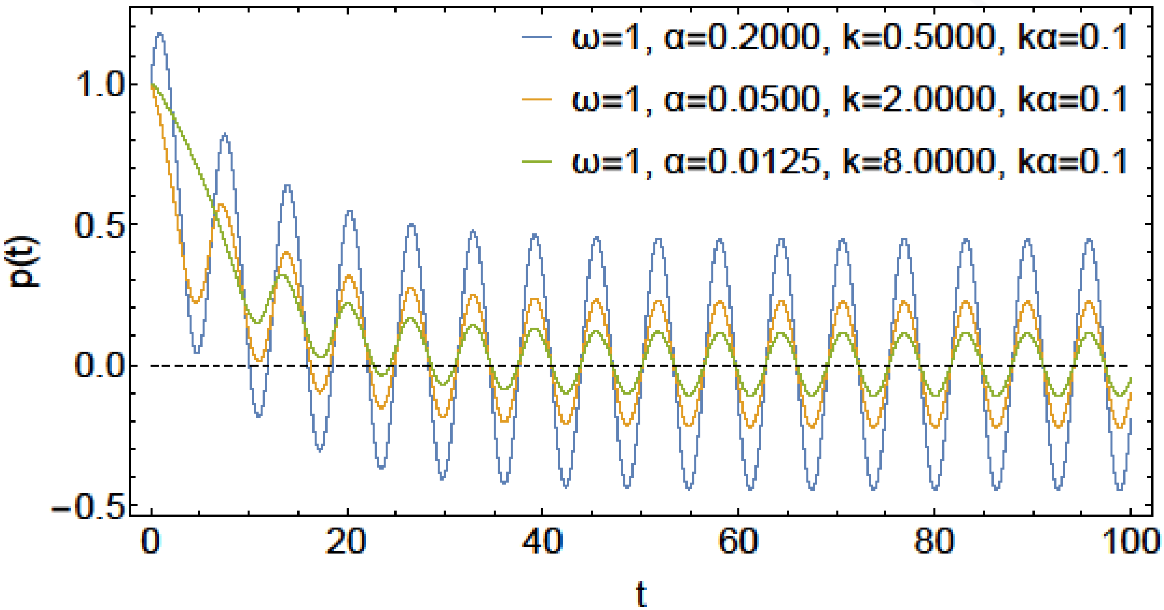
- **The corresponding equation**

$$\frac{dp_i}{dt} = \sqrt{\alpha_i \omega_i}\cos[\omega_i t + kC(\{p_i(t)\})]$$

- **The averaged equation = gradient descent!**

$$\dot{\bar{p}}_i = -0.5k\alpha_i\,\nabla C(\bar{p})$$

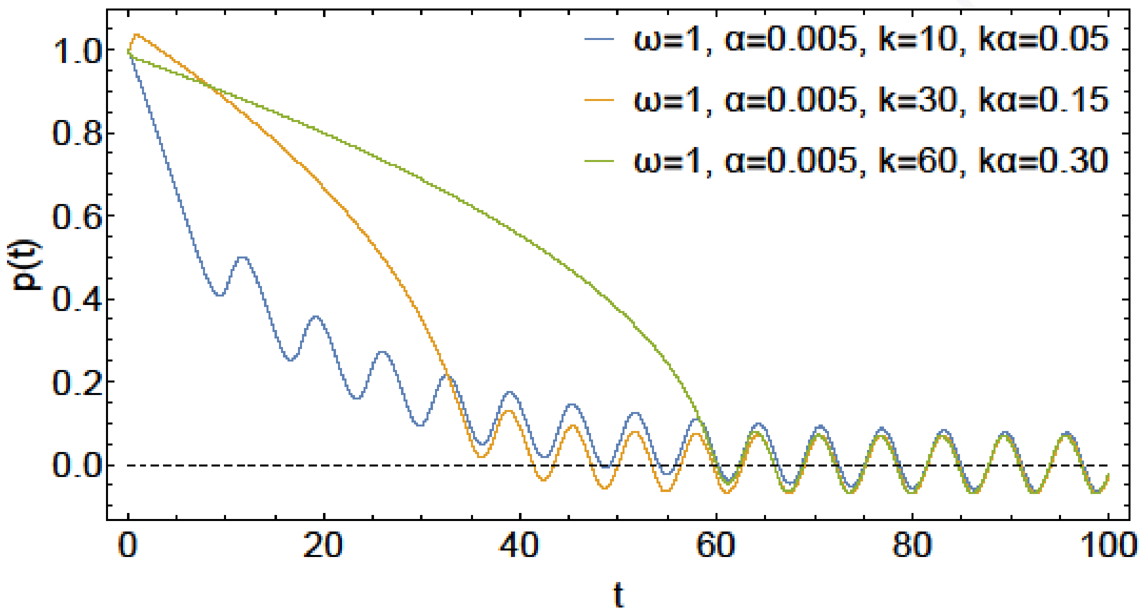
$C(p) = p^2$ illustration of the ES



Averaged solution is $\bar{p}(t) = p_0 e^{-k\alpha t}$***;***

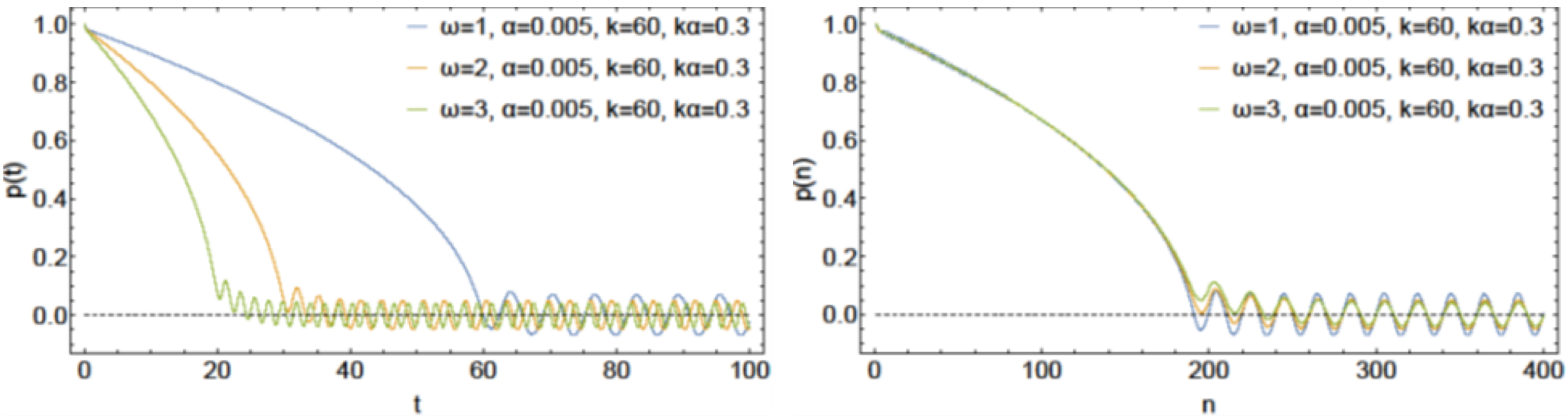
Final solution is $p(t) = \sqrt{\frac{\alpha}{\omega}} \sin(\omega t + \phi_0)$

$C(p) = p^2$ illustration of the ES



High $k > \frac{\omega dt}{C(p_n) - C(p_{n-1})}$ ***prevents the oscillations from developing and the ES loses its convergence efficiency.***

$C(p) = p^2$ illustration of the ES



The convergence of the ES algorithm for large k is restored if the frequency ω is increased such that $\omega > k\frac{C(p_n)-C(p_{n-1})}{dt}$.

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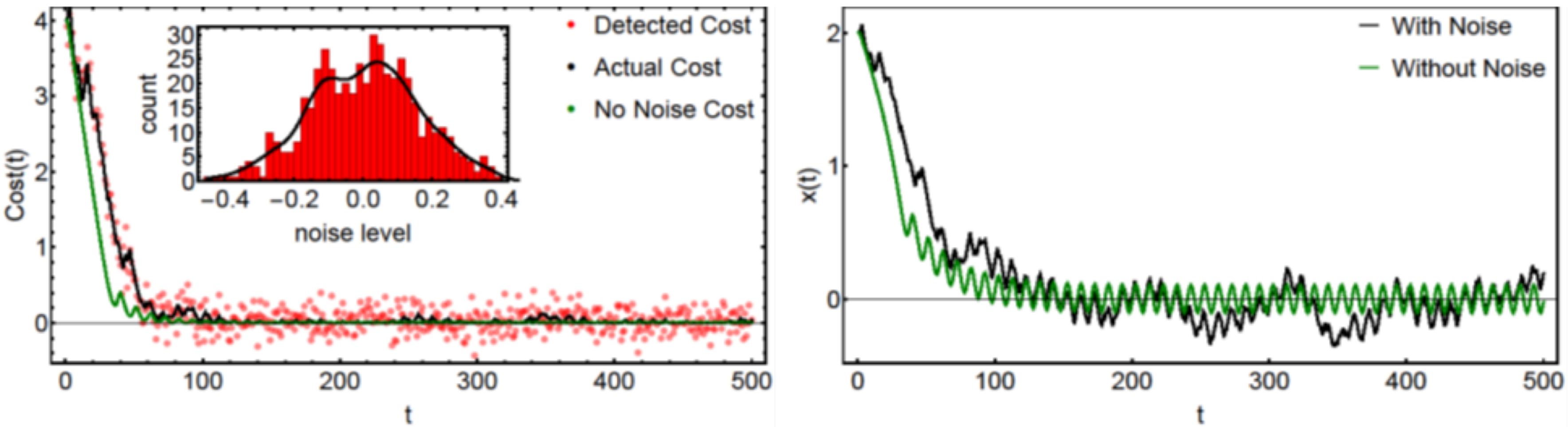
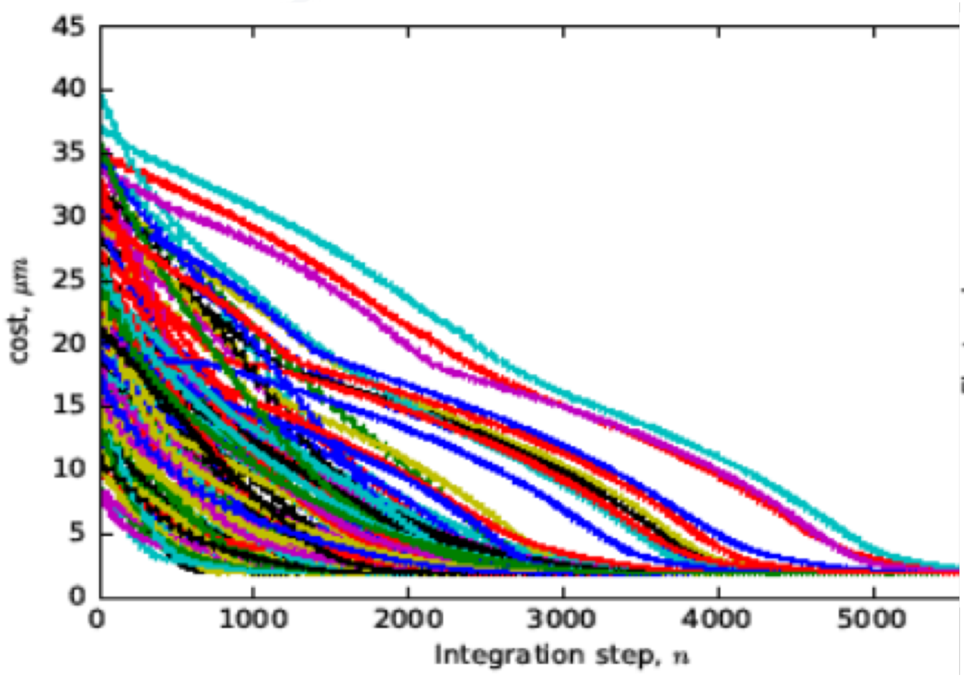
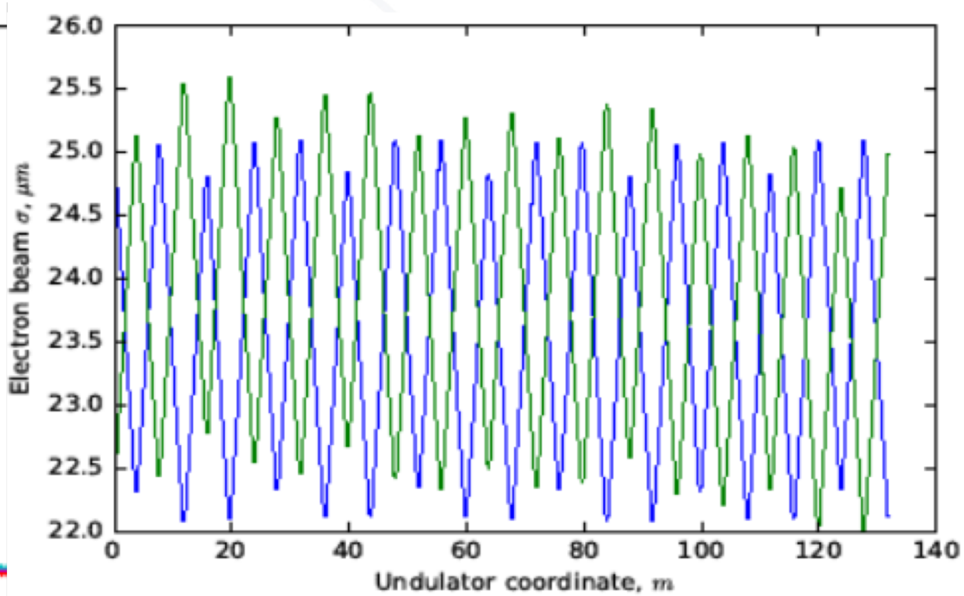
$C(p) = p^2$ illustration of the ES



The ES optimization algorithm in the presence of an additive noise (see the histogram) that masks an actual cost (black line vs red dots).

LCLS FODO matched beam





Minimizing the cost function $C(\sigma_x, \sigma_y, \alpha_x, \alpha_y) = \Delta\sigma_x + \Delta\sigma_y$ ***with the ES algorithm***

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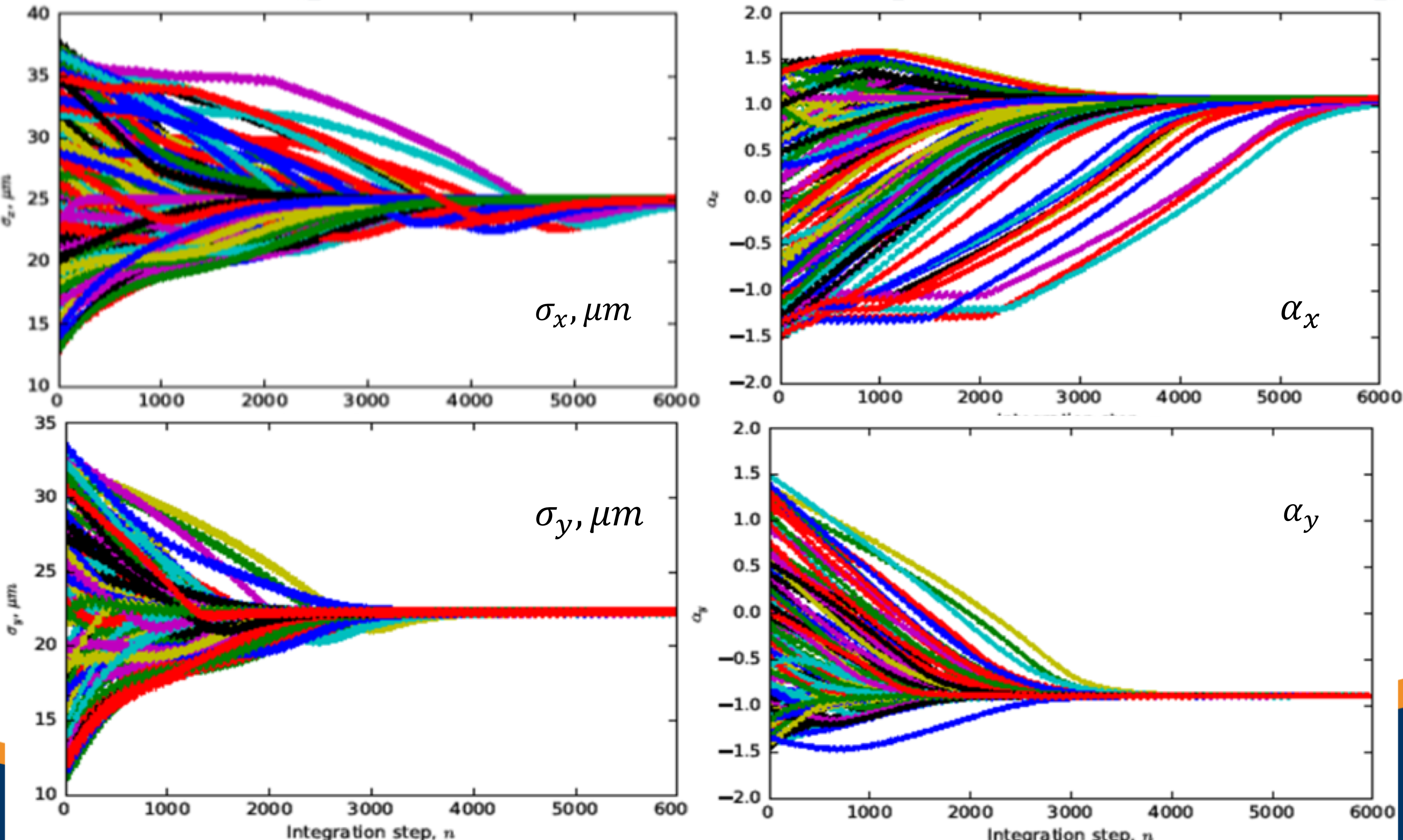
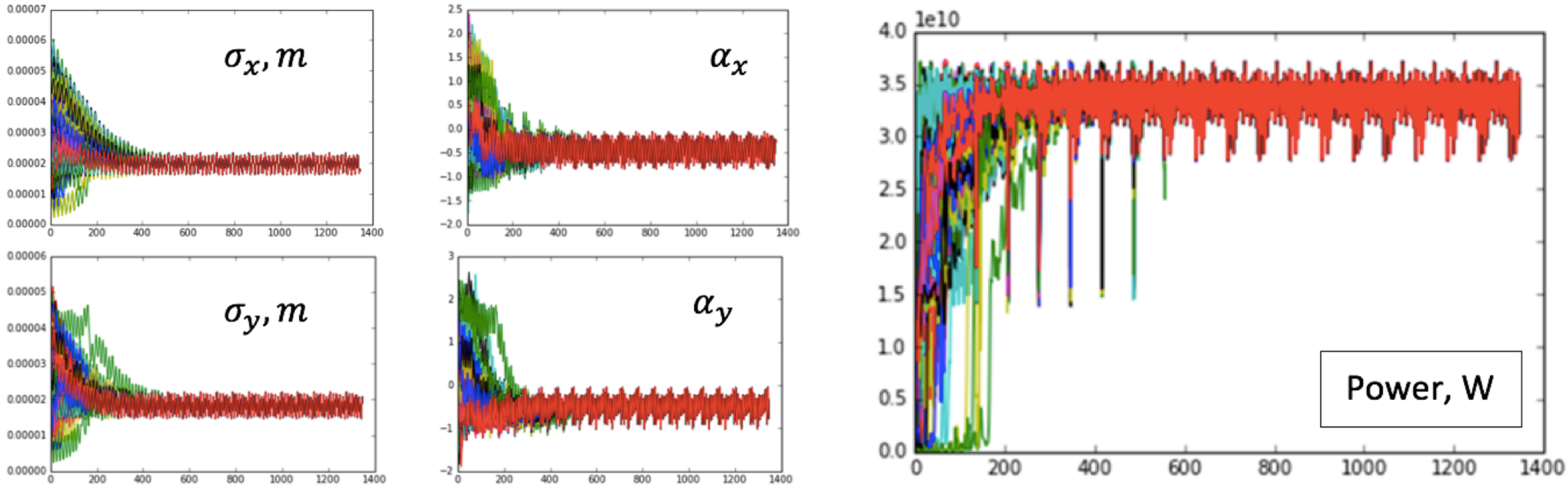
LCLS FODO matched beam (2)



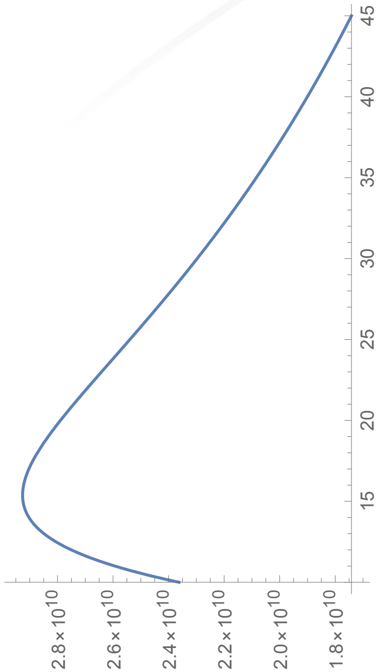
LCLS power optimization with steady state Genesis simulations

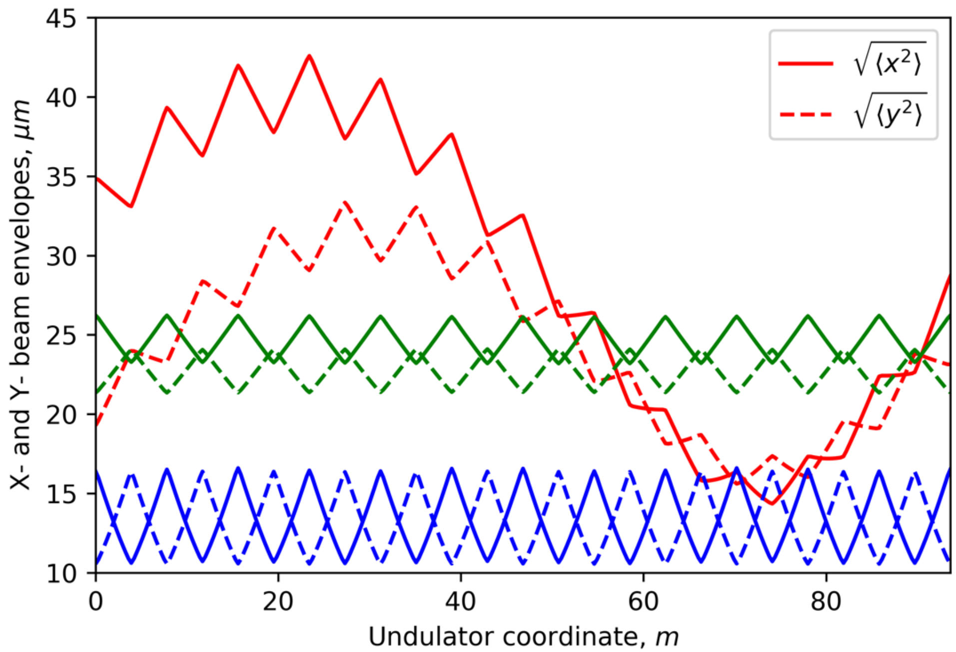


Maximizing the cost function $C(\sigma_x, \sigma_y, \alpha_x, \alpha_y) = P_{peak}$ with the ES algorithm: 36 GW vs 29 GW for a FODO matched beam!

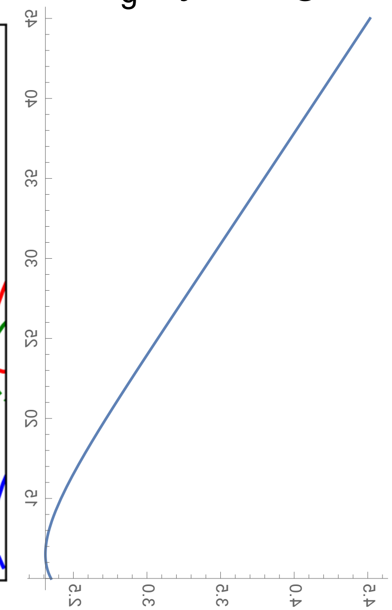
Pinched Electron Beam in Gapless Undulator

P_{sat} by Ming Xie





L_g by Ming Xie



Equal strength FODO simulation: (green) "LCLS-like" beam; (blue) "best Ming Xie" beam; (red) "pinched" beam for LCLS

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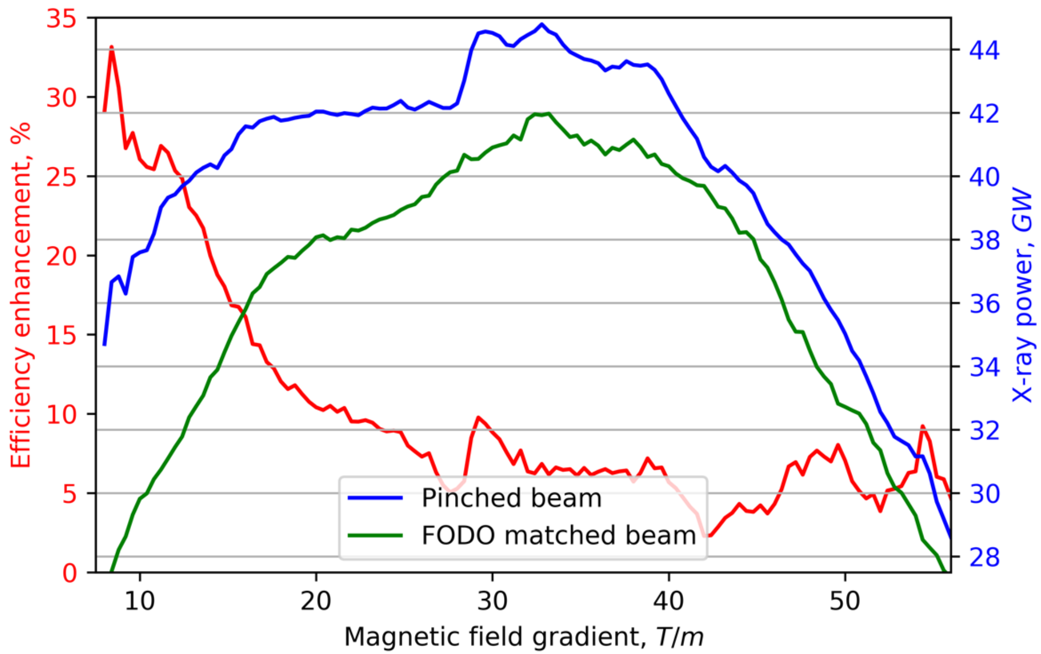
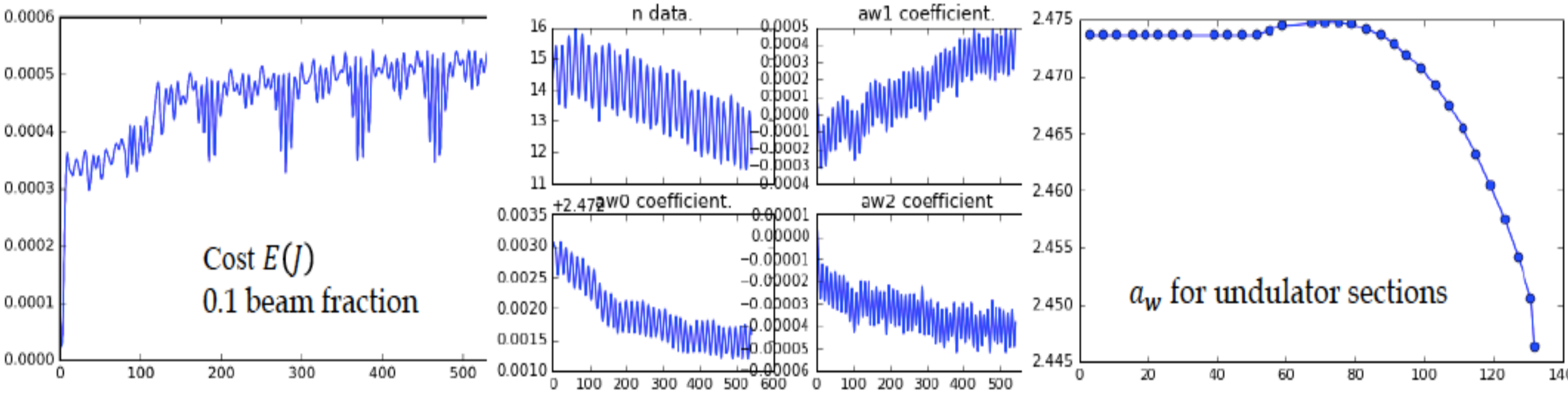
Pinched Electron Beam in Gapless Undulator (2)



We scan the quadrupole strength of the FODO lattice and find that the power is always greater with the Pinched Beam ☺

This comes at a cost of delayed saturation ☹

LCLS energy optimization with time dependent Genesis simulations



Finding the best taper $a_w(n) = a_w^{(0)} + a_w^{(1)}(n - n_0) + a_w^{(2)}(n - n_0)^2$ ***by maximizing*** $C\left(n_0, a_w^{(0)}, a_w^{(1)}, a_w^{(2)}\right) = E_{total}$ ***cost function***

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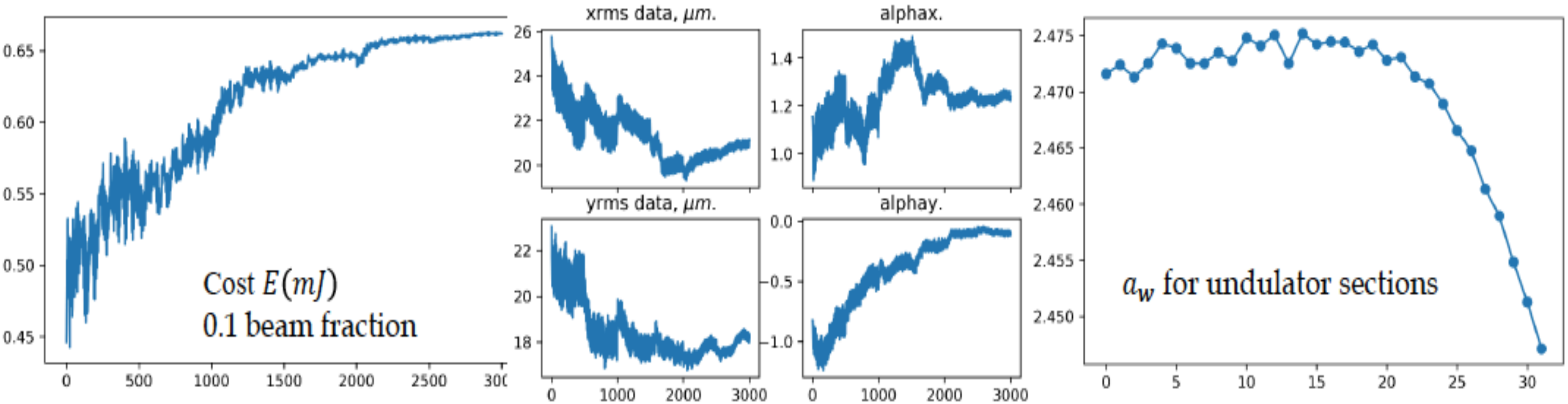
LCLS energy optimization with time dependent Genesis simulations (2)



Finding the best taper and a perfect pinch by maximizing $C\left(\sigma_x, \sigma_y, \alpha_x, \alpha_y, a_w(\{n\})\right) = E_{total}$ ***cost function with the ES algorithm***

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Conclusions

- The ES algorithm can be used for optimization of numerical models as well as online tuning;
- The Pinched Beam operation always provides extra power and does not require upgrades;
- It comes at a cost of delayed saturation;
- It does not compete with tapering but complements it in longer undulators!