Two Novel Laser-Based Seeding Schemes for X-ray FELs

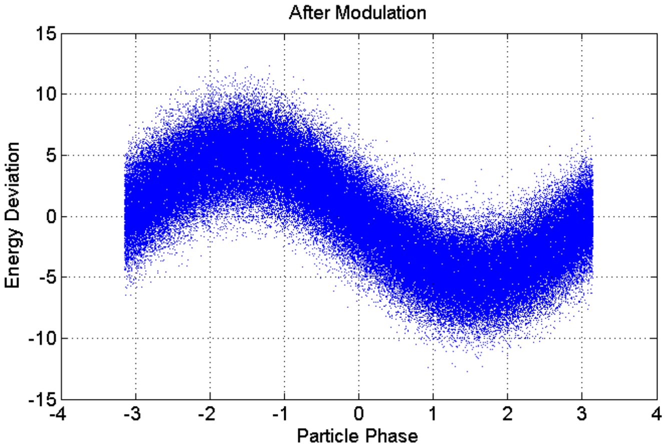
Quinn Marksteiner

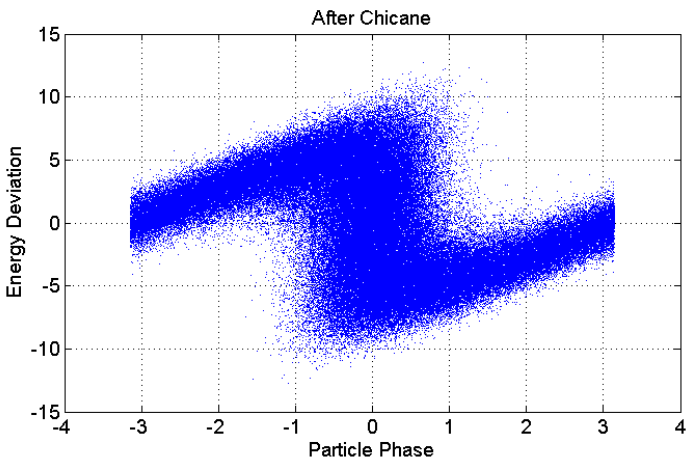
Los Alamos National Lab

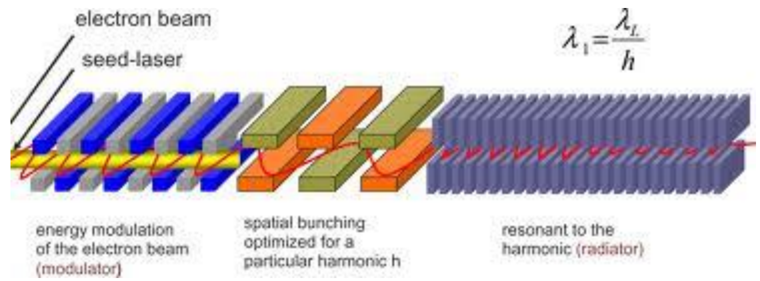
Collaborators: Kip Bishofberger, Bruce Carlsten, Leanne Duffy, Cliff Fortgang, Peter Walstrom, Nikolai Yampolsky

Hybrid EEHG-HGHG Scheme

High Gain Harmonic Generation





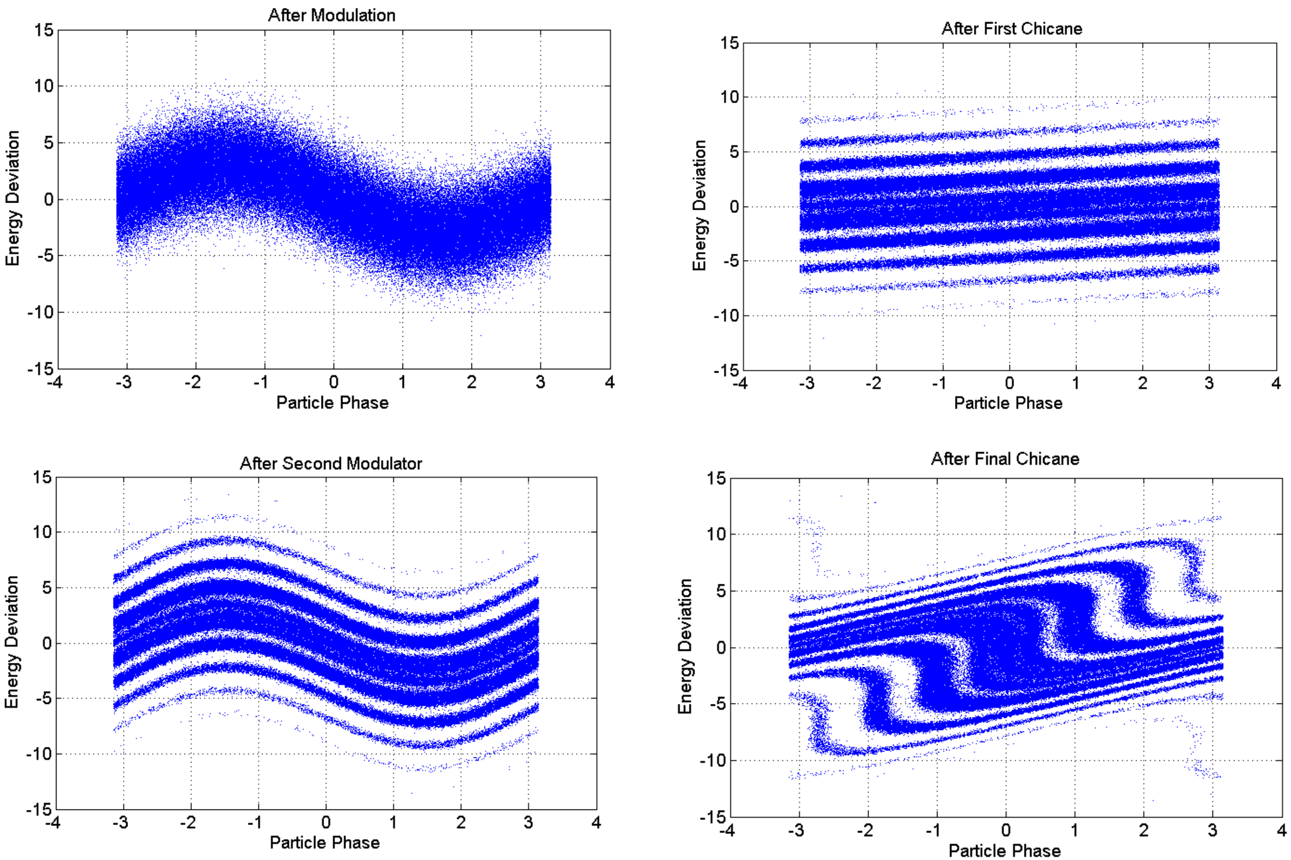


- High Gain Harmonic Generation uses a single modulator and a single chicane to generate harmonics in the electron current profile.
- The bunching factor at higher harmonics is severely limited by the electron beam energy spread[1]:

$$b_n = 2\exp\left[-\frac{1}{2}n^2\left(\frac{\sigma_E}{\Delta E}\right)^2 a^2\right]J_n(na)$$

[1] L.H. Yu, Phys. Rev. A (1991)

Echo-Enabled Harmonic Generation

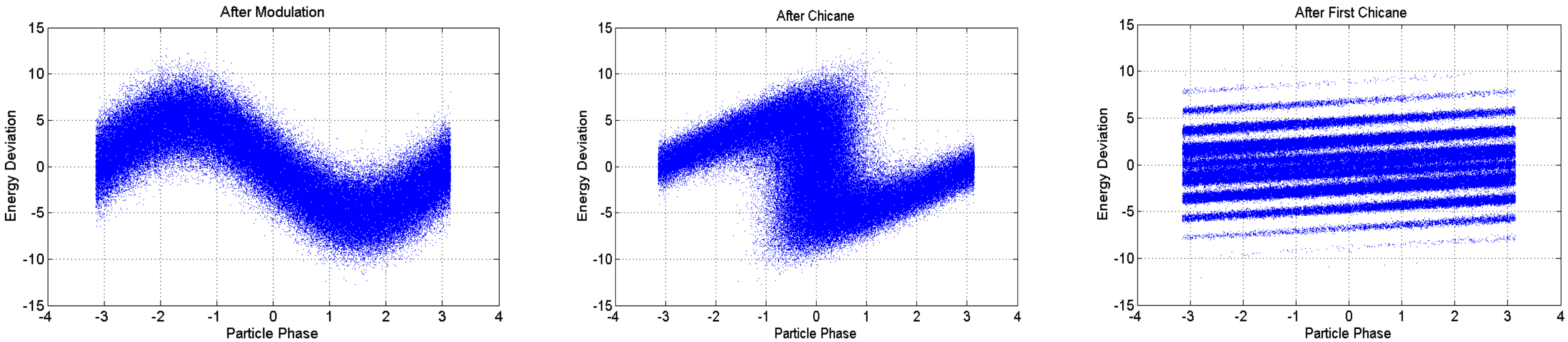


- Echo-Enabled Harmonic Generation[1] uses 2 modulators and 2 chicanes. The 1st chicane is large, and breaks the modulated beam into energy bands.
- Theory shows that EEHG has a very favorable scaling with harmonic number[1]:

$$b_n \approx \frac{0.39}{m^{1/3}}$$

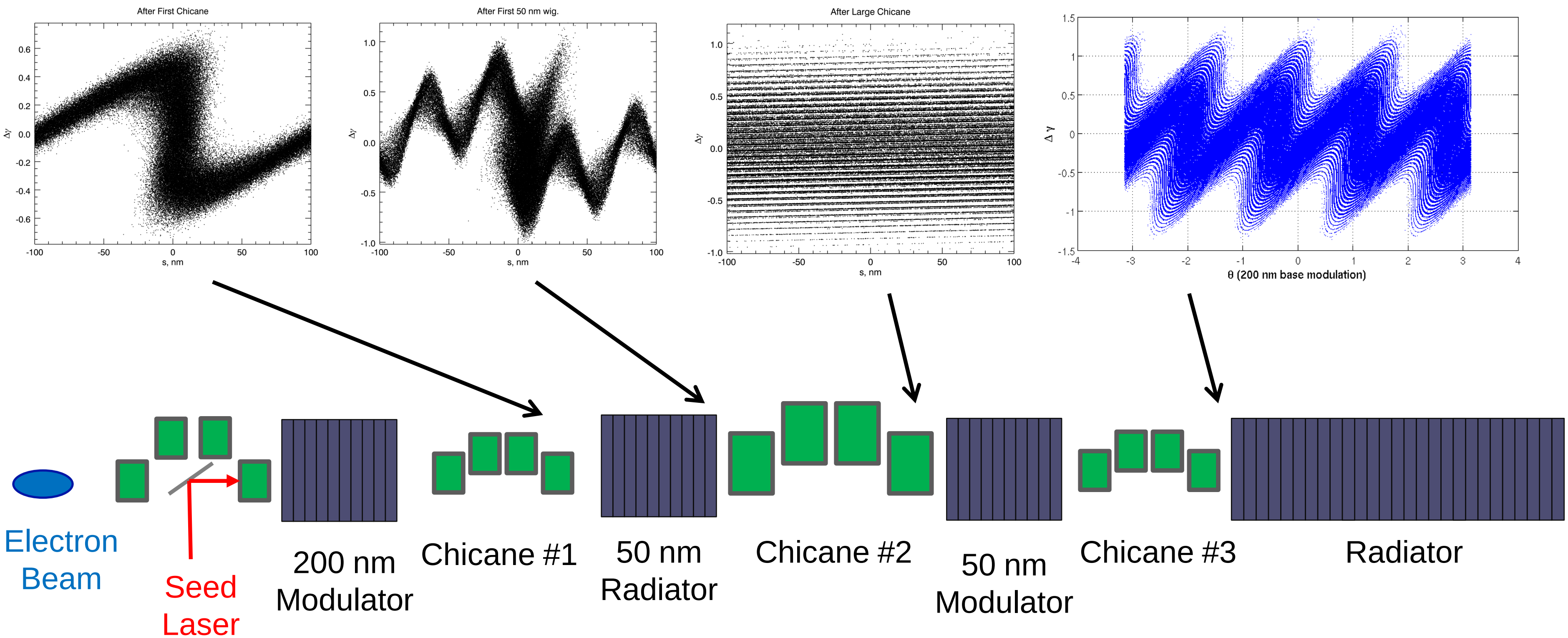
[1] Stupakov, PRL (2009)

Before Energy Bands, you get Harmonic Bunching



- With EEHG, you modulate beam, then send through large chicane so that you get energy bands.
- Without any additional modulation, beam passes through a point where there is bunching at higher harmonics.
- Can use beam at this point to get “free”radiation at a higher harmonic, then break beam into energy bands.

Phase Space of electrons in scheme



- Phase space distorts (compared to EEHG) in 50 nm radiator, but does not change required R_{56}s from EEHG theory.

Simple Justification for Idea

- EEHG theory gives:

$$(\kappa m-1)A_2B_2 = m+0.81m^{1/3} \quad \text{and} \quad B_1 = (\kappa m-1)B_2$$

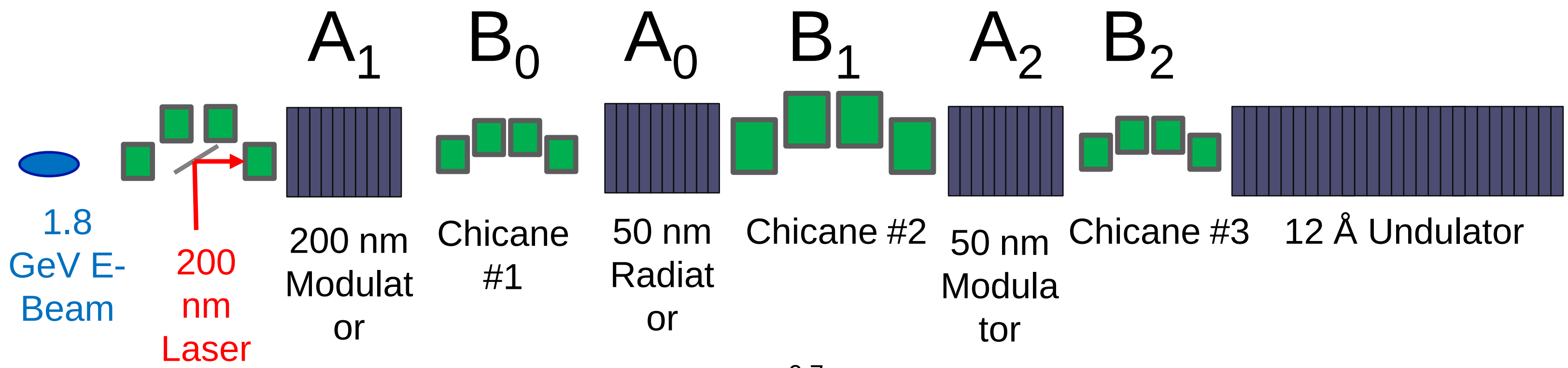
With $A_1 = \Delta E_1/\sigma_E$, $B_1 = R_{56}^{(1)}k_1\sigma_E/E_0$, $\kappa = k_2/k_1$

For high harmonic numbers, you get:

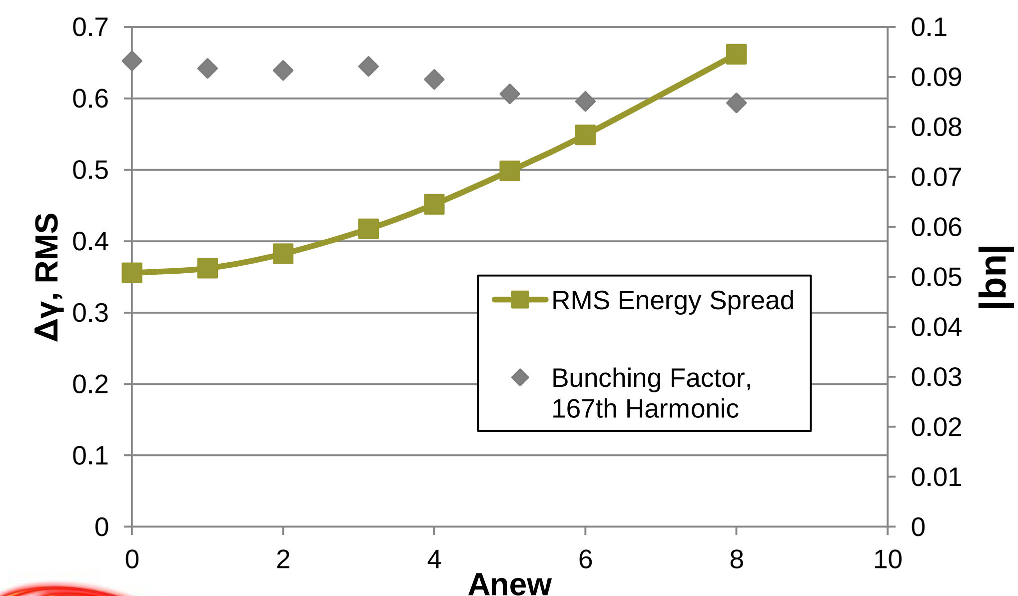
$$B_2 \approx \frac{1}{\kappa A_2} \quad \text{and} \quad B_1 \approx \kappa m B_2$$

By producing κ^{th} harmonic in a radiator section, you can achieve the same final harmonic with m smaller by the factor κ. Size of chicanes also goes down by ~ κ. Higher harmonics can be achieved without ISR, inter-particle collisions, and nonlinearities playing as important a role.

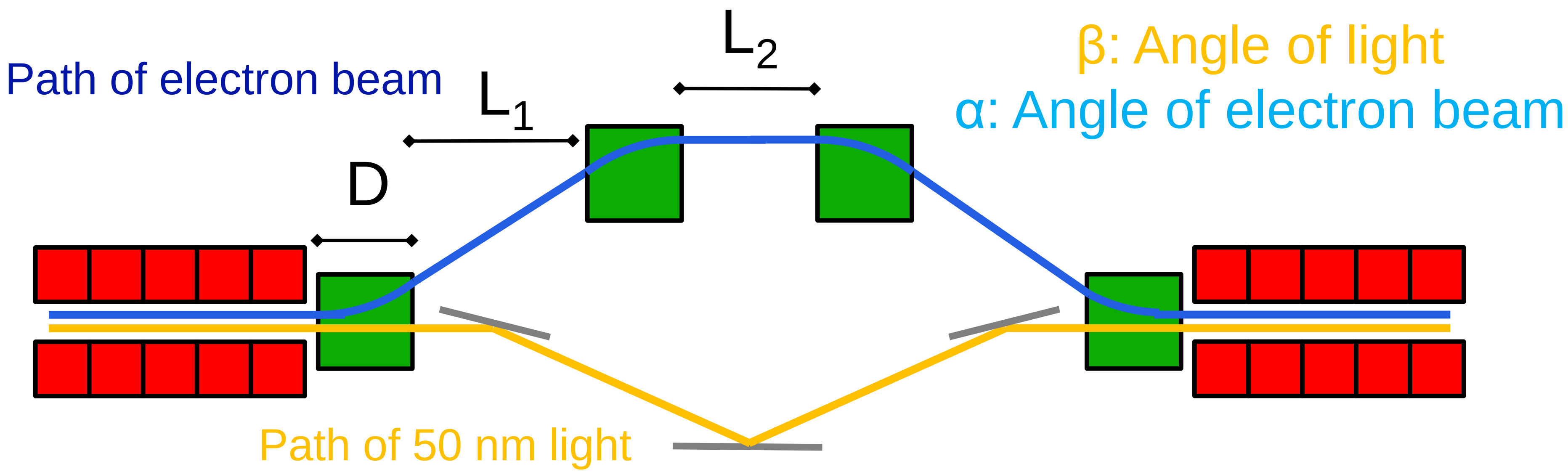
The Effects of “Parasitic Modulation”



Name	Hybrid	EEHG
A1	3.3	3.3
B_{new}	0.32	NA
A_{new}	plot	NA
B1	12.68	13.0
A2	3.52	3.52
B2	0.075	0.075

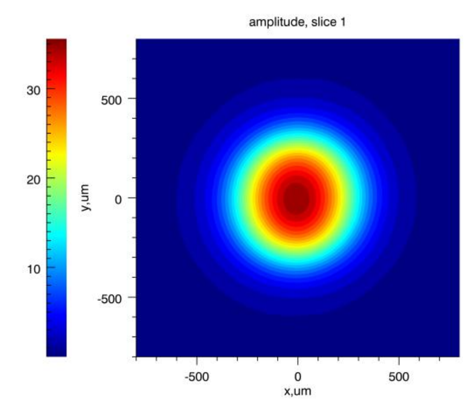


Mirror Design to Delay 50 nm Radiation



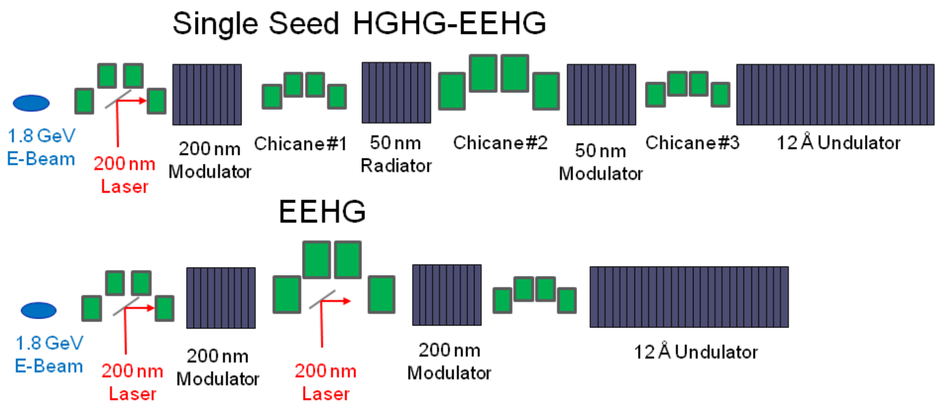
Distance Traveled by Electron Beam: $$4\alpha\rho + \frac{2L_1}{\cos\alpha} + L_2$$

Distance Traveled by Light: $$2D + L_1 + \frac{L_1 + L_2 + 2D}{\cos\beta}$$



Comparison With NGLS EEHG Design

- NGLS has a design to use EEHG to generate coherent 1.2 nm bunching from a 200 nm seed using EEHG[1].
- EEHG design predicts a theoretical bunching factor of 4.1%, and simulation gives bunching of 2.6%. Requires 2 lasers, one at 31.9 MW and one at 127.1 MW.
- New hybrid design gives a theoretical bunching of 10%, simulations (with ideal R_{56}s and simple lenses as mirrors) gives 6% bunching at 1.2 nm. Requires only one 16 MW laser, with weaker chicanes than EEHG.
- Hybrid design requires one extra chicane and one extra wiggler.



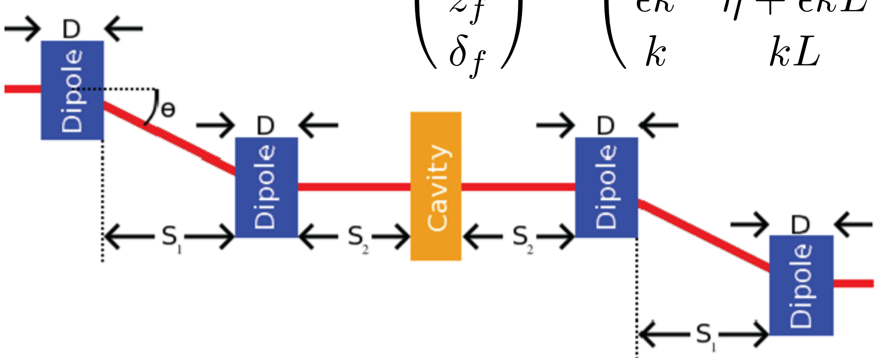
[1] G. Penn and M. Reinsch, J. Mod. Optics, **58**, 16 (2011) p. 1404

Laser Modulator with Double EEX Compressor

Introduction: EEX Basics

- The Emittance Exchanger (EEX) uses a deflecting cavity sandwiched between two doglegs to swap the emittances between the longitudinal dimension and a transverse dimension.
- Zeroing out the block-diagonal elements requires correct adjustment of the cavity strength.
- Beyond that, multiple parameters can be adjusted to play with specific elements in the transfer matrix.

$$\begin{pmatrix} x_f \\ x'_f \\ z_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} 0 & 0 & kL & \eta + \epsilon kL \\ 0 & 0 & k & \epsilon k \\ \epsilon k & \eta + \epsilon kL & 0 & 0 \\ k & kL & 0 & 0 \end{pmatrix} \begin{pmatrix} x_i \\ x'_i \\ z_i \\ \delta_i \end{pmatrix}$$



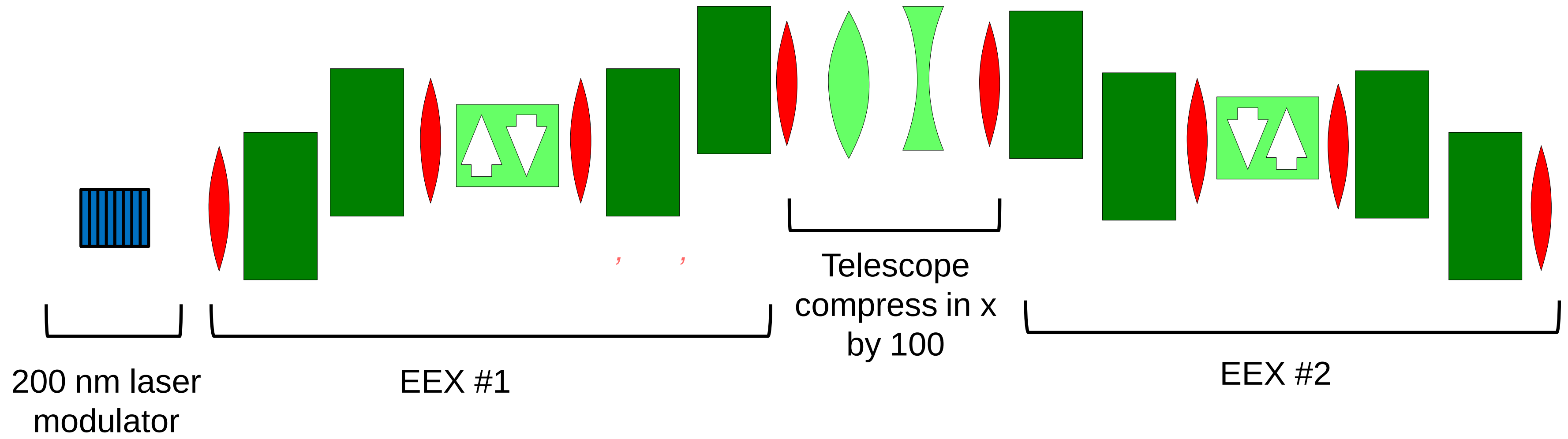
$$L = \frac{S_1}{\cos^3\theta} + \frac{2D}{\cos\theta} + S_2$$

$$\eta = \frac{S_1 \sin^2\theta}{\cos^2\theta} + \frac{2D}{\sin\theta}\left(\frac{1}{\cos\theta} - 1\right)$$

$$\epsilon = \frac{S_1 \sin^2\theta}{\cos^3\theta} + \frac{2D}{\sin\theta}\left(\frac{\sin\theta}{\cos\theta} - \theta\right)$$

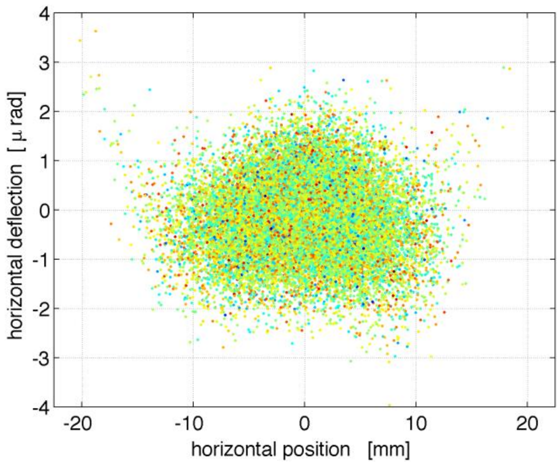
EEX Compressor Setup

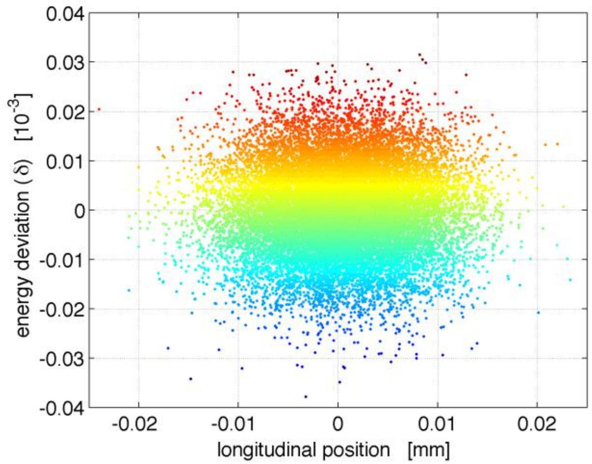
- Seed the electron beam with a 200 nm laser, then compress beam down 100x.
- One EEX swaps x and z emittances, and a second EEX swaps them back. In between, a transverse focusing telescope in between the EEXs will provide longitudinal beam compression, without any need for a chirp.
- Challenge is to eliminate nonlinearities by using quads, sextupoles, and octopoles.

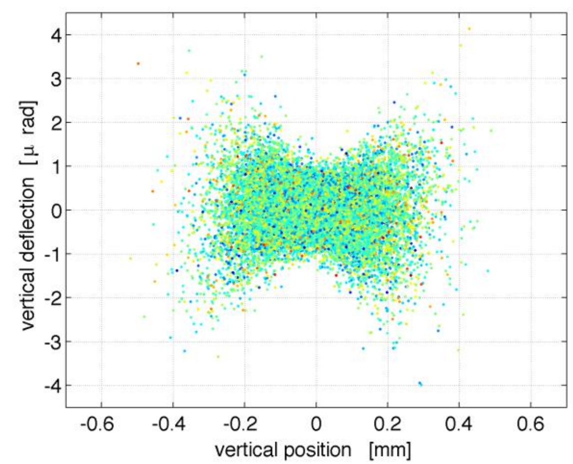


This idea is similar to a design proposed by Zholents,Zolotorev (PAC11).

Bulk Beam Compression Results







- Quads and sextupoles used to preserve emittance in x and z, while compressing z by a factor of 100.
- Nonlinearity remains in y, bringing y emittance up to 0.175 um (from 0.1 um).
- Unfortunately, nonlinearities remain that wash out the 200 nm modulation.
- Working on finding solution that preserves y emittance and modulation.

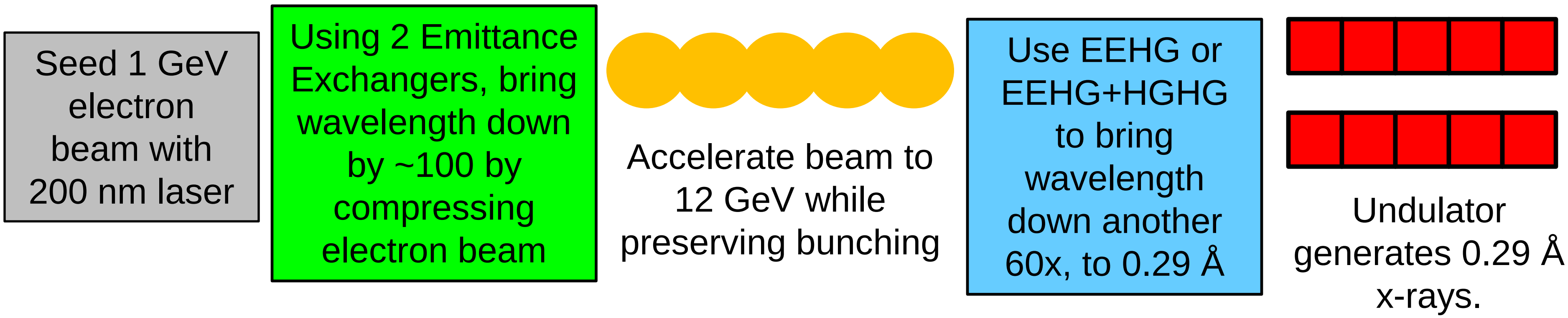
σ_i = (0.1 0.1 0.4) mm

ε_i = (0.100 0.100 7.83) μm

σ_f = (0.074 0.164 0.00397) mm

ε_f = (0.101 0.175 8.08) μm

Introduction to Our Scheme



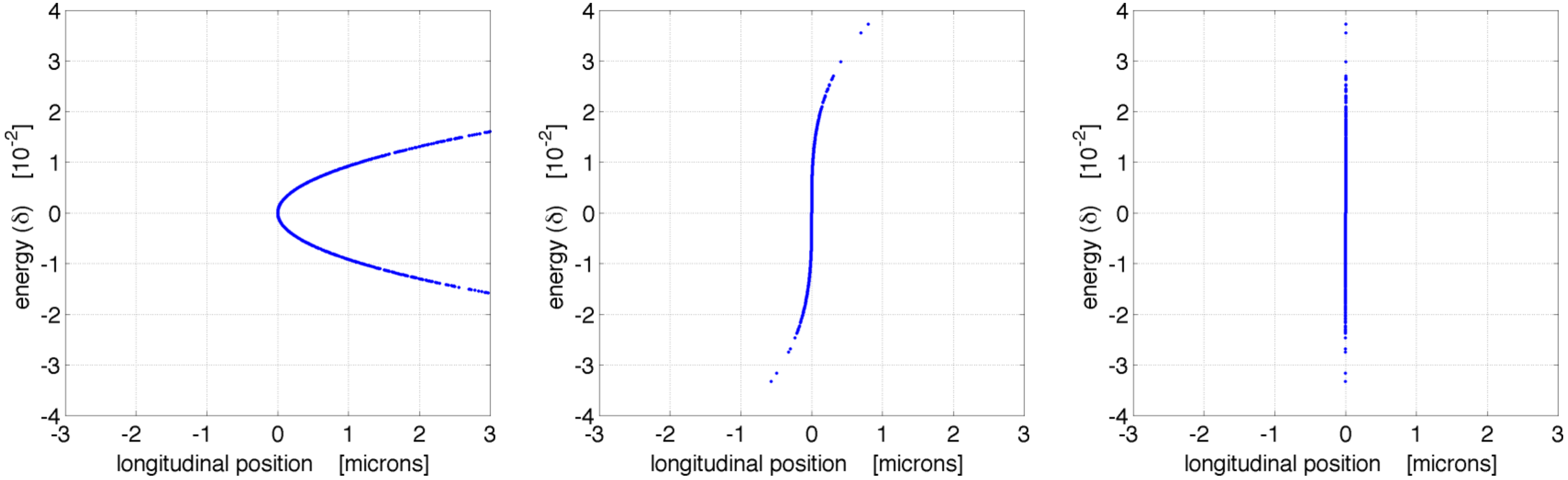
- Seed electron beam at 1 GeV with 200 nm laser.
- Use double emittance exchanger to compress electron beam by ~100, while also compressing bunching down to 2 nm. At higher electron beam energies, bunching would wash out from ISR.
- Accelerate beam to 12 GeV, while preserving the 2 nm bunching.
- Finally, use hybrid EEHG-HGHG scheme seeded with beam bunching to bring wavelength down another 60x.

Conclusions

- New single laser hybrid HGHG-EEHG design only needs a single laser at relatively low power, and gets high bunching factors at very high harmonic number with modest sized chicanes.
- HGHG radiator distorts phase space, but extra energy spread is small, and simulation shows that bunching is only mildly degraded from pure EEHG.
- Double EEX looks promising: we can preserve 0.1 μm emittances while compressing 100x.
- Work in progress for Double EEX: preserve nm-scale modulation.

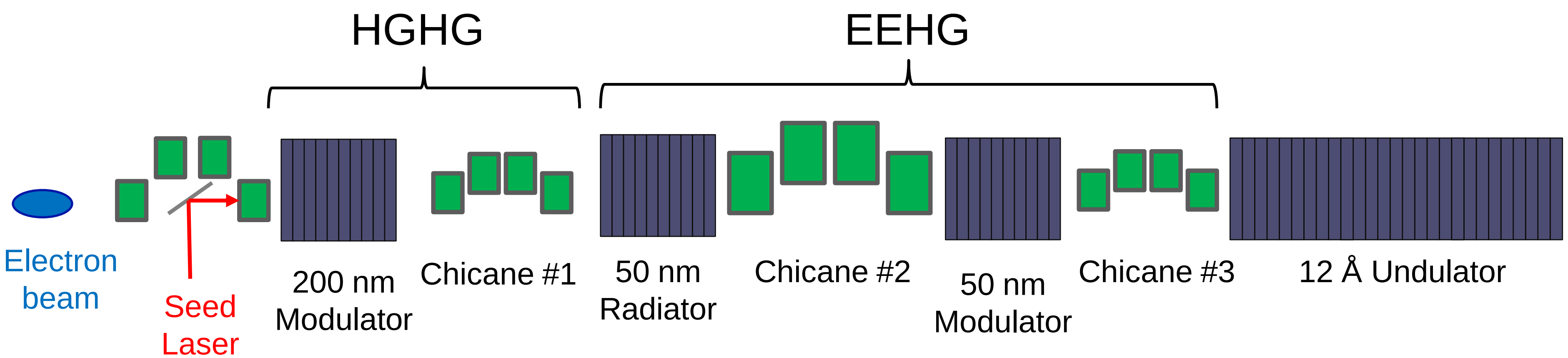
Extra Slides

Preservation of 200 nm modulation in double EEX



- A zero-emittance beam, with 10e-5 energy spread, offers 17-nm longitudinal resolution “out of the box.”
- With sextupole and octopole correctors, that resolution improves to less than 1 nm.
- However, finite beam size (x,y) quickly destroys this resolution.
- Optimization of the longitudinal resolution is being actively pursued, with a goal to preserve nanometer-scale modulations and bunching.

Introduction to Single Laser Hybrid HGHG-EEHG Scheme



- First seed electron beam with 200 nm laser.
- After 200 nm modulator, use chicane #1 to get bunching at 50 nm (HGHG), and then generate 50 nm radiation in radiator.
- Use chicane #2 to create EEHG-like energy bands, while delaying and focusing 50 nm radiation with mirrors.
- Chicane #3 produces bunching at large harmonic of laser

Description of Parameters in Simulation

Chicane #	R_{56}
1	363 µm
2	12.1 mm
3	68.3 µm

Beam Input	Value
Energy	1.8 GeV
E Spread	50 keV
Current	500 A
ε_N	0.6

Wiggler #	Aw0	λ_w	Length
1	4.872	20 cm	1 m
2	4.0	7.29 cm	0.875 m
3	4.0	7.29 cm	0.875 m
4	0.7	2 cm	25 m

Param.	Value
50 nm b_n after chicane #1	13%
50 nm power after wiggler #1	14.1MW

Harmonic Generation with a Phase Chirp[1]

A Gaussian laser beam with a frequency chirp is given by:

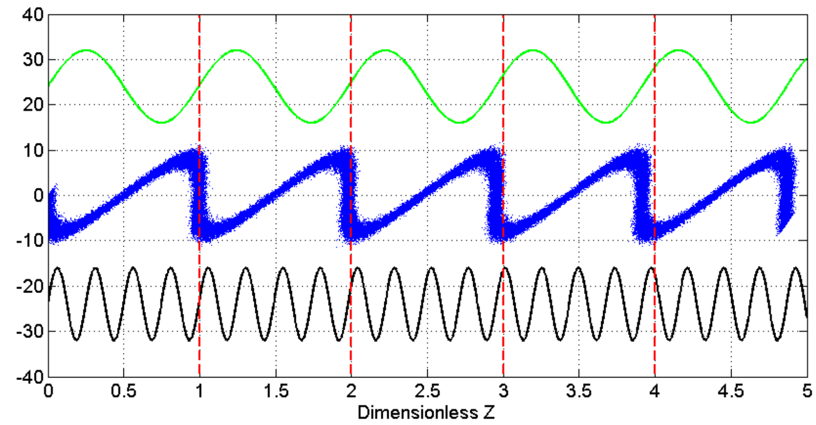
$$E_{in}(\varsigma) = E_0 \exp\left[i\left(\varsigma + \frac{\alpha\varsigma^2}{2\sigma_L^2} \right) - \frac{\varsigma^2}{2\sigma_L^2} \right]$$

Departure from FT limited pulse:

$$\Delta\omega\Delta\tau = 4\ln 2\,\mathrm{M}^2 = 4\ln 2\sqrt{1+\alpha^2}$$

For Ti:Sa laser, M^2-1 = ~10^{-2}, ie. almost FT limited. After HG, you get:

$$E_{out}(\varsigma) = E_0 \exp\left[i\left(N\varsigma + \frac{N\alpha\varsigma^2}{2\sigma_L^2} \right) - \frac{\varsigma^2}{2\sigma_L^2} \right]$$



This has a departure from FT limited pulse given by:

$$\Delta\omega\Delta\tau = 4\ln 2M^2 = 4\ln 2\sqrt{1+N^2\alpha^2}$$

For NGLS, N~667, which will be 94 more broadband than FT limit.

[1] G. Geloni, V. Kocharyan, and E. Saldin, "Analytical studies of constrains on the performance for EEHG FEL seed lasers"

Phase Chirp with Short Electron Beam

If you are in a regime where the electron beam is shorter than the laser pulse, $\sigma_e << \sigma_L$, then:

$$E_{out}(\varsigma) = E_0 \exp\left[i\left(N\varsigma + \frac{N\alpha\varsigma^2}{2\sigma_L^2} \right) - \frac{\varsigma^2}{2\sigma_e^2} \right]$$

Let *s* denote the factor by which the laser is longer than the electron beam. Then you can substitute $\sigma_L = s\,\sigma_e$ into above to get:

$$E_{out}(\varsigma) = E_0 \exp\left[i\left(N\varsigma + \frac{N\alpha\varsigma^2}{2s^2\sigma_e^2} \right) - \frac{\varsigma^2}{2\sigma_e^2} \right]$$

Deviation from FFT limit is now:

$$M_N^2 = \sqrt{1 + N^2\alpha^2 / s^4}$$

For a high quality beam, initial M_0^2 is:

$$M_0^2 - 1 \approx \alpha^2 / 2$$

Then we have a formula for the necessary quality of a long laser, so that the final harmonic is FT limited:

$$\frac{N\sqrt{2\left(M_0^2 - 1\right)}}{s^2} \leq 1$$

For M_0^2 -1 = 1%, need a laser that is 11 times longer than electron beam to achieve FT limit.

With less power demands, can you get a longer electron pulse with the same M_0^2?

Parasitic Modulation in 50 nm radiator

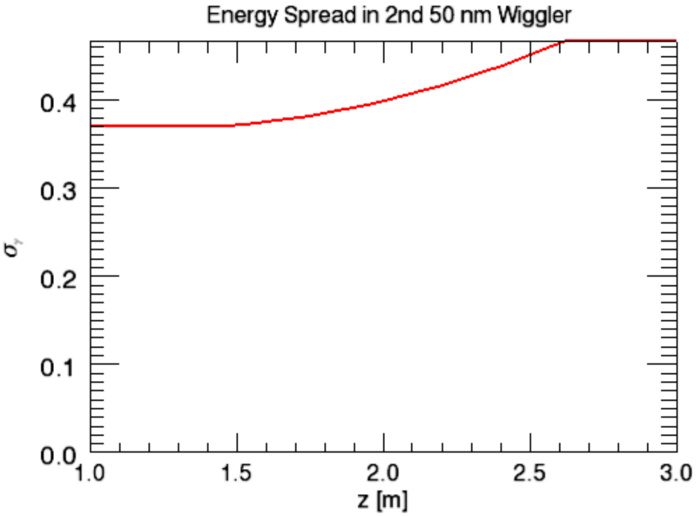
You want to maximize power out, while minimizing increase in energy spread from 50 nm radiator.

Assume 50 nm bunching factor is constant in radiator. Then you get:

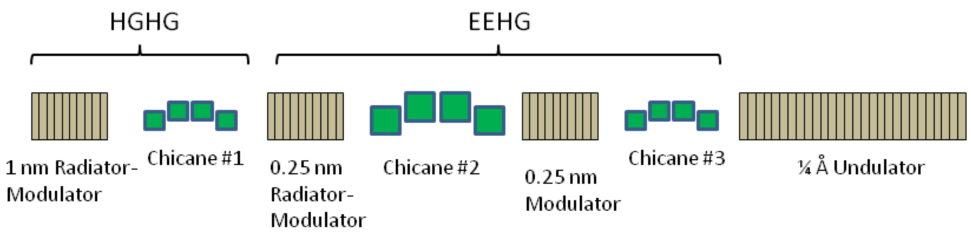
$$E_{x0} = -\frac{\mu_0 c \hat{K} z}{4\gamma_r}\tilde{j}_n \quad ; \quad P = \frac{A_b}{\mu_0 c}E^2 \quad ; \quad \frac{d\eta_{\max}}{dz} = \frac{e\mu_0 \tilde{K}^2 \tilde{j}_n}{8mc\gamma_r^3} z$$

Combining these, we get: $\dfrac{P}{\eta} = \dfrac{A_b mc^2 \gamma \tilde{j}_n}{e}$

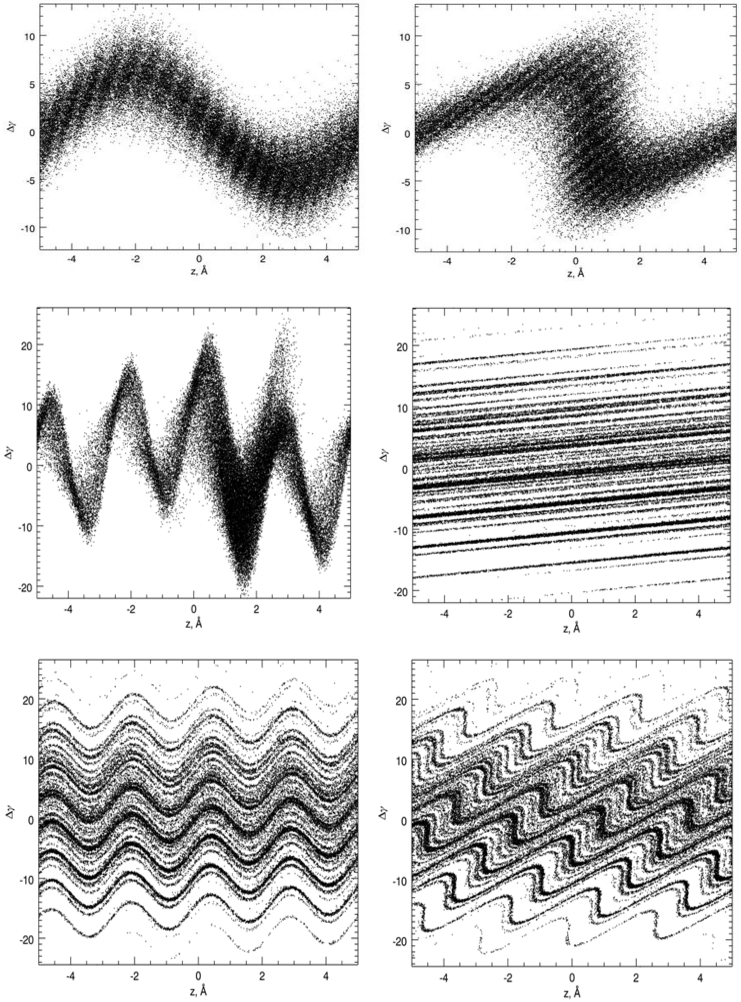
- You need high bunching factor at 4th harmonic to get favorable ratio of 50 nm power to induced energy spread. Length of radiator does not effect ratio.



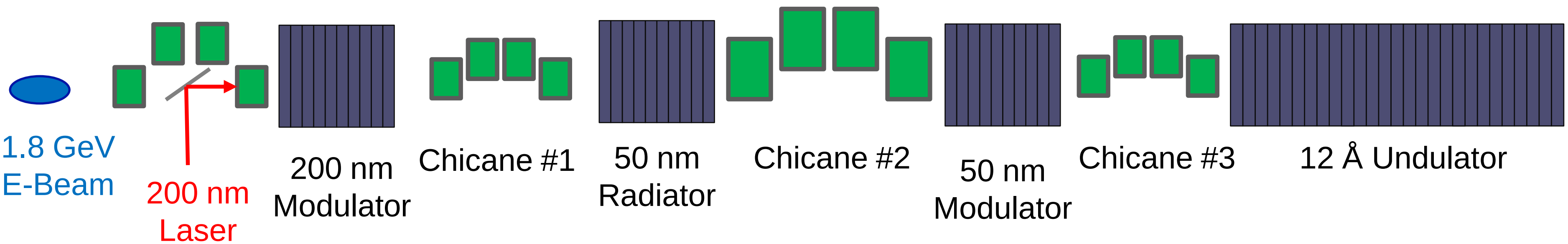
Harmonic Generation with Hard X-rays



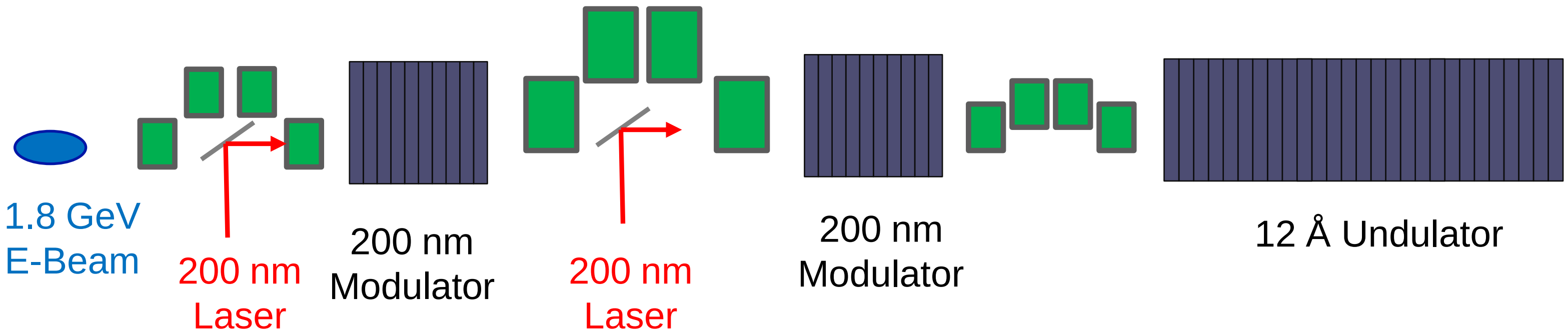
- We developed an HGHG-EEHG scheme for stepping from 1 nm to 0.25 Å at 20 GeV (old MaRIE parameters).
- Uses bunching in beam, instead of laser seed, to generate harmonics.
- Biggest issue is 10 fs slippage between x-rays and beam in large chicane.
- Input bunching is 10% at 1 nm, with an energy spread of 5×10^{-5}, output is 9.2% at 0.25 Å with an energy spread of 2.1×10^{-4}.

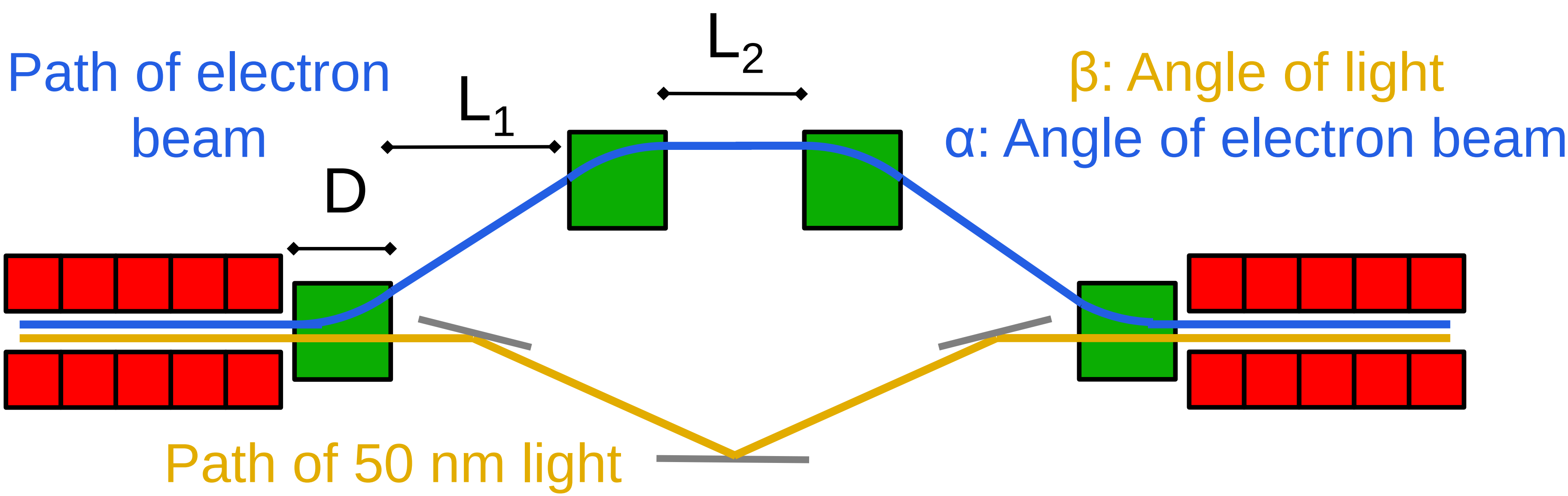


Single Seed HGHG-EEHG

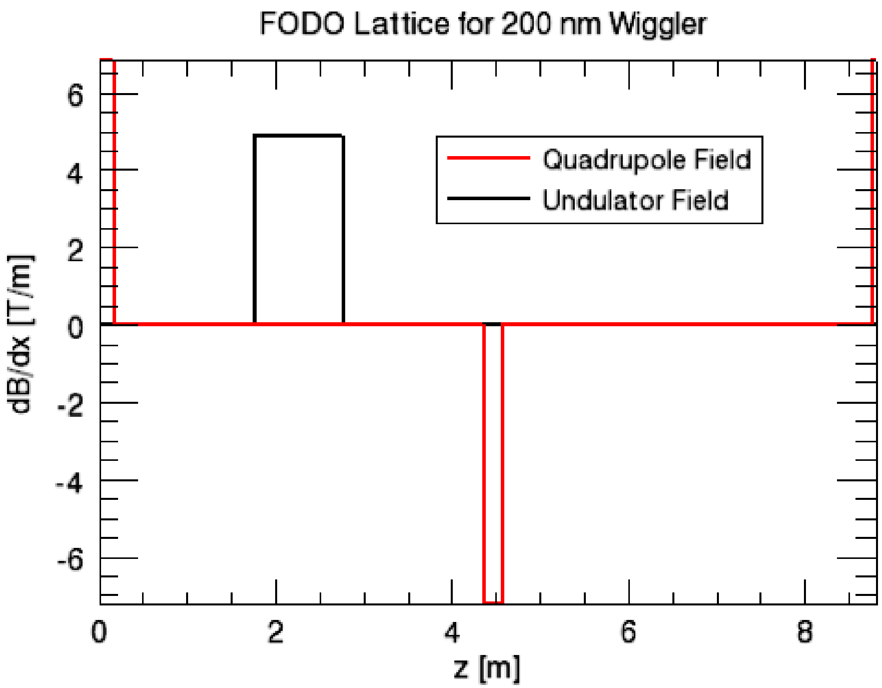


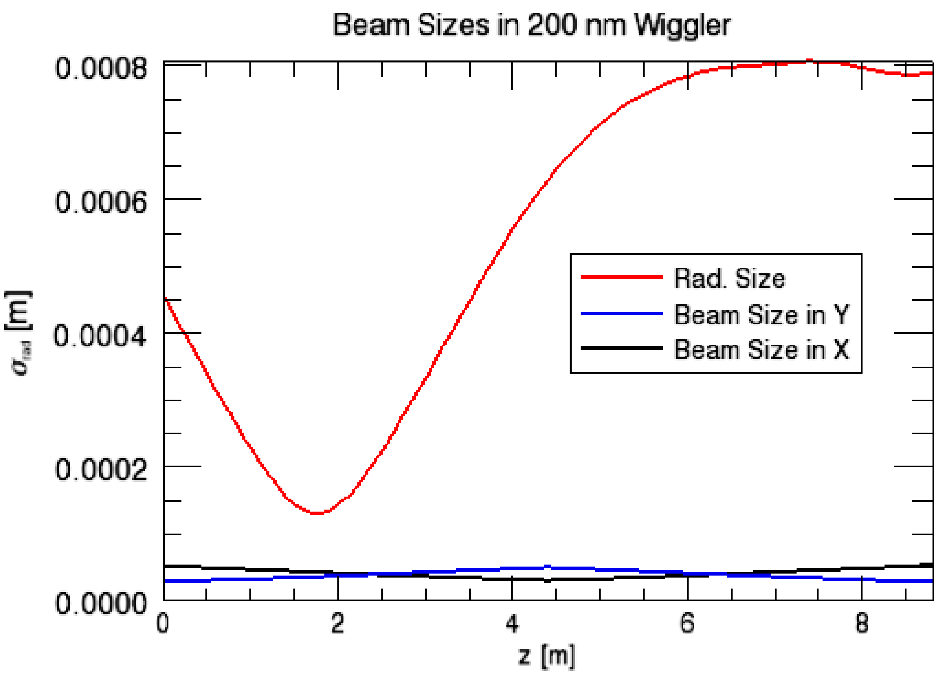
EEHG




Path of electron beam
L_2
L_1
D
β: Angle of light
α: Angle of electron beam
Path of 50 nm light

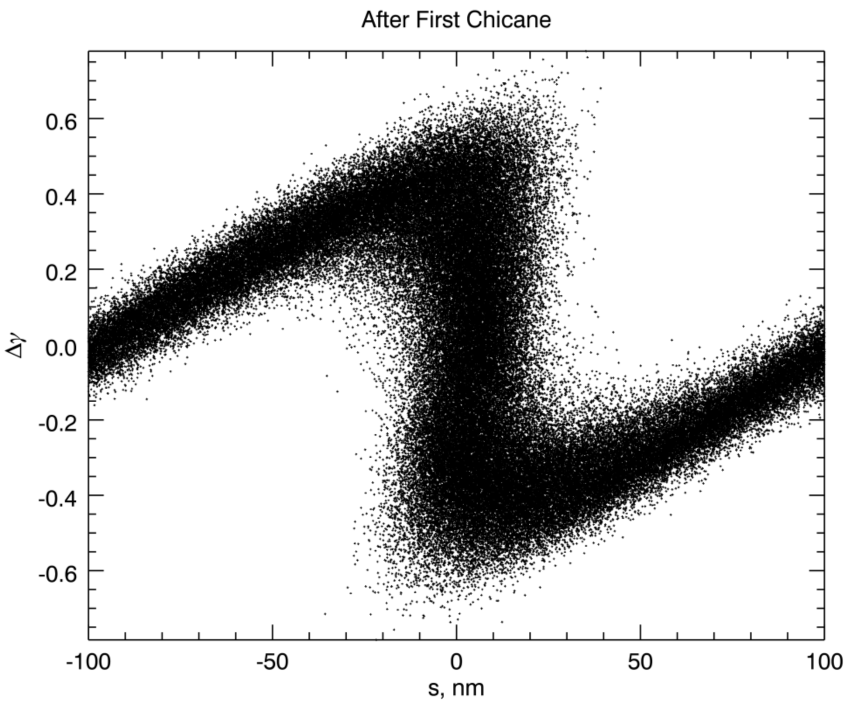
200 nm modulator

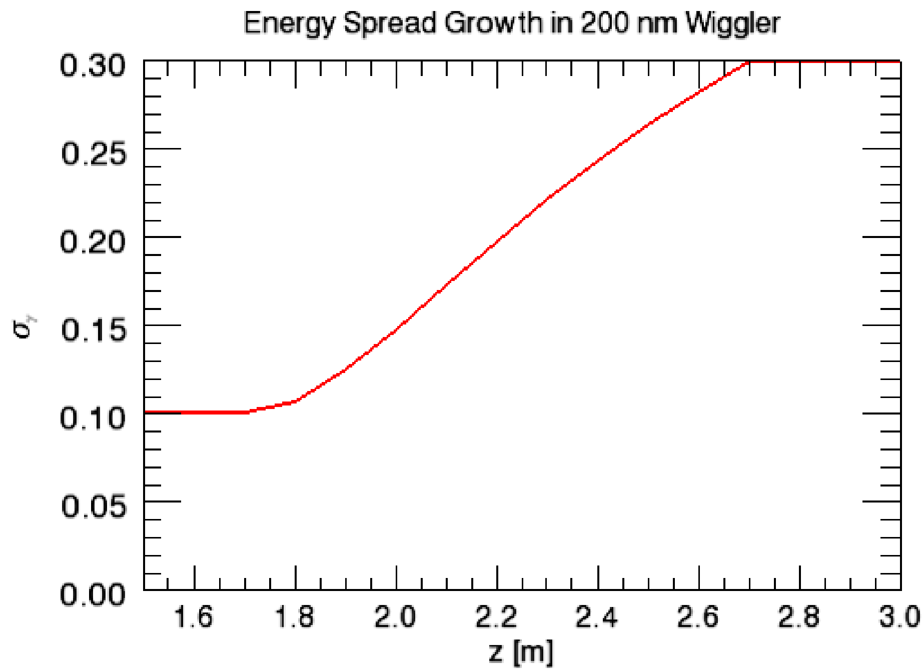




- 200 nm modulator is same design as NGLS – 1 meter long, Aw0 = 4.872 and wiggler period = 20 cm.
- Light can be focused down a lot, so that power requirement is low.

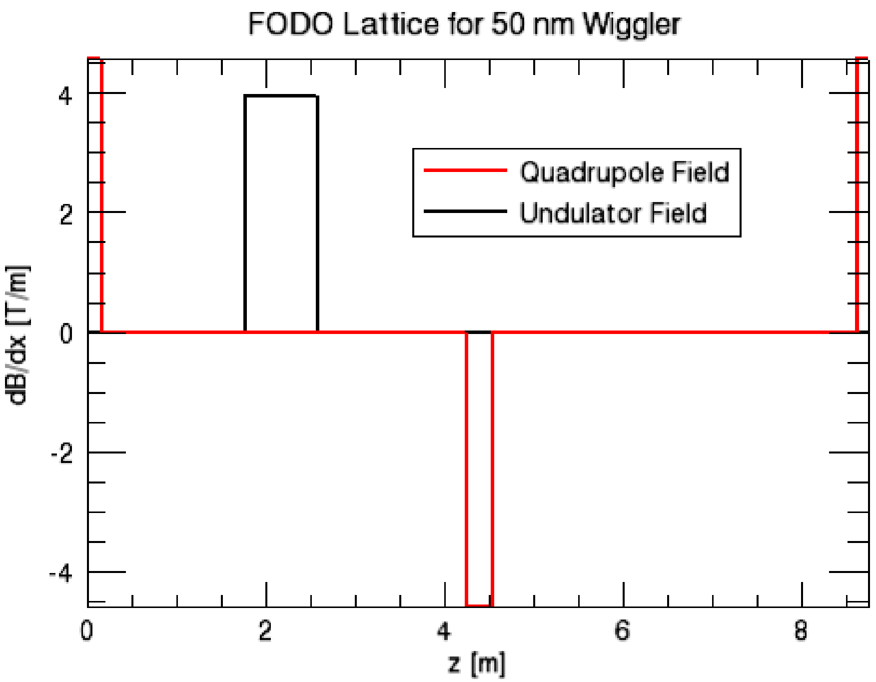
200 nm modulator

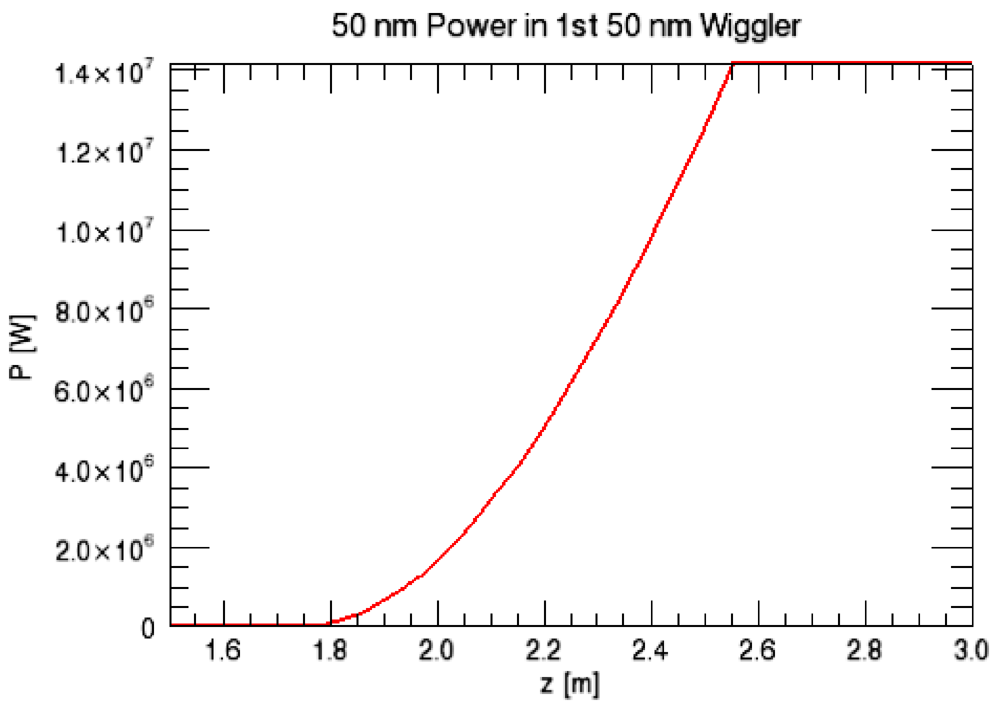




- Right now I apply an ideal R56, but let the particles drift an appropriate amount to approximate the emittance nonlinearity.
- I include ISR in wigglers, but not chicanes (need Elegant).
- Bunching at 4th harmonic is 13%.

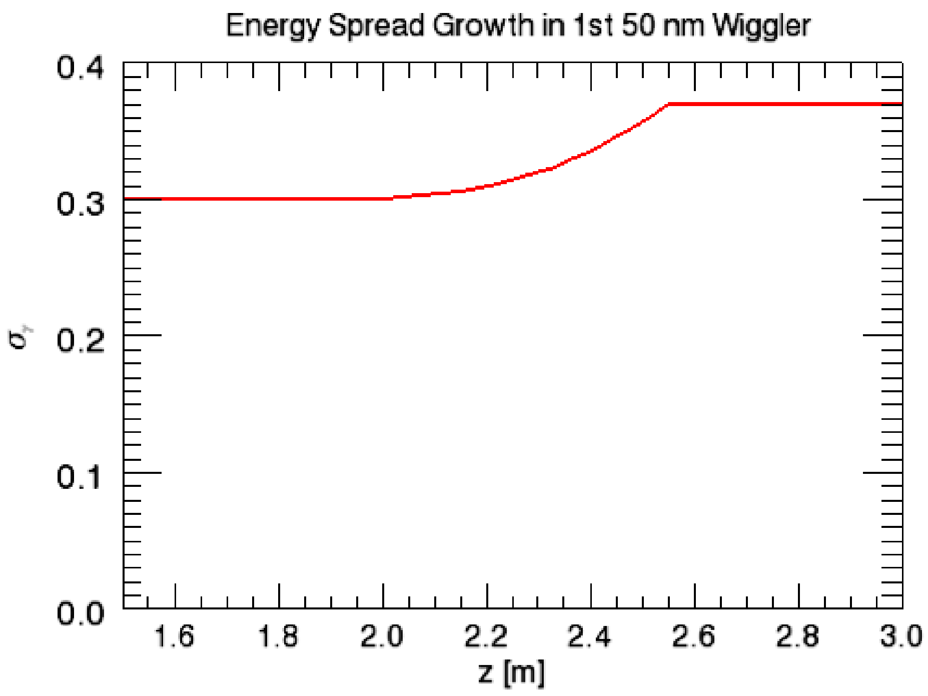
50 nm modulator

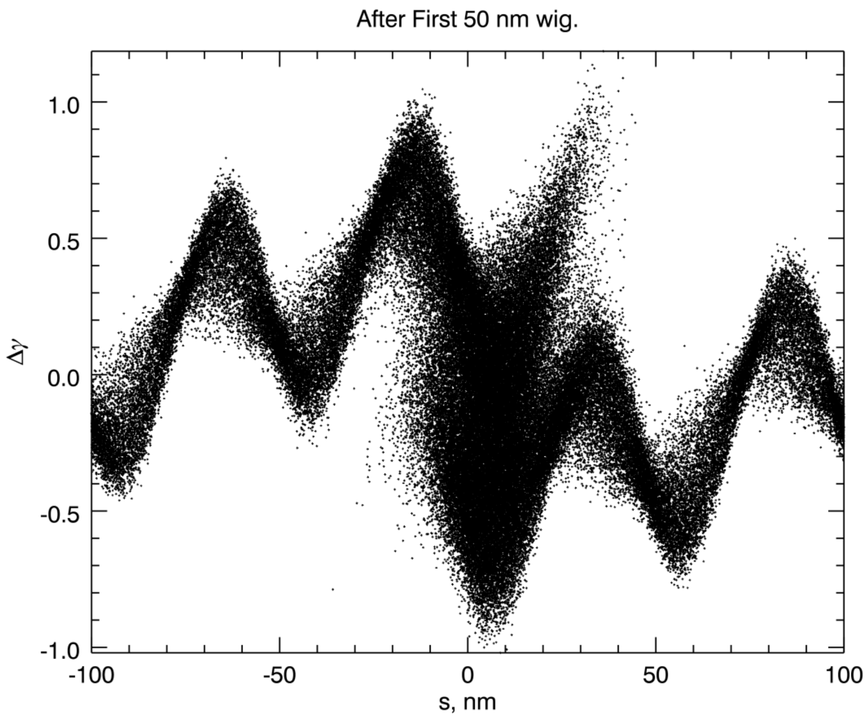




- 50 nm wigglers are Aw0 = 4.0, wiggler period 7.29 cm. This has not been optimized.
- The power I get is less than what NGLS design uses in final modulator, but still seems adequate.

50 nm modulator



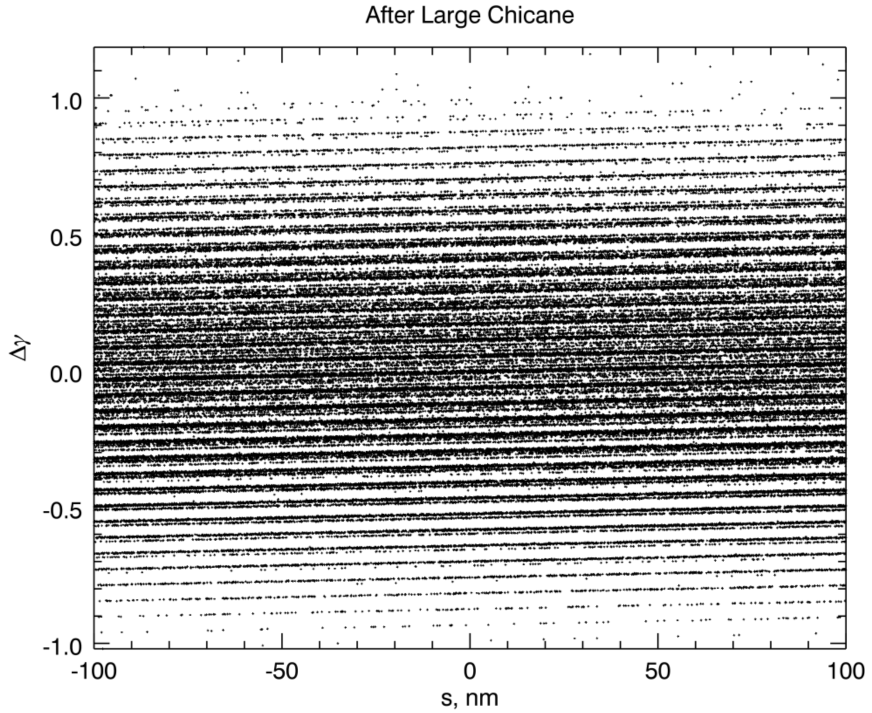


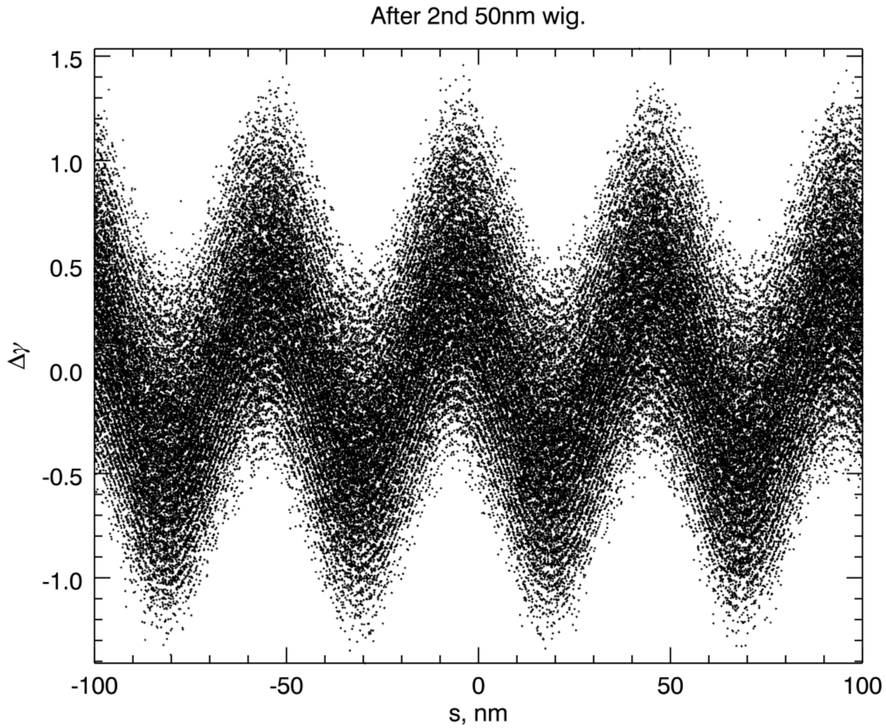
• It is impossible to generate 50 nm radiation without also modulating the beam. Ratio of power to modulation is:

$$\frac{P}{\eta} = \frac{A_b mc^2 \gamma \tilde{j}}{e}$$

• Increase in energy spread is small, but phase space is distorted over traditional EEHG. Kinetic code gives 10% bunching at 12 Å, but large chicane is larger than pure EEHG, and some harmonics may be suppressed.

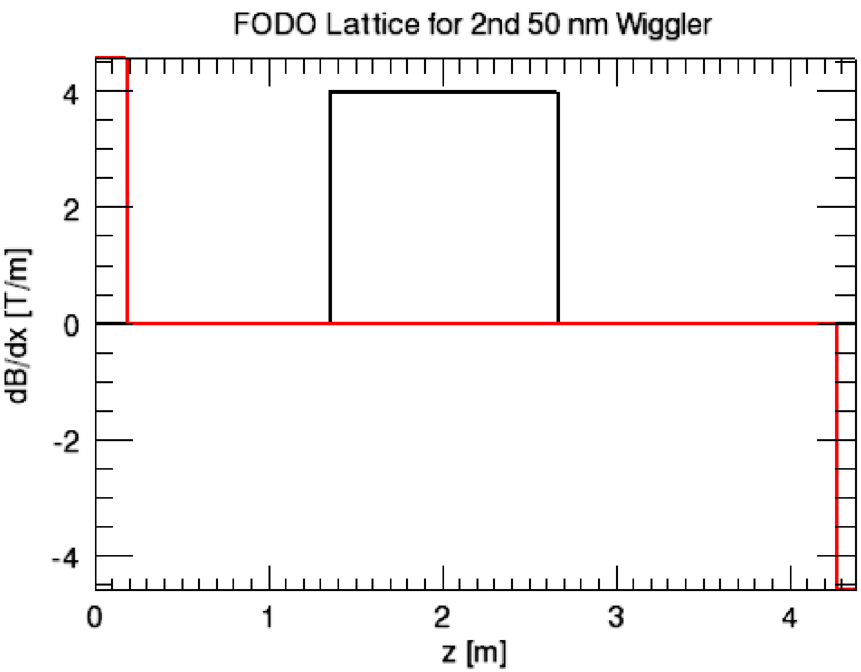
Second 50 nm modulator

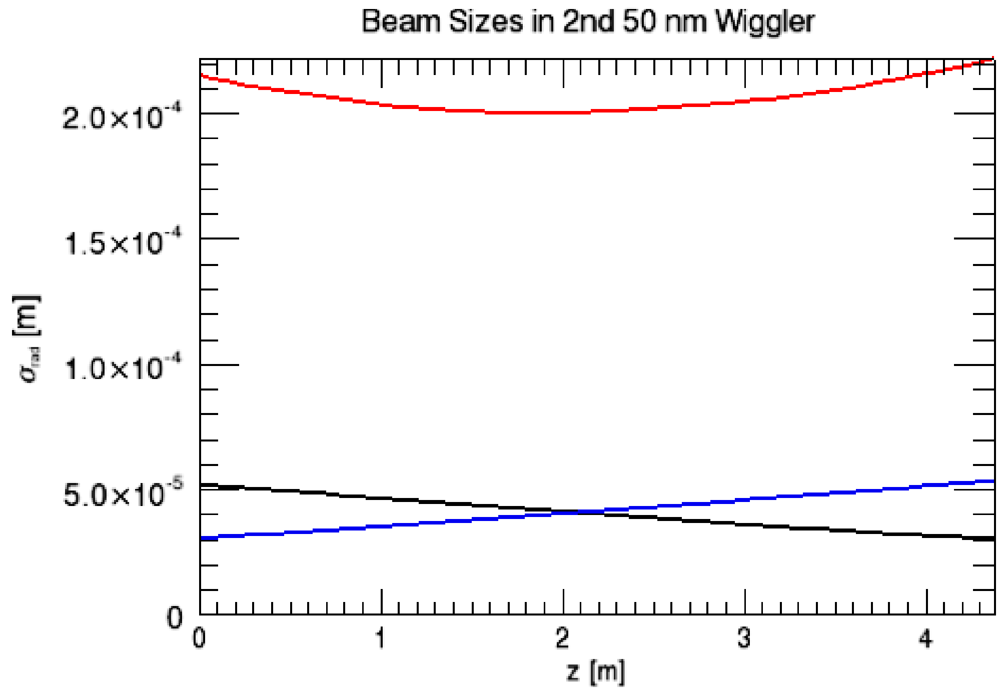




- ISR, nonlinearity, and finite transverse radiation size reduce energy bands in wiggler.
- Still, I am getting 6% bunching at 12 Å, I may be able to improve this by optimizing Aw0 and transverse electron beam size.

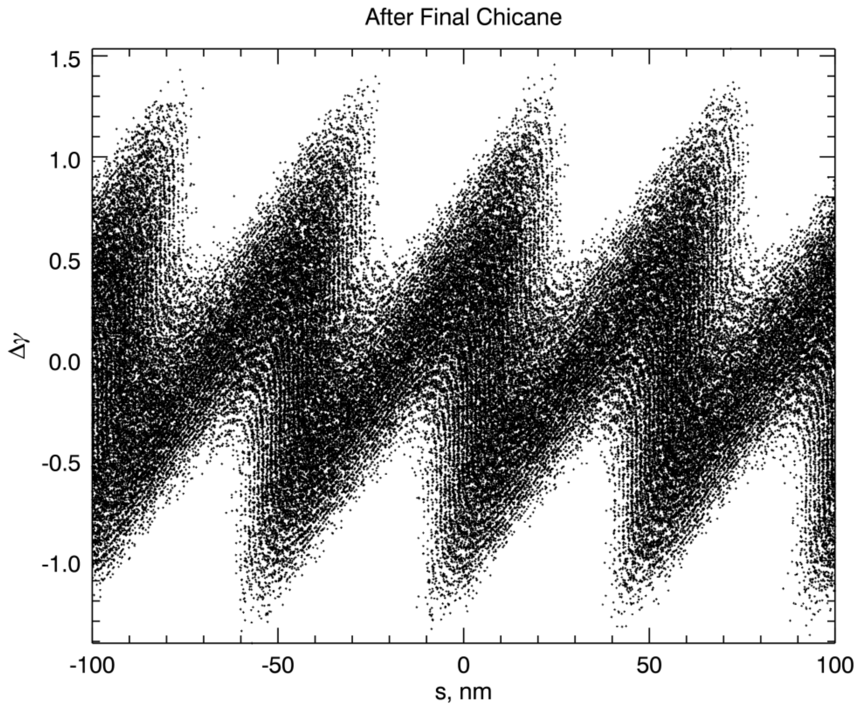
Second 50 nm modulator

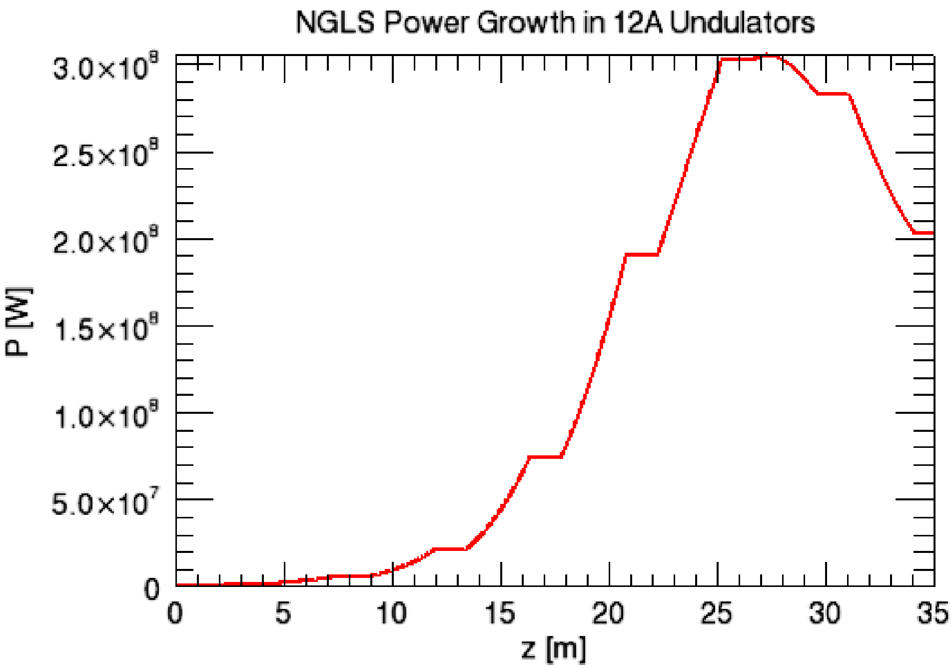




- Size of 50 nm radiation is very important.
- Also need to keep distance between 50 nm and 12 Å wiggler short. Because my final chicane is ~1/3 size of current NGLS, we can make this distance ~1 m.

12 Å Undulator





- Saturation length is 10 m shorter than NGLS design, power about the same.