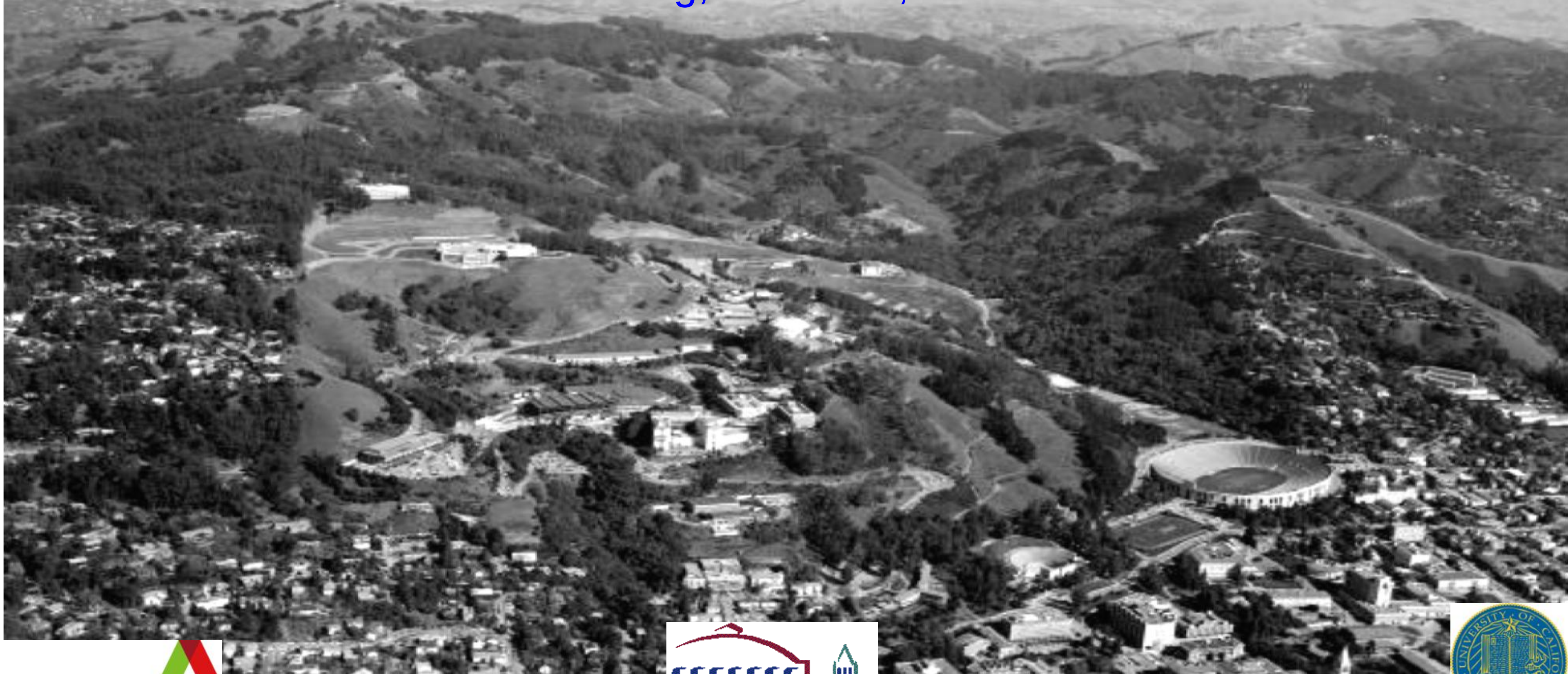
Soft X-ray FEL Oscillators

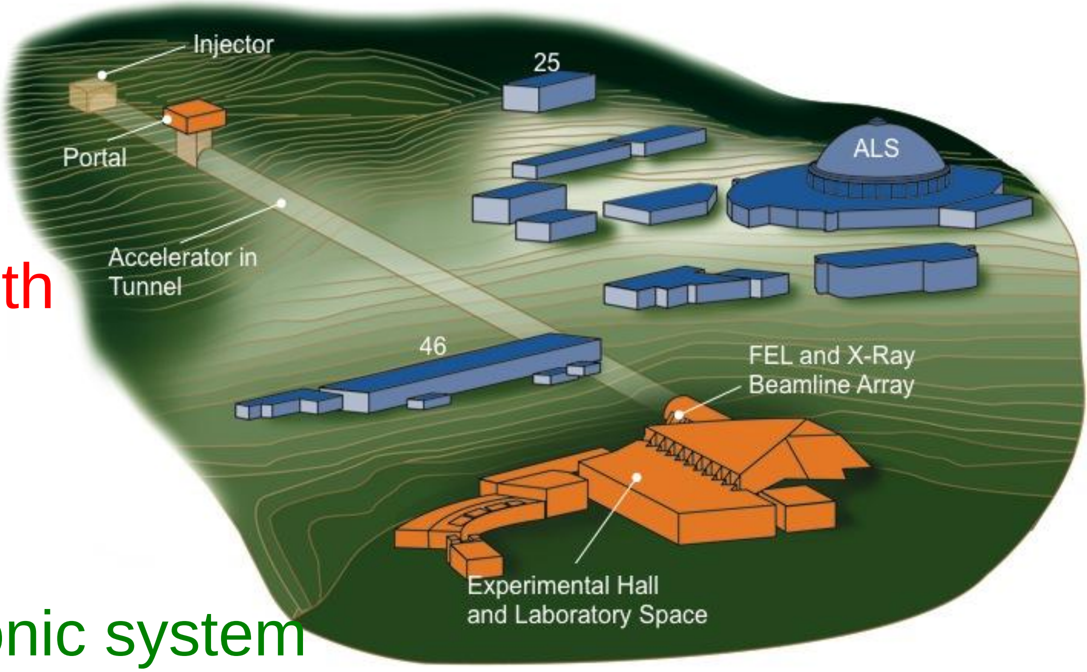
32nd International Free Electron Laser Conference
Malmo, Sweden

J.S. Wurtele
UCB/LBNL
Co workers: W. Fawley, P. Gandhi, X.-W. Gu, G. Penn, M. Reinsch
R. R. Lindberg, K.-J. Kim, A. Zholents



A coherent CW soft x-ray laser

Next Generation Light Source at LBNL



- 10 eV - 1 keV range

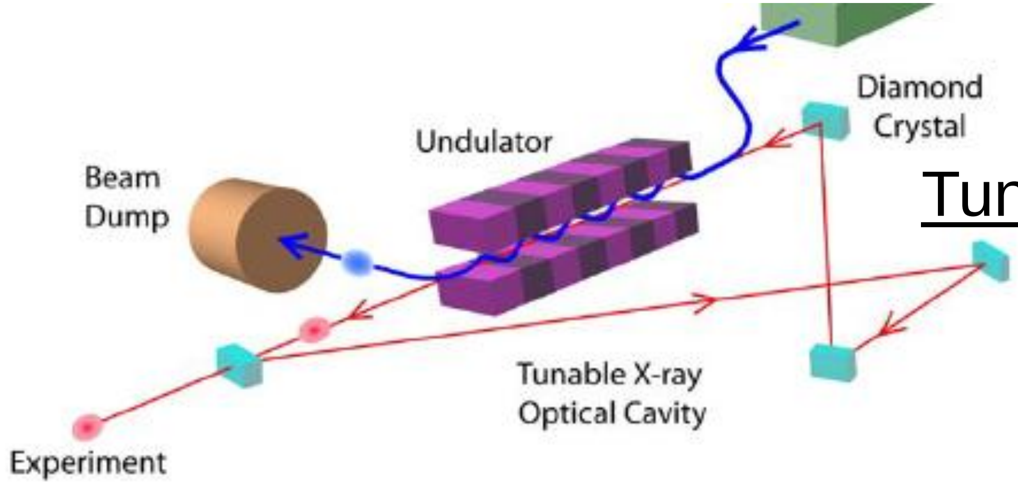
Tunability and time-bandwidth limited pulses <=1ps

High repetition rate

- Seeding by laser,
  - *OR* Oscillator-driven harmonic system

- High average power – below damage threshold peak power for low scattering rate experiments

Hard X-Ray FEL Oscillator



Tunable and small bandwidth

K.J. Kim et al

- Store an X-ray pulse in a Bragg cavity→ multi-pass gain & spectral cleaning
- Provide meV bandwidth ($\Delta\omega/\omega \sim 10^{-7}$)
- MHz pulse repetition rate→ high average brightness

Originally proposed in 1984 by Collela and Luccio and resurrected in 2008 (KJK, S. Reiche, Y. Shvyd'ko, PRL 100, 244802 (2008))

What can we do in the soft X-ray regime?

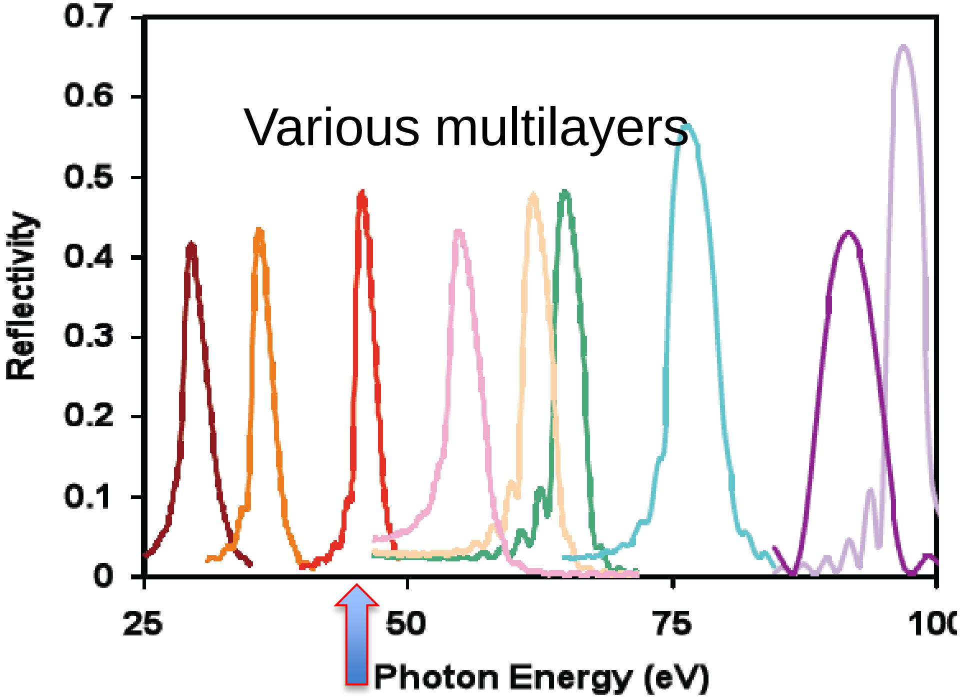
- Cannot use Bragg reflection in the soft X-ray regime
- Reflectivity at 1nm is poor for layered dielectrics
- High repetition rate sources at 1nm are not available
- Short bunch (single SASE spike): we consider longer bunches
- layered dielectric mirrors good for 13.4 nm and longer wavelengths

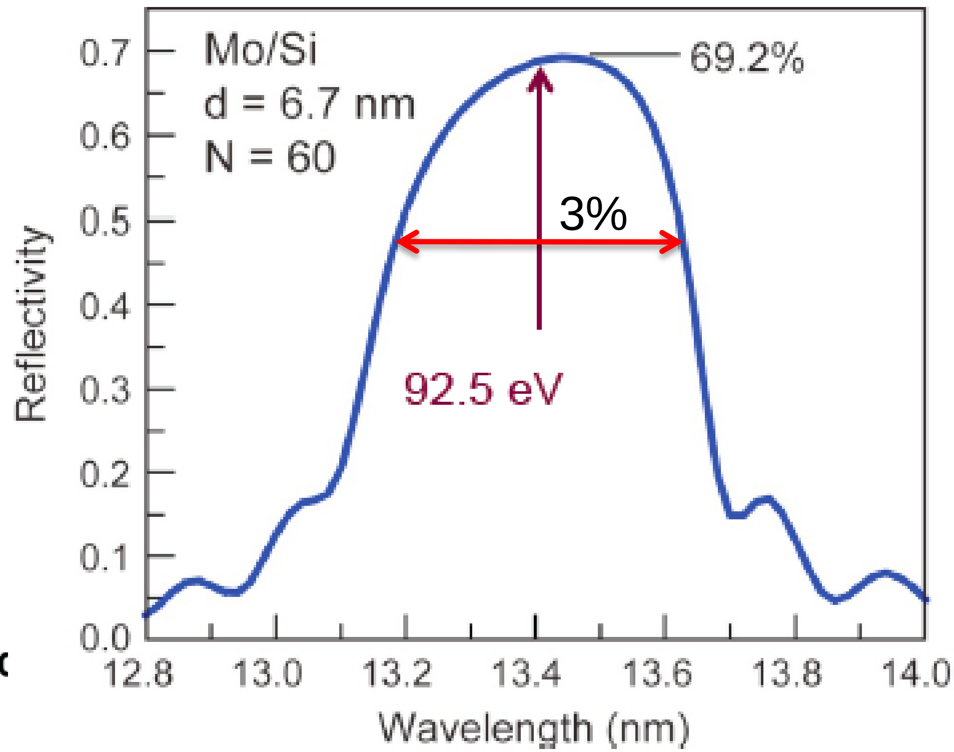
→ ECHO scheme for high harmonics and tuning

→ Source can be FEL itself using an oscillator

High reflectivity multilayer mirrors

The gold standard for soft x-ray mirrors

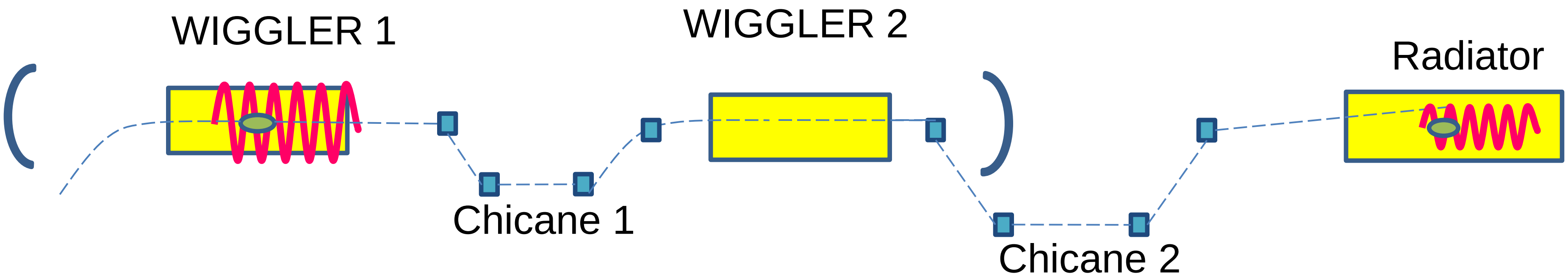




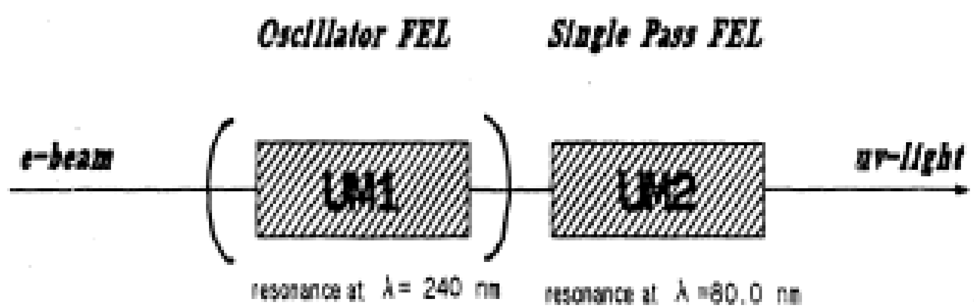
Need to operate at high harmonic for full tunability

Courtesy Eric Gulickson and David Attwood, LBNL

Oscillator Bunching and Radiator



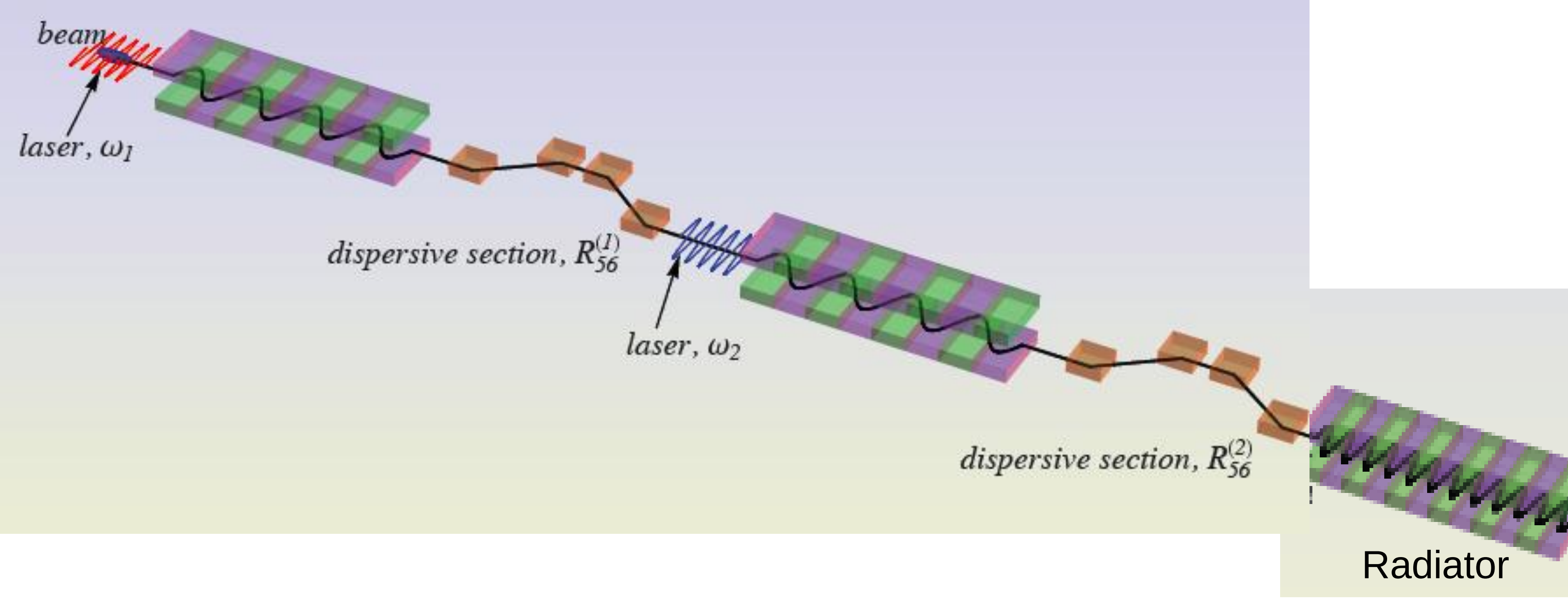
Chicane 1 acts to reduce bunching and lower intracavity power
Chicane 2 bunches at desired harmonic for radiator



Barbini et al 1990 BNL 52273

Later with optical klystron configuration [Dattoli et al 2004]

Echo Enabled FEL



Stupakov, PRL 2009

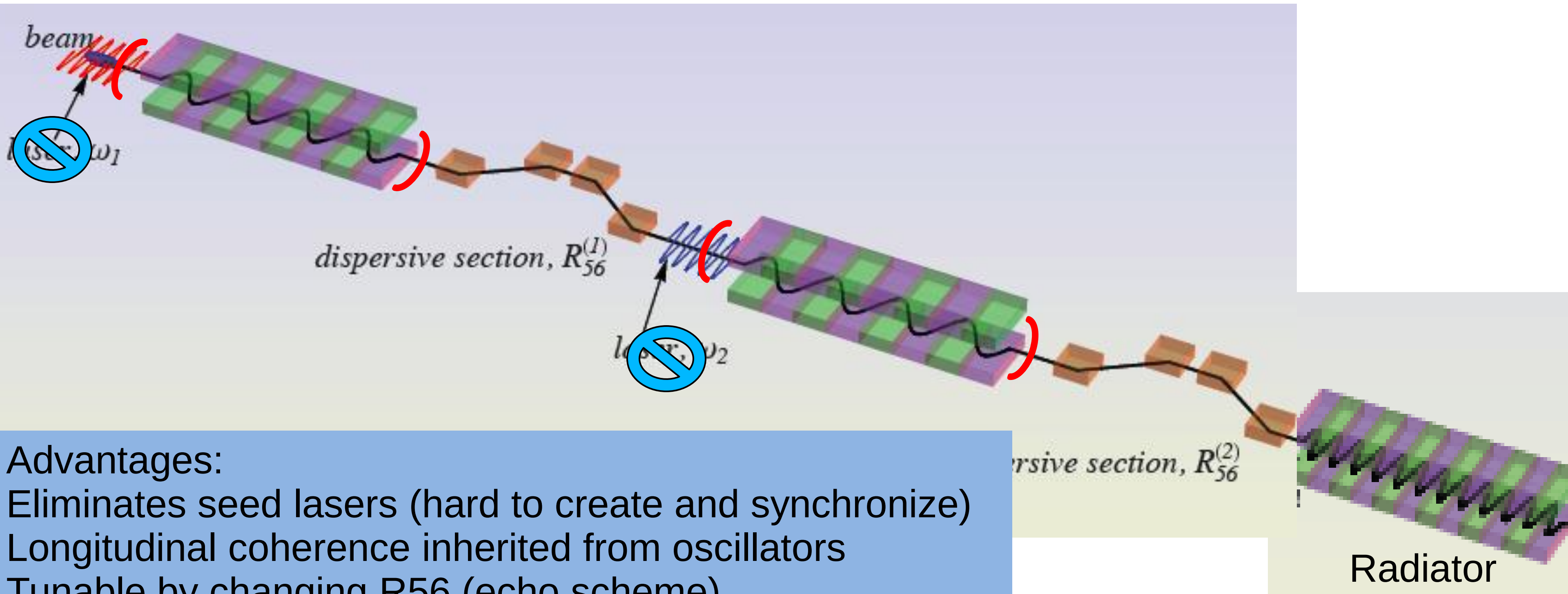
Compact method for lasing at high harmonics without cascade

Stability of bunching determined by ebeam and seed lasers

Longitudinal coherence and small bandwidth is important for many users

FEL oscillators provide longitudinal coherence but are not tunable over a wide band

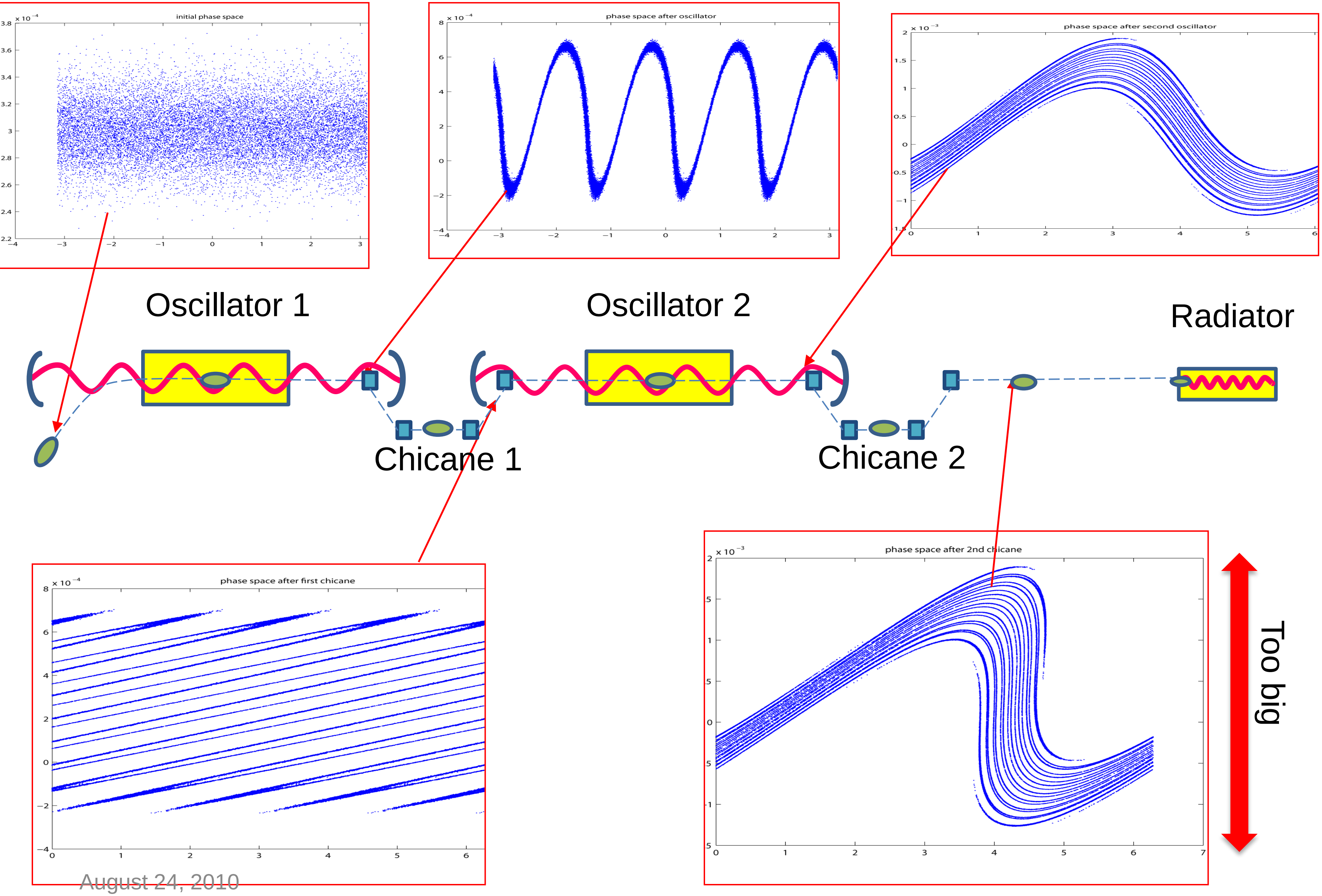
Two-oscillator echo enabled tunable soft x-ray FEL



Advantages:
Eliminates seed lasers (hard to create and synchronize)
Longitudinal coherence inherited from oscillators
Tunable by changing R56 (echo scheme)

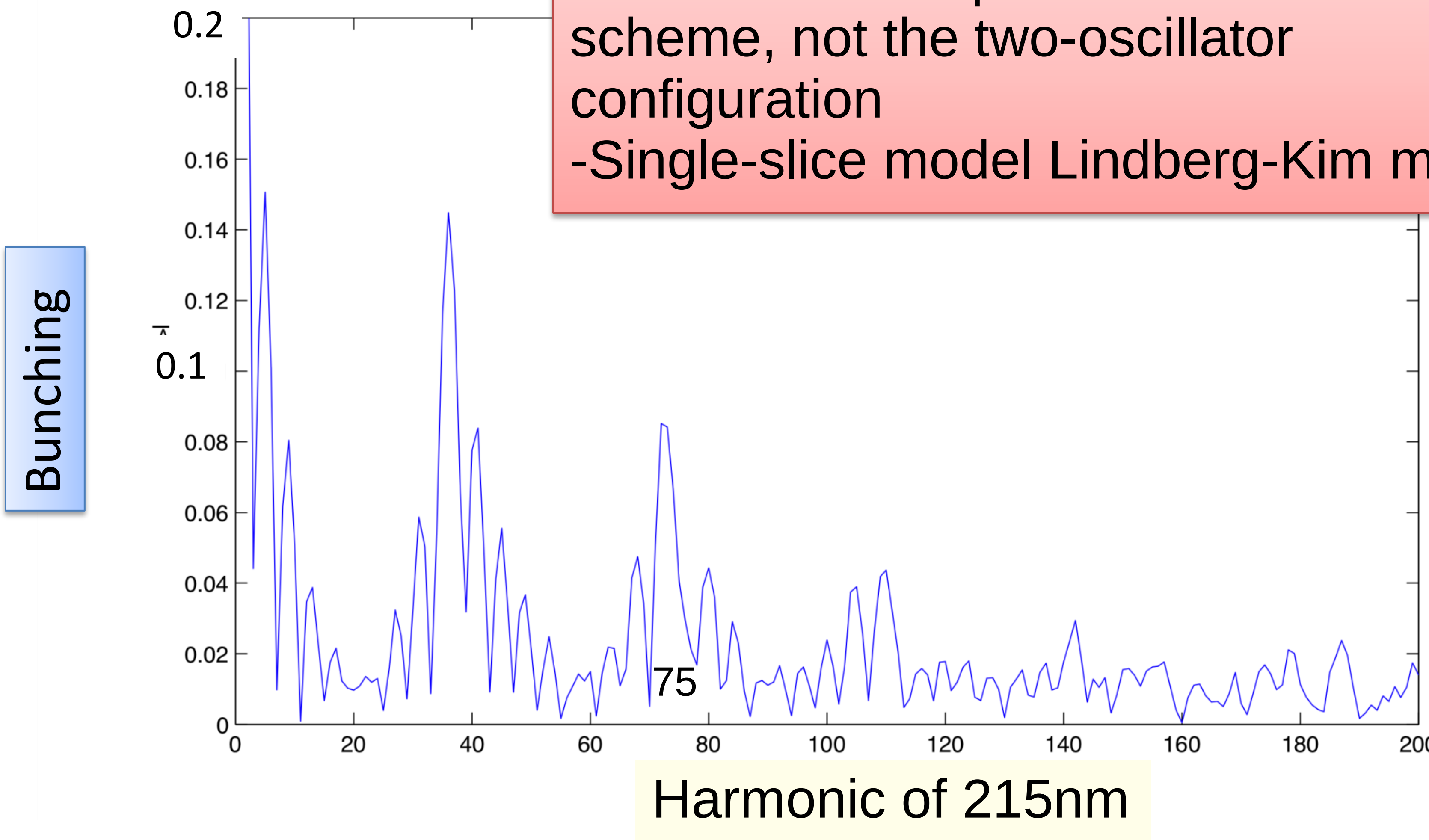
Disadvantages:
Oscillators induce energy spread and overbunching
Requires optics in soft xray regime

Two-oscillator echo-enhance FEL: time independent simulation



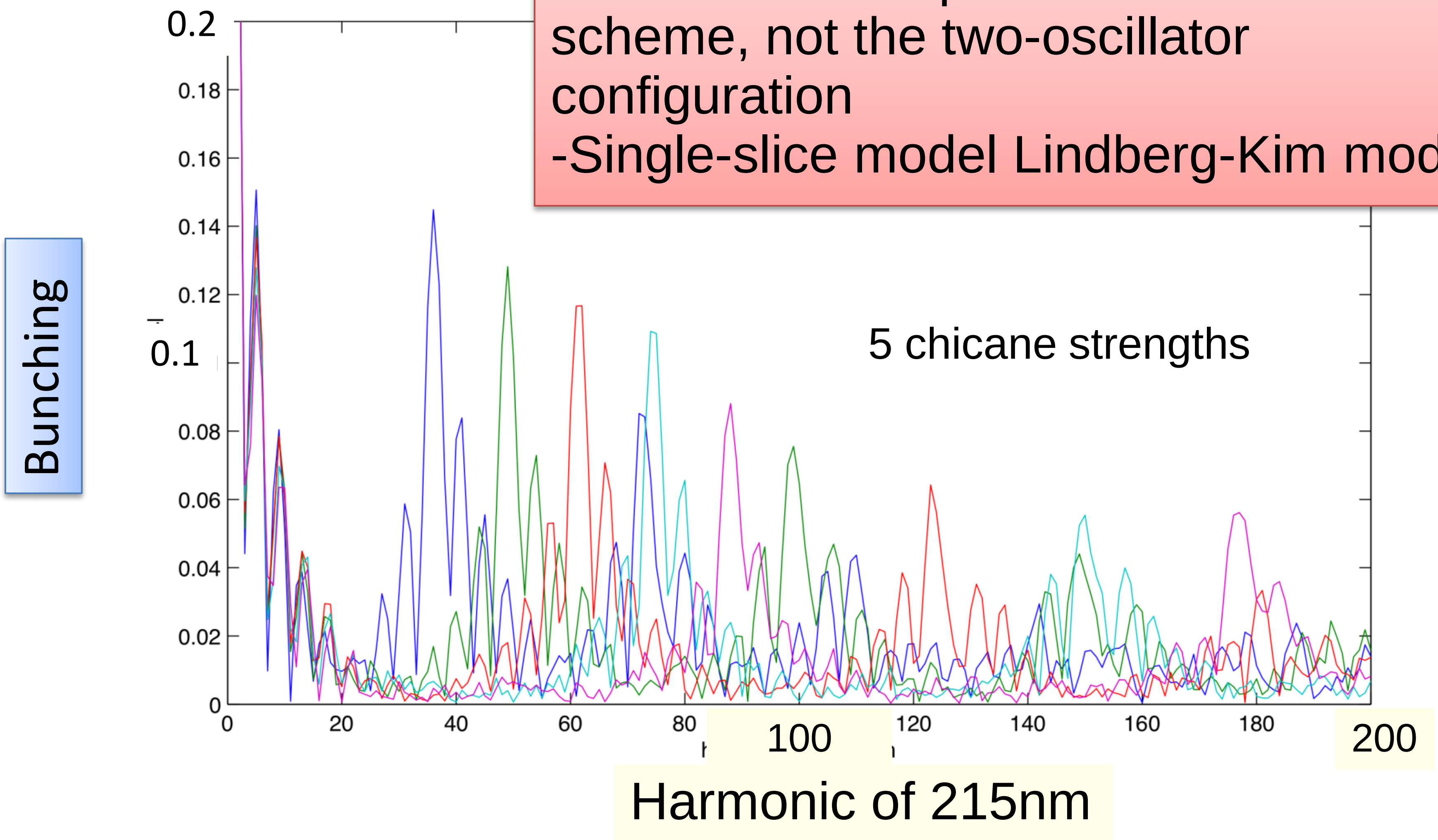
Tunability

-Harmonic bunching is shifted by adjusting the chicanes.
-This is a consequence of the echo scheme, not the two-oscillator configuration
-Single-slice model Lindberg-Kim model.



Tunability

-Harmonic bunching is shifted by adjusting the chicanes.
-This is a consequence of the echo scheme, not the two-oscillator configuration
-Single-slice model Lindberg-Kim model.



Comments

- The induced energy spread is too large---the bunching is OK, but the radiator will have trouble; FEL oscillators ‘like’ to overbunch bunch the beam.
- Time dependent GINGER simulations do not produce uniform bunching along the bunch.
- We need not have the FEL produce 215nm radiation. We assume an input laser seed
- We insert a chicane to reduce the induced energy spread in oscillator #1

Numerical Simulation: How we model the oscillator-echo scheme with time-dependent GINGER

43nm oscillator: Time-dependent Ginger oscillator calculation with a dispersive element(800 contiguous 43 nm slices)

First Chicane: 6-dimensional phase space transformation code from Genesis. Then re-bin and re-group to 215nm slices.

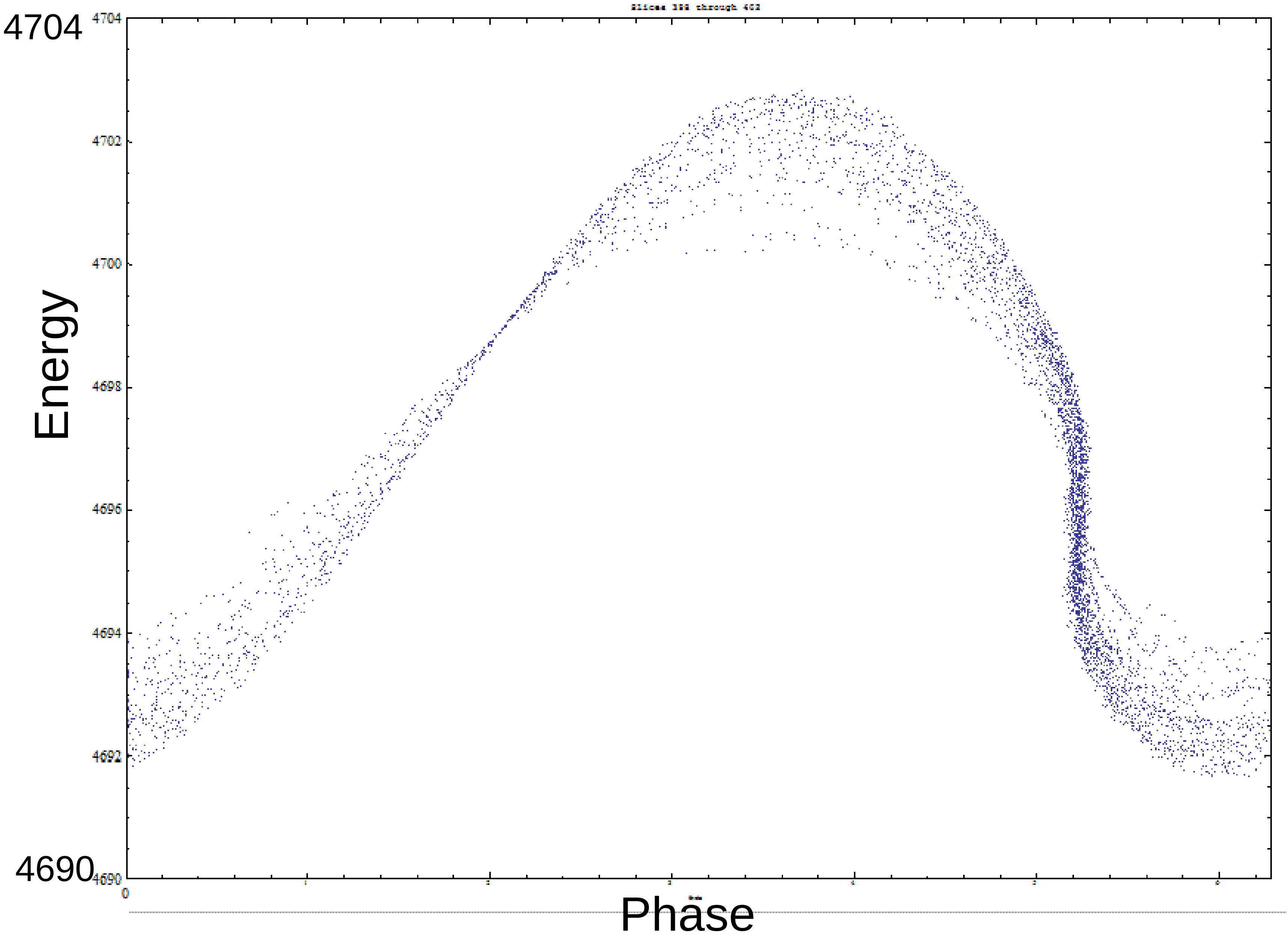
215nm modulator: Time-dependent Ginger run. LASER SEED

Second Chicane: 6-D phase space transformation

Radiator: Time-dependent Ginger run

43 nm oscillator phase space

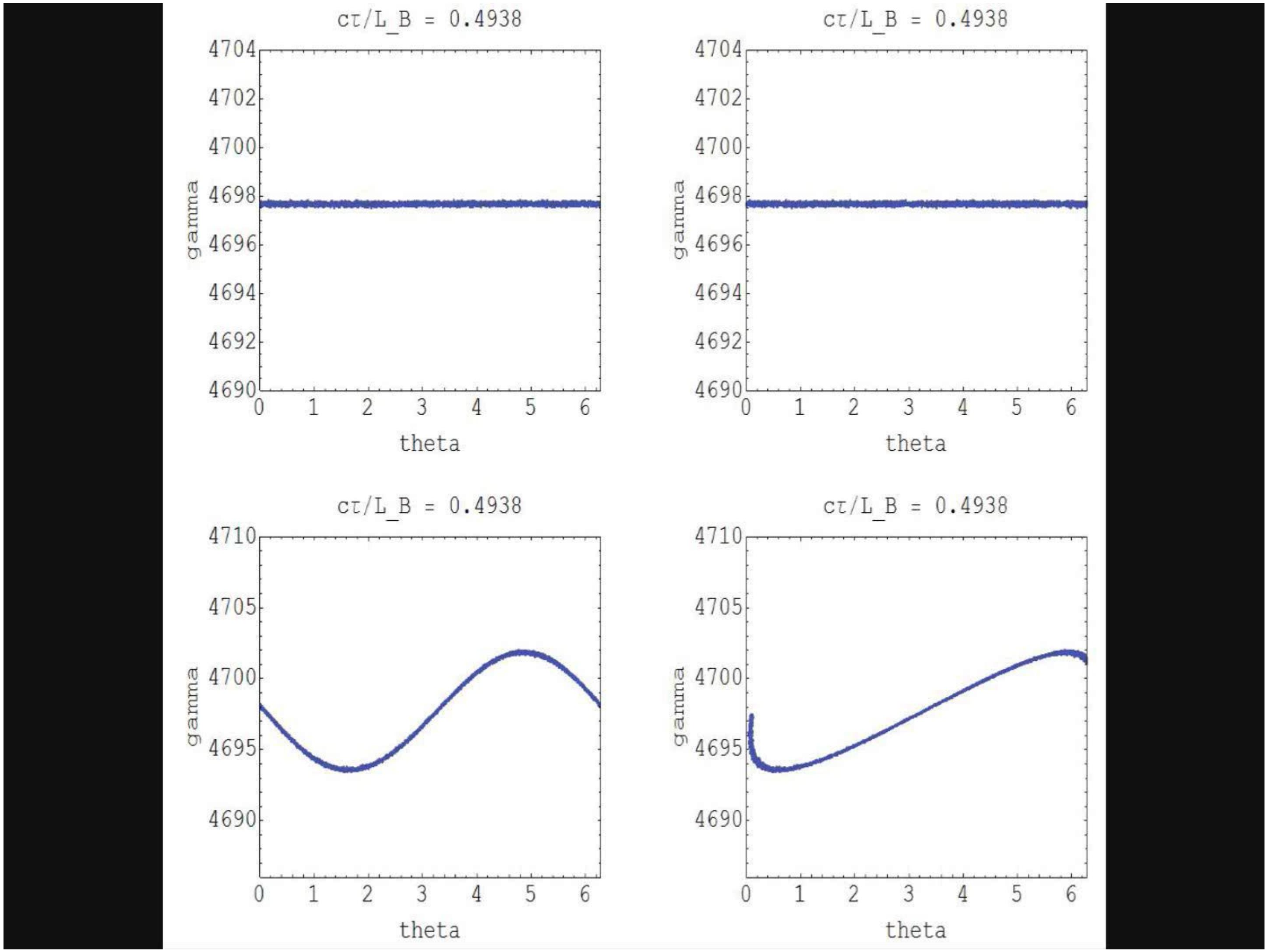
Central slices (typical)



Bunch phase space at 4 locations vs position in bunch

Osc 1 exit

Modulator 2 exit



Chicane 1

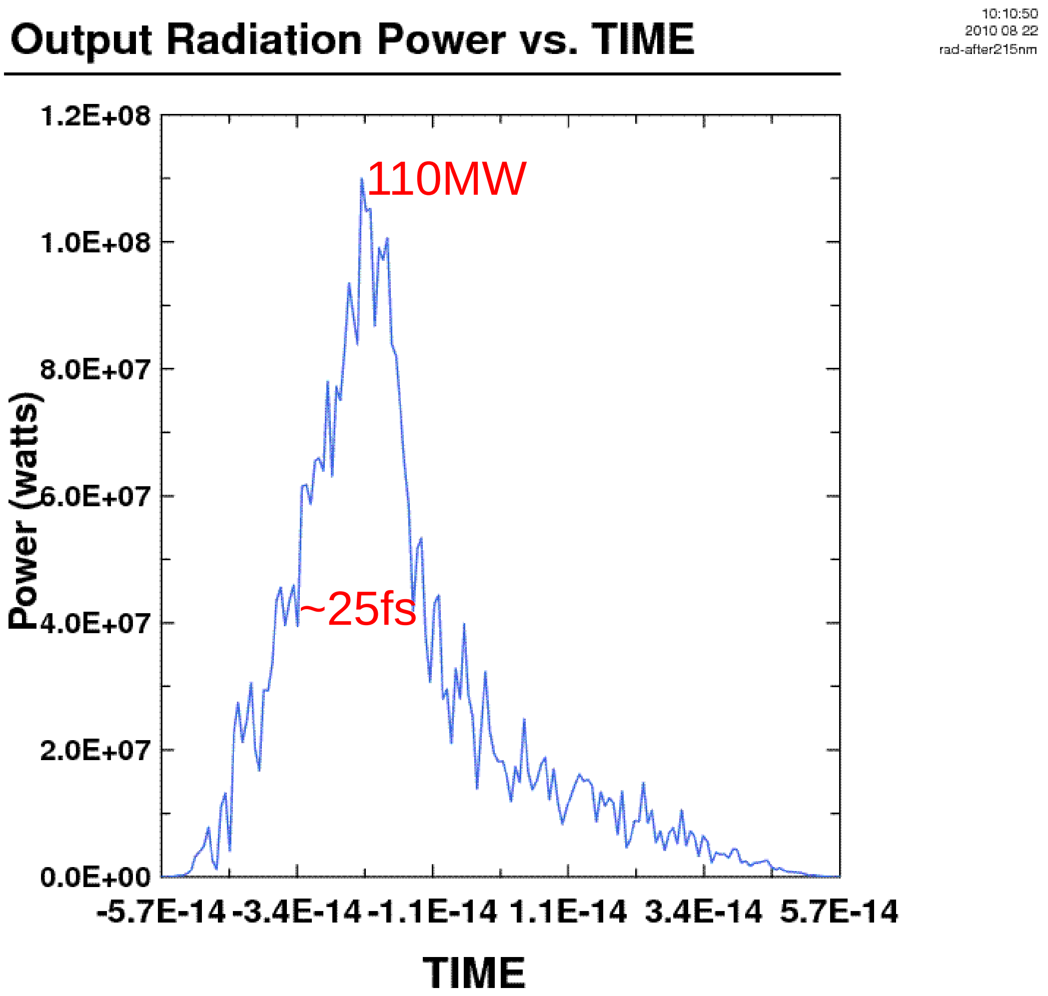
Chicane 2

Radiator output at 2.7 nm

80th harmonic of 215 nm

25m undulator

2.2 cm period and a_w=2

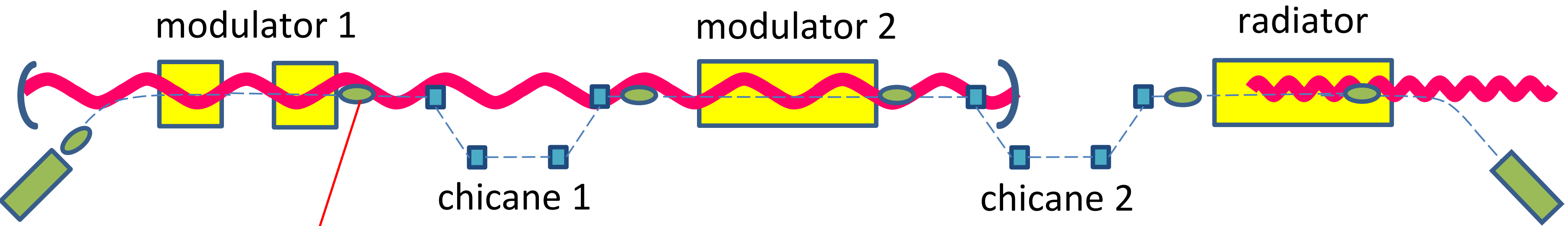


Note: HGHG does better ~300MW,~50fs

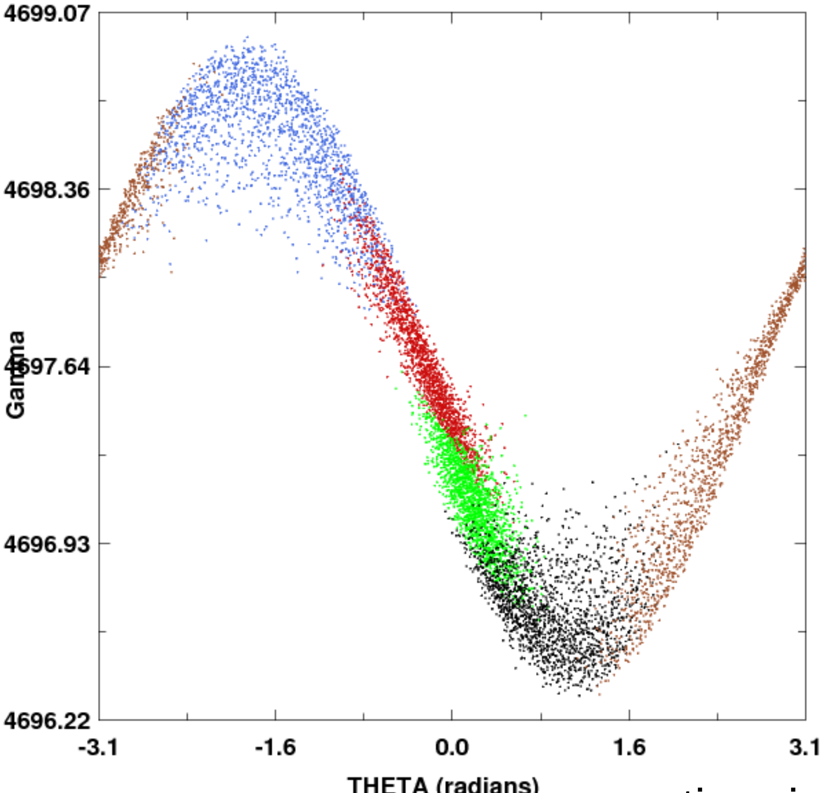
Comments

- The above runs are not optimized with respect to the large number of possible parameter combinations
- A nonlinear optical element can change the saturated FEL dynamics.
- This should allow for more uniform bunching
- This should allow for less energy spread.
- We are looking for such an element, and will be happy to know of one!
- There are two geometries that avoid the problems completely (but use more real estate).
- We can use one cavity instead of two. Studied with time-independent GINGER at 13nm:

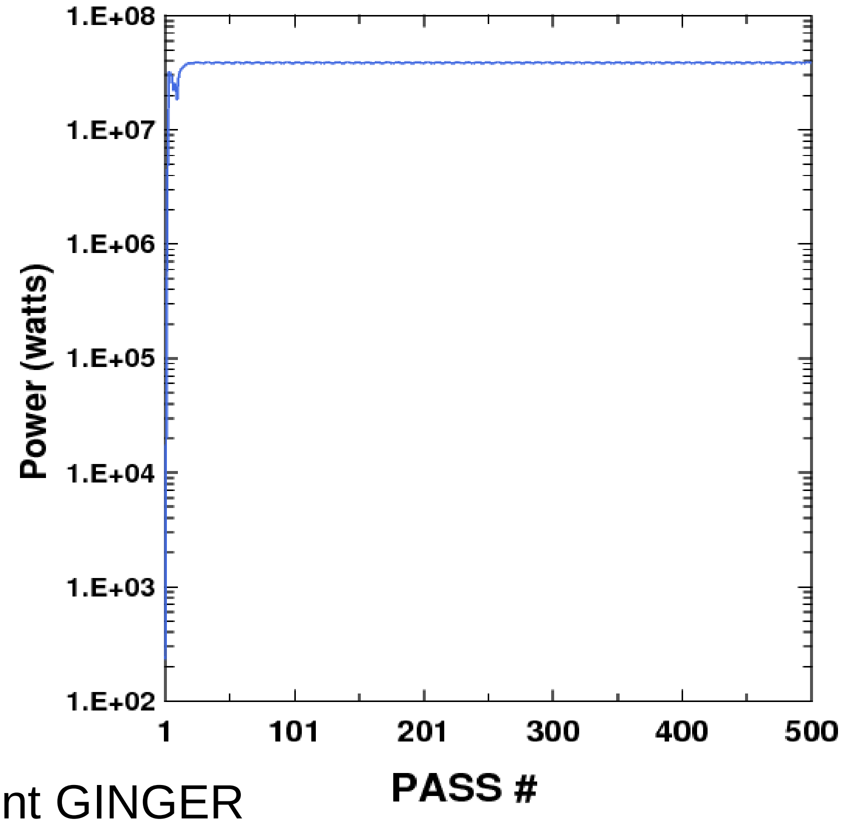
ECHO Oscillator Configuration: single cavity 13nm



Phase space end of modulator 1

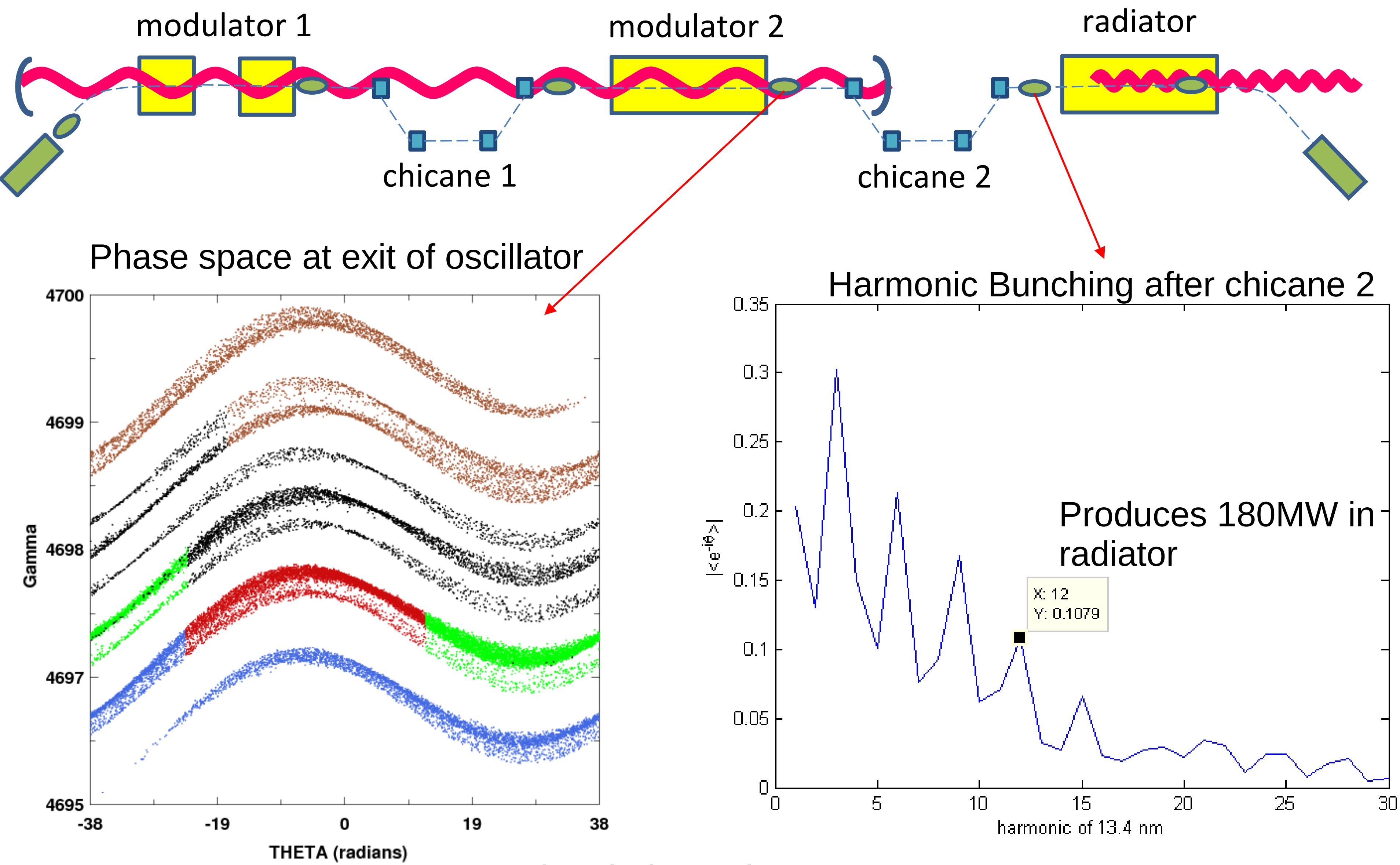


Output power in oscillator



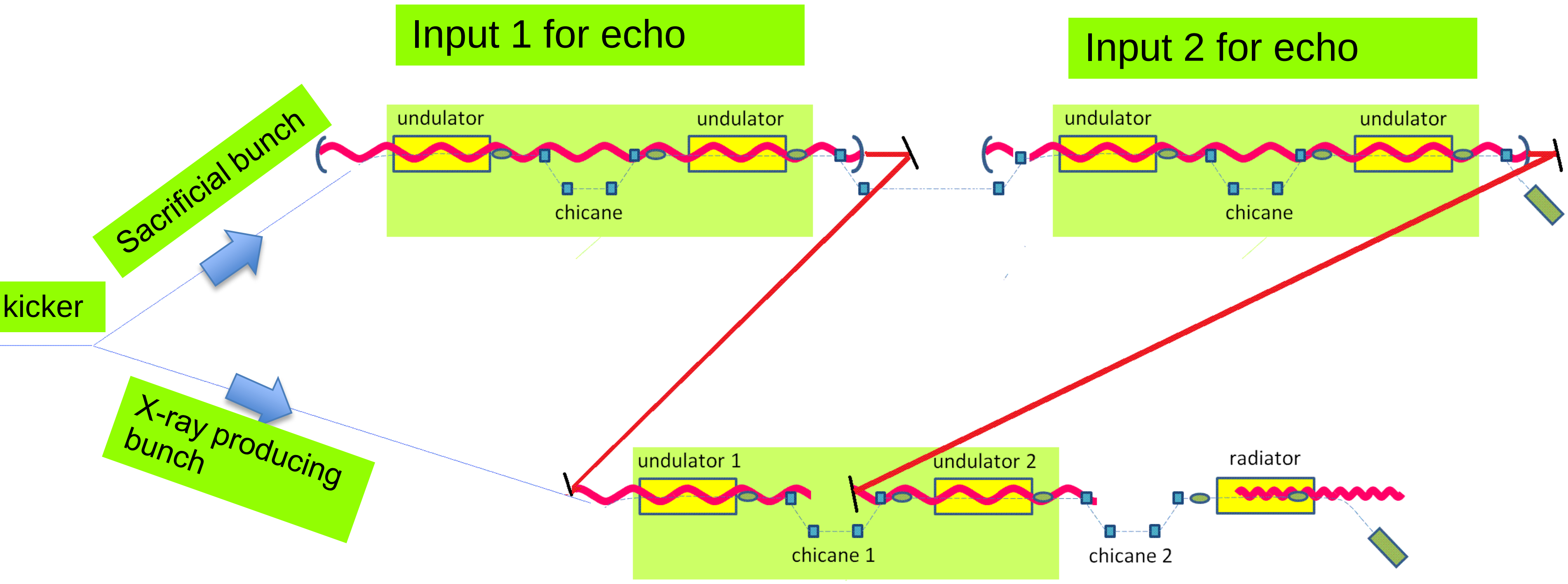
time-independent GINGER

ECHO Oscillator Configuration: single cavity 13nm



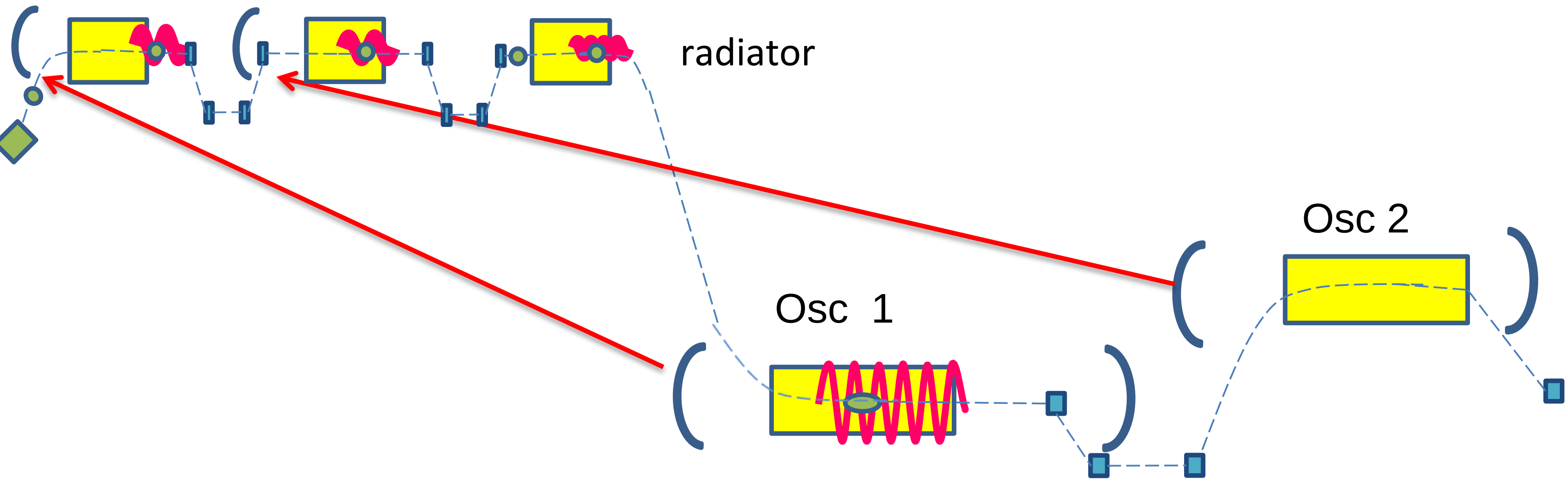
time-independent GINGER

Sacrificial bunch scheme



ECHO SCHEME USING FRESH BUNCH

Radiator-First Scheme

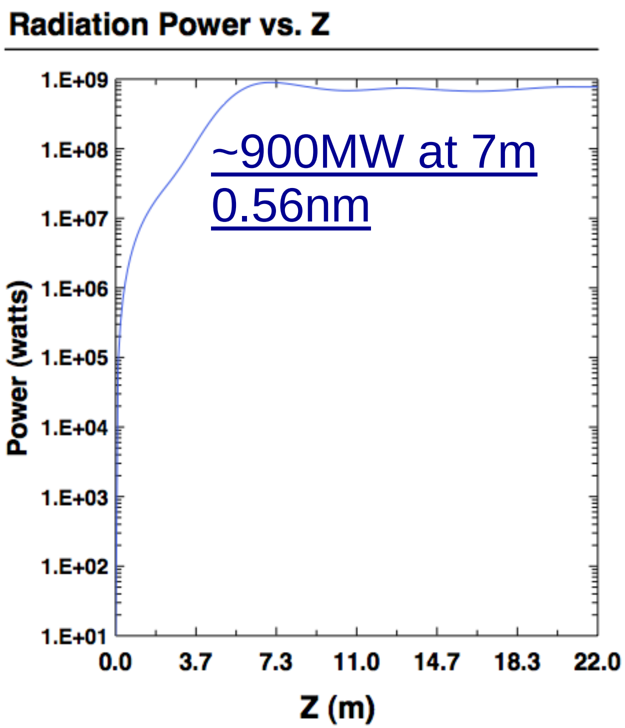


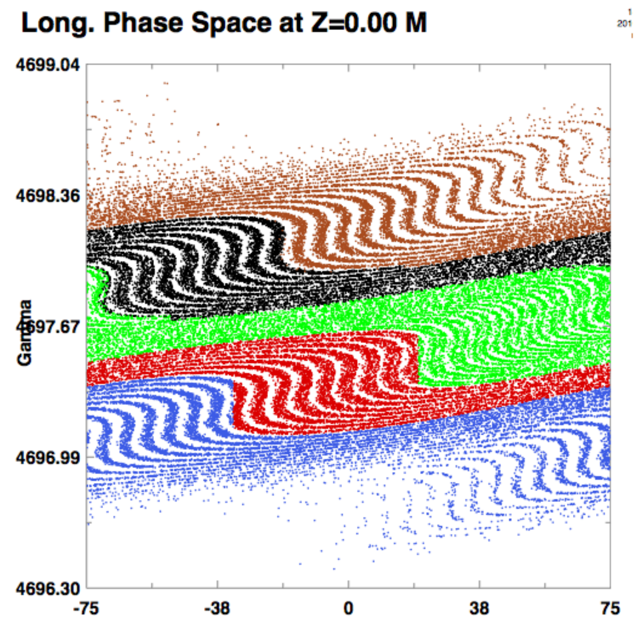
Short wavelength radiator precedes oscillators

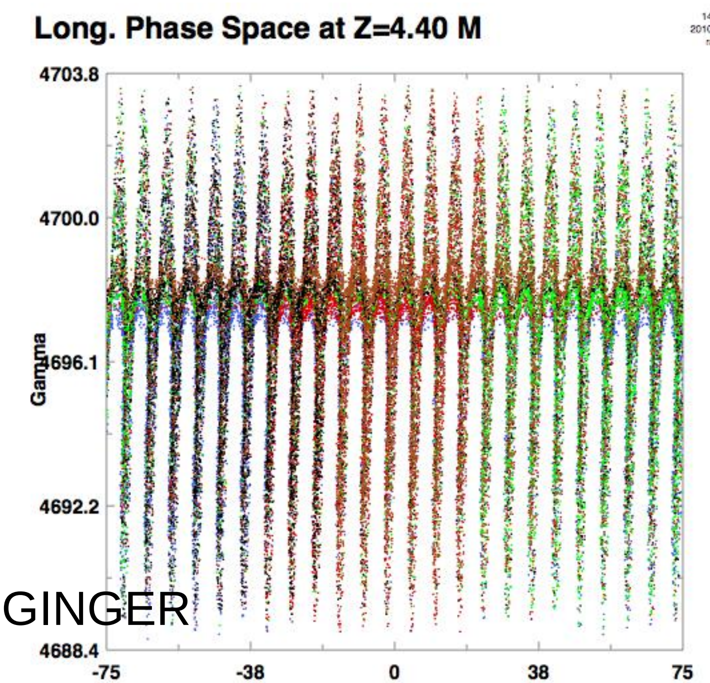
Oscillators should work if radiator energy spread is not too large

Oscillator FELs only produce power

24th Harmonic echo with I=600A







Sacrificial bunch or radiator-first echo scheme [i.e., original echo FEL proposal]

Assumes oscillators work for radiator first scheme
-not yet simulated

Brightness conserved:
600A current, x4 energy spread

time-independent GINGER

13nm Echo Summary

2.4 GeV
Emittance~10^{-7} m
150 A
24 keV energy spread

	Energy spread at start of radiator	Bunching at start of radiator	Saturation length in radiator	Saturation power in radiator
Oscillator echo 12th harmonic	0.0190 %	0.11	20 m	180 MW
HGHG Oscillator 12th harmonic	0.0085 %	0.09	18 m	280 MW
Oscillator echo with sacrificial bunch: 24th harmonics 600A	0.04%	0.09	7 m	900 MW

Simulations were performed using GINGER in time independent mode

Conclusions

- Soft x-ray optics and high brightness bunches with FEL oscillators yields promising ideas for tunable X-rays based on EEHG.
- The use of oscillators avoids the need for external seeding. The use of EEHG allows for tuning.
- Improvements:
  - Nonlinear optical element to control saturation and enhance stability
  - Sacrificial bunches for echo seed radiation generation
  - Radiator-first geometry
  - Sensitivity (jitter, error) studies; long bunch, high harmonic and brightness limitations, possible experiment, microwave tube version (?).
  - There are many possible configurations of soft X-ray FEL systems, and further work is required to understand their limitations and capabilities, costs and challenges.