Optimization of TW XFELs

C. Emma
Physics and applications of high efficiency
free electron lasers workshop
April 11
UCLA

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Presentation Outline

1. Physics of tapered FELs

1.1.Review of theory: 1-D, 3-D, and time dependent effects

2. Optimization of tapered FELs

2.1.Improving the undulator - simulation

2.2.Tailoring the initial conditions

2.2.1. Fresh-bunch self-seeding - experiment

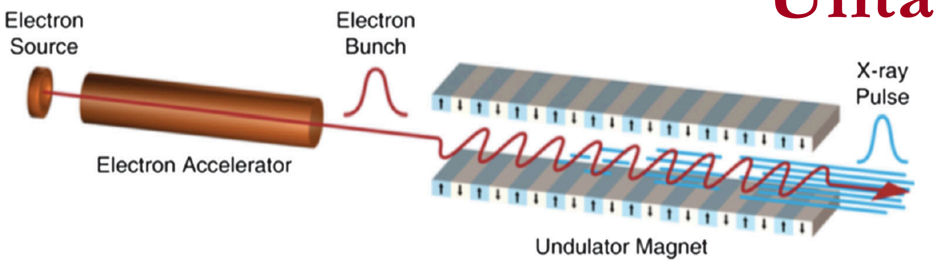
2.2.2.Pre-bunching - simulation

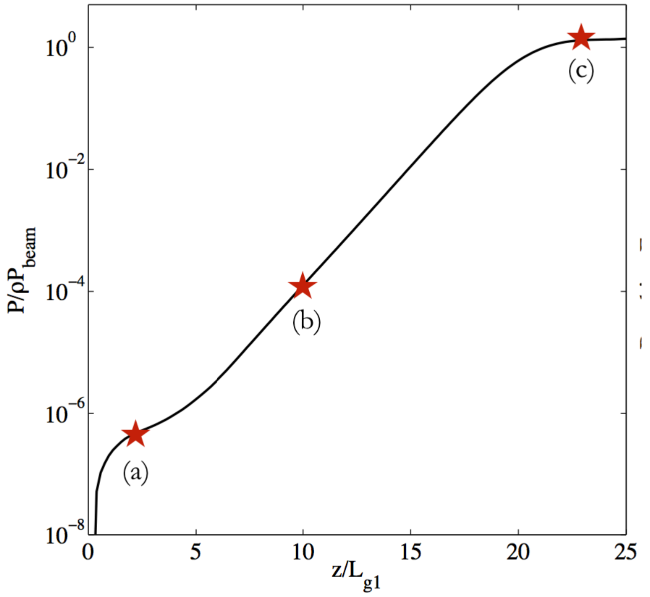
2.2.3.PWFA-FEL for TW-attosecond pulses - simulation

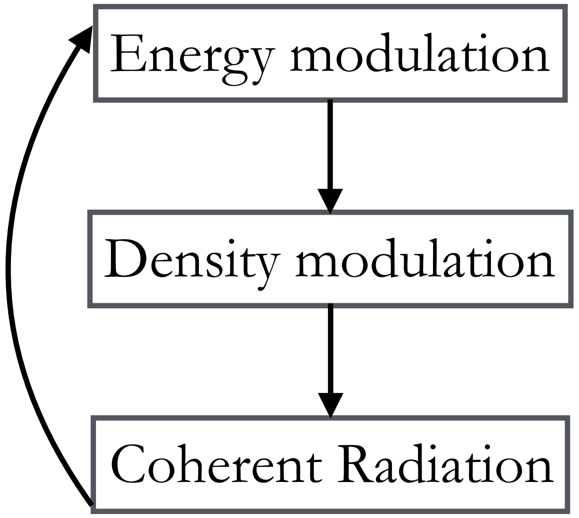
3. Conclusions

Why tapering to reach TW XFEL?

Untapered FEL






Energy modulation

Density modulation

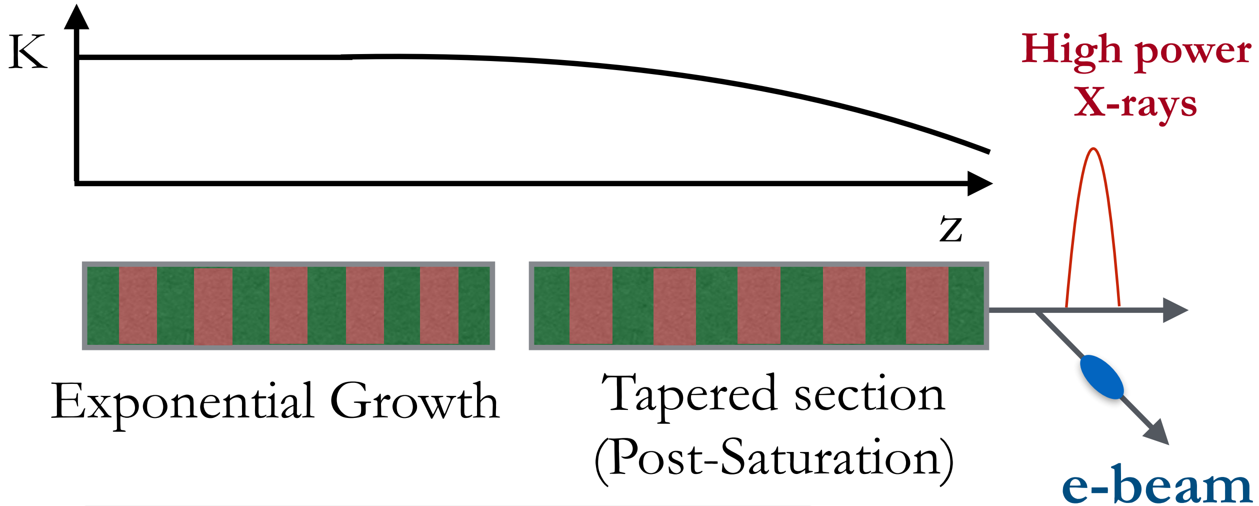
Coherent Radiation

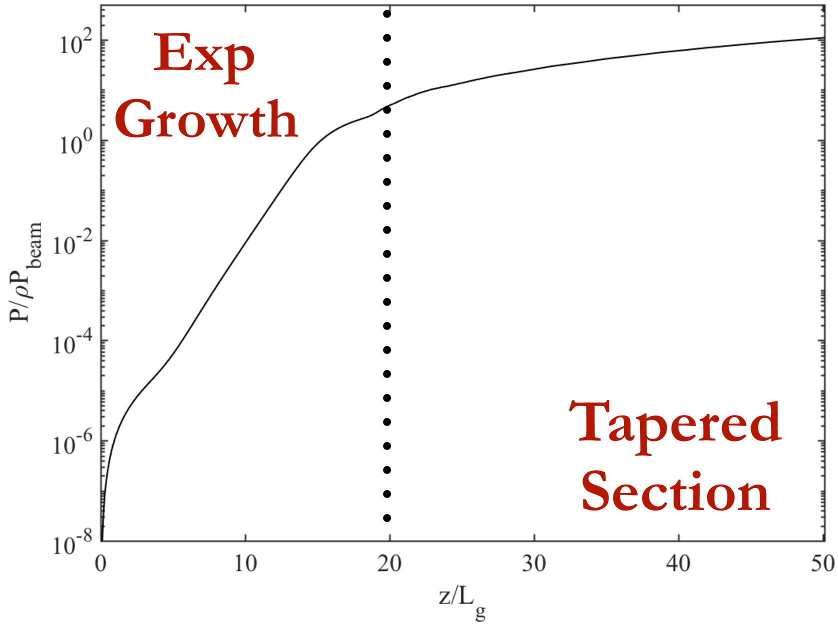
- Collective variable description gives analytic solution for power (BPN Opt Comm. 1984) described by single parameter ϱ.

$$P_{sat} = \rho P_{beam} \qquad \rho = \frac{1}{\gamma}\left(\frac{I}{I_A}\left(\frac{K}{4k_u\sigma_x}\right)^2\right)^{1/3}$$

- Typical numbers for XFEL:
  E_e=10 GeV, I = 1 kA, P_{beam} =10 TW, ϱ = 10^{-3}
  => P_{sat} ~10 GW
- For TW we want~ 100x increase in efficiency to ~10 %

Tapered FEL





$$\lambda = \frac{\lambda_u}{2\gamma_r^2}(1+K^2)$$

- Resonant interaction can continue *past saturation* by tapering the magnetic field K(z) to match the e-beam energy loss γ(z)
- Questions are:
  - How do you optimize the taper to achieve the max efficiency?
  - What is the maximum achievable efficiency?

1-D effects: How to choose the taper for max. power

Power scaling in post-sat regime

$$P_{rad} = P_0 + \underbrace{P_1 \bar{z}}_{\text{Dominant for short undulators or large seed}} + \underbrace{P_2 \bar{z}^2}_{\text{Dominant for long undulators}} \quad \longleftrightarrow \quad K = K_0 - bz - \frac{cz^2}{2}$$

1-D effects: How to choose the taper for max. power

Power scaling in post-sat regime

$$P_{rad} = P_0 + \cancel{\boxed{P_1\bar{z}}} + \boxed{P_2\bar{z}^2}$$

Dominant for short undulators or large seed

Dominant for long undulators

$$\sin\psi_r \propto \frac{|K'|}{E}$$

$$P_2 = \boxed{\frac{Z_0}{8\pi}\left(\frac{K}{\gamma}\frac{\lambda_u}{\sigma_e}I\right)^2} \boxed{(f_t \sin\psi_r)^2}$$

Initial Condition contribution

Tapering contribution

1-D effects: How to choose the taper for max. power

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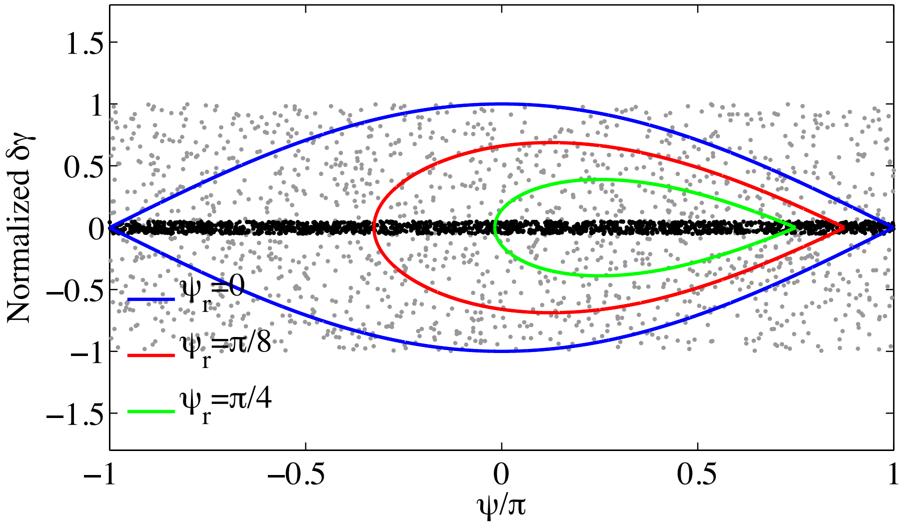

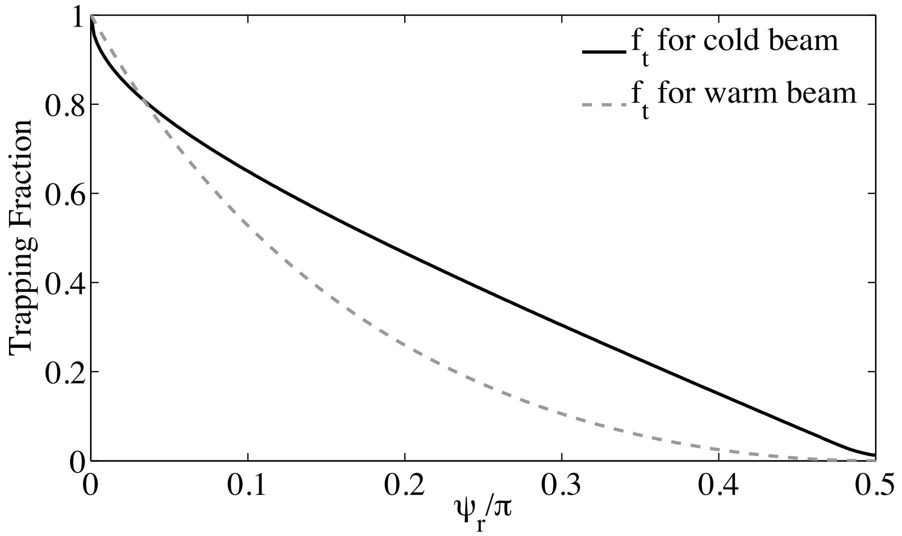

1-D effects: How to choose the taper for max. power

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Initial Condition contribution

Tapering contribution

Take home messages from 1-D theory

(1) **Resonant phase ψ_r sets the speed of the taper and the size of the bucket**

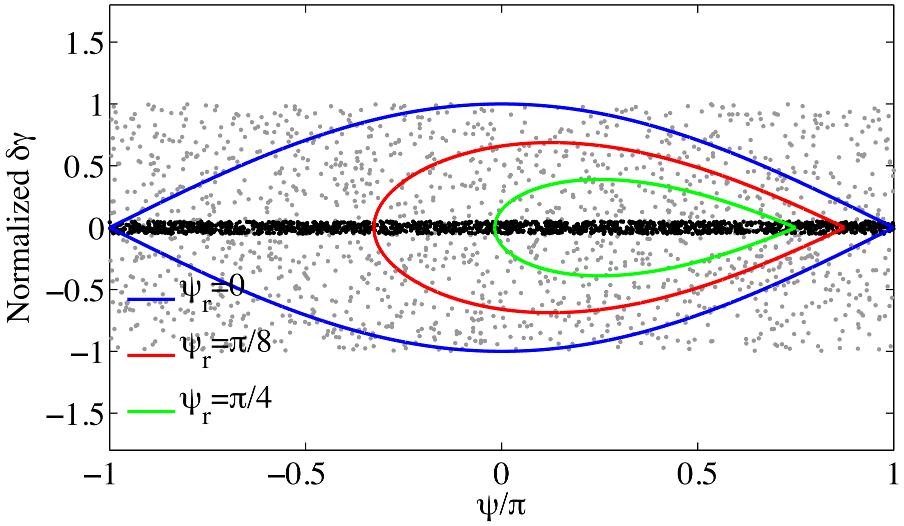
∴ Trade-off between number of electron trapped and how quickly the electrons are decelerated

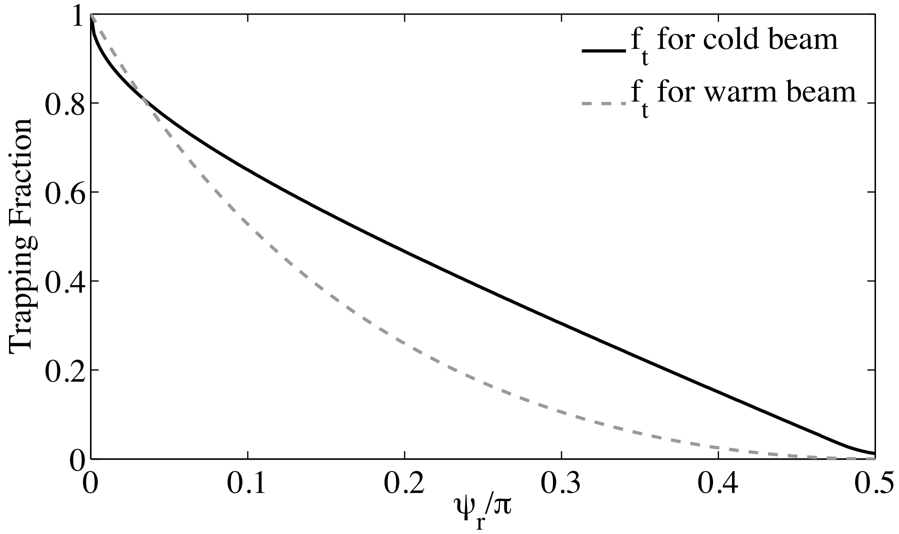
(2) **Power scales like $(f_t \sin\psi_r)^2$**

∴ Increasing the trapping by e.g. pre-bunching can increase P

(3) **Power scales like $I^2/\sigma_e^2 = I^2/\beta\varepsilon_n$**

∴ Brighter beam/smaller beta conducive to high efficiency





1-D effects: How to choose the taper for max. power

SLAC

Power scaling in post-sat regime

$$P_{rad} = P_0 + \cancel{P_1 \bar{z}} + P_2 \bar{z}^2$$

$$\sin \psi_r \propto \frac{|K'|}{E}$$

Dominant for short undulators or large seed

Dominant for long undulators

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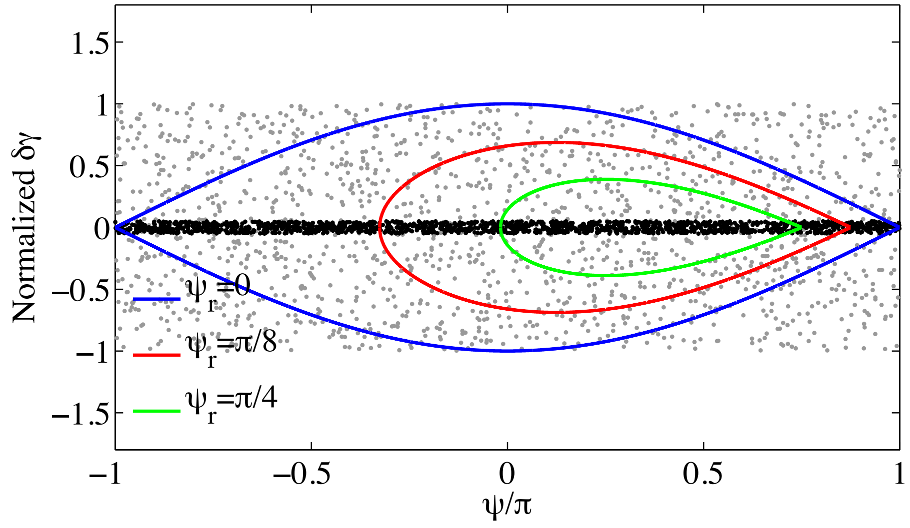
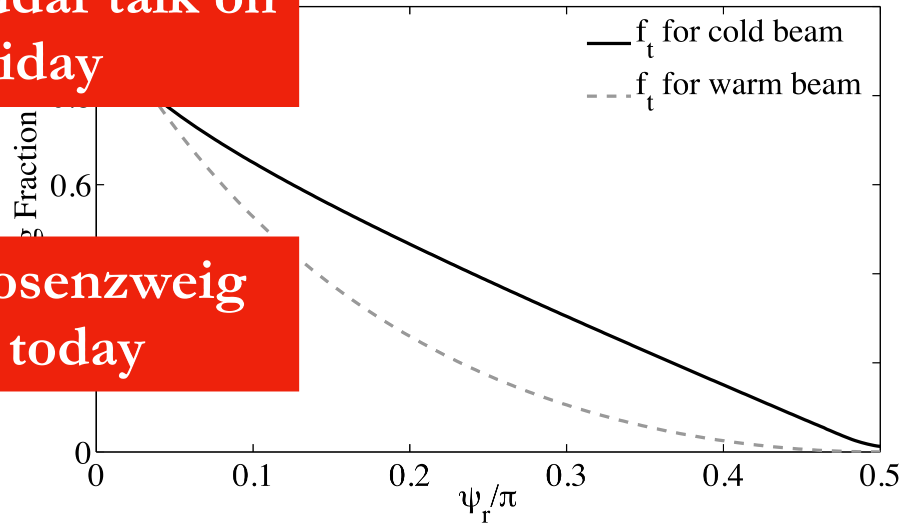


See N. Sudar talk on Friday

See J. Rosenzweig talk today

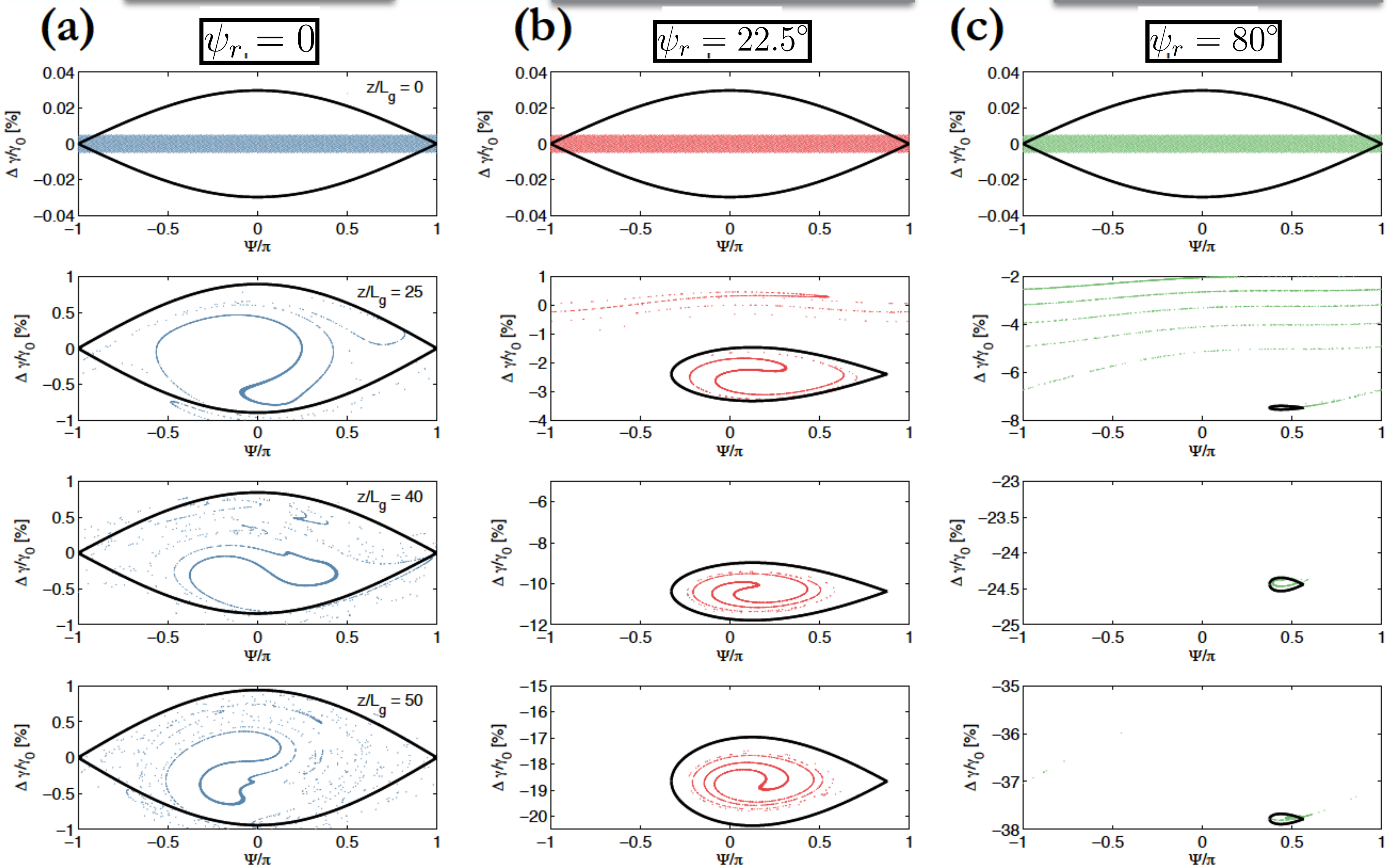


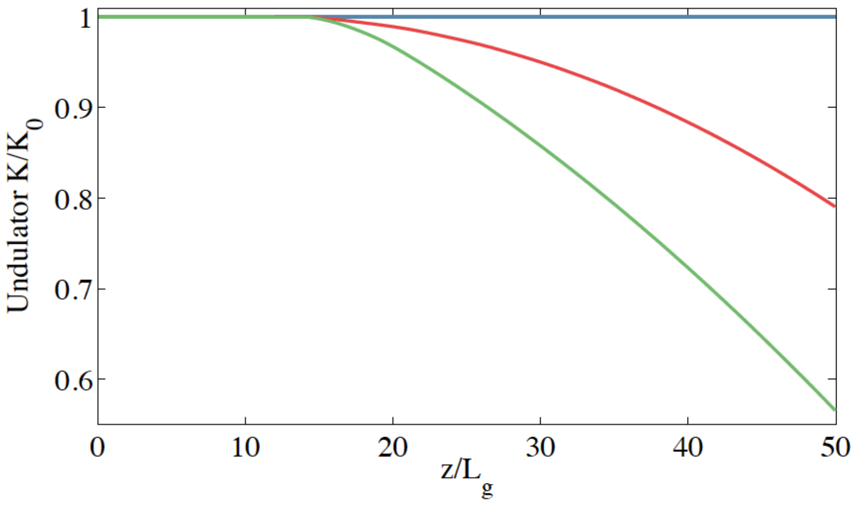
1-D effects: trade-offs and design considerations

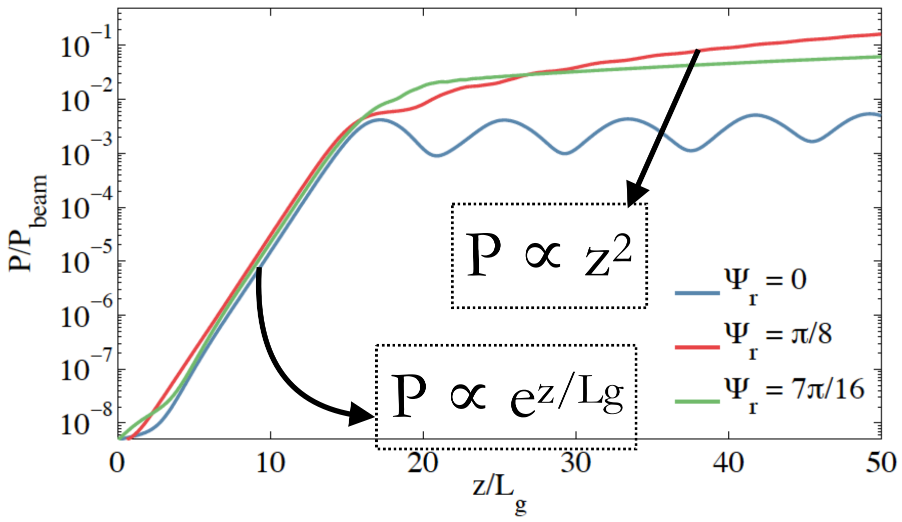
No tapering

“Slow” tapering

“Fast” tapering







$P \propto z^2$

$P \propto e^{z/Lg}$

No tapering efficiency is the same as saturation

“Slow” taper strikes the balance between total energy loss and trapping fraction

“Fast” taper has larger net energy loss but smallest fraction captured

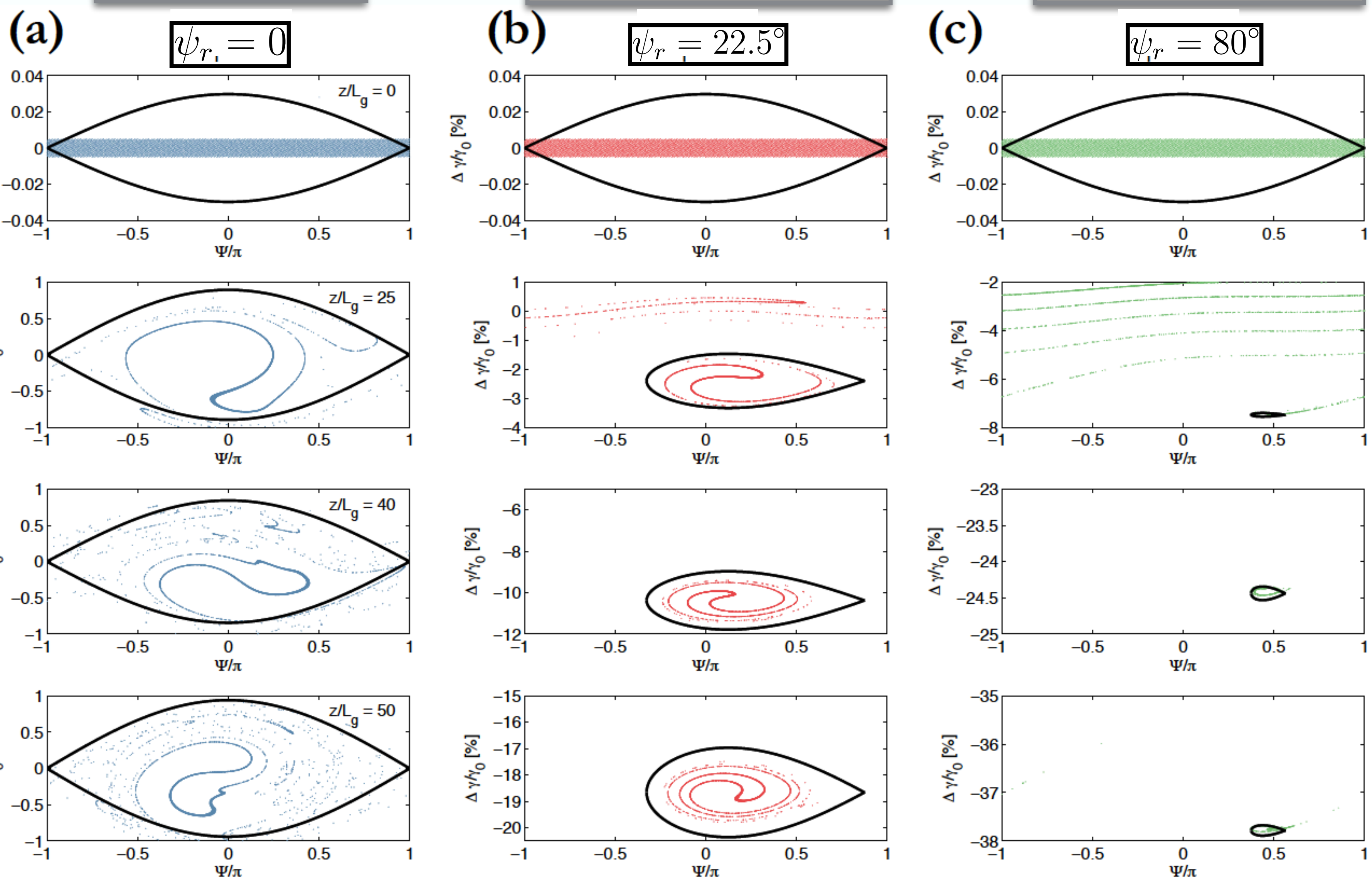
In 1-D theory, with a judiciously chosen taper you can continue to increase power by adding undulators

1-D effects: trade-offs and design considerations

No tapering

"Slow" tapering

"Fast" tapering



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"Slow" taper strikes the balance between total energy loss and trapping fraction

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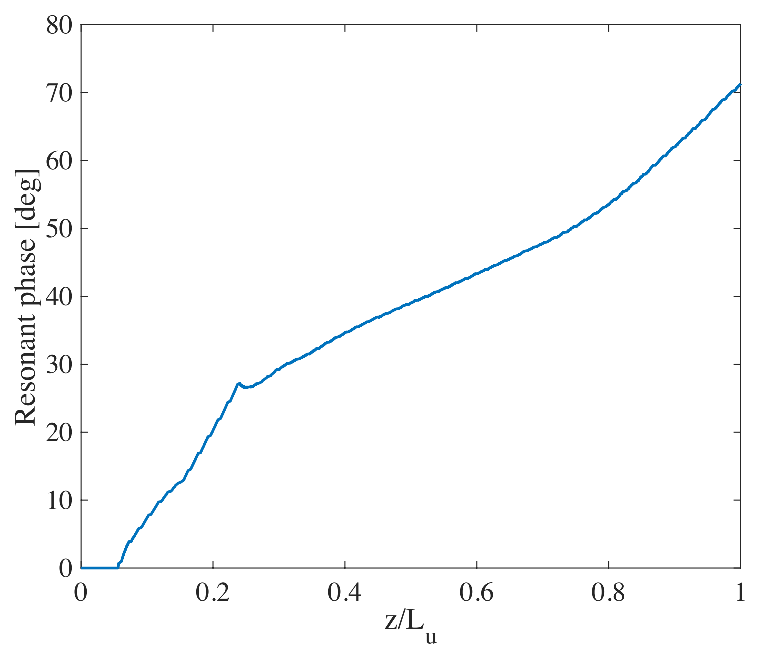
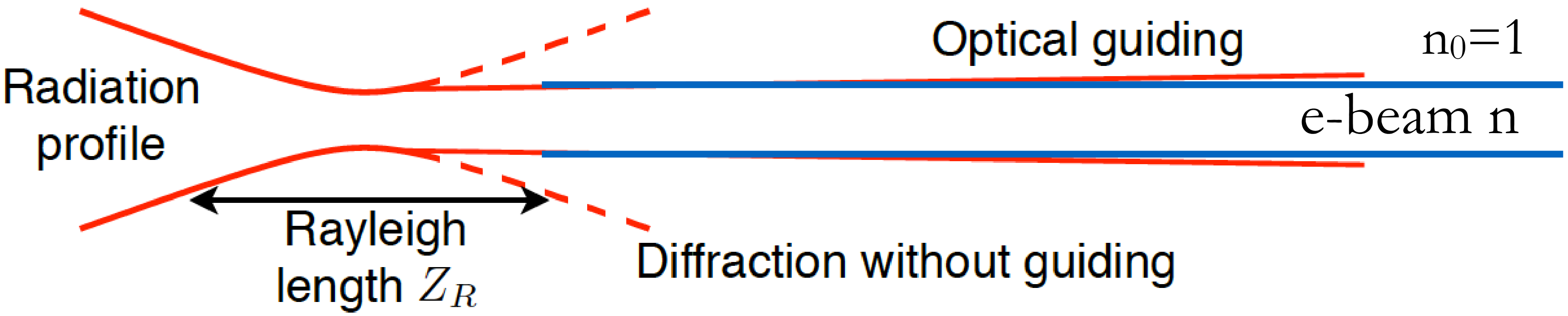
Note: for a fixed length undulator the resonant phase *variation* can be optimized and tends to increase along *z* when de-trapping becomes less important towards the end of the undulator



3-D effects: diffraction limits to the 1-D model



E-beam refractive index

$$n-1=\frac{\chi_2}{k}\frac{K}{\gamma}\frac{\boxed{\langle e^{i\psi}\rangle}}{\boxed{E}}$$

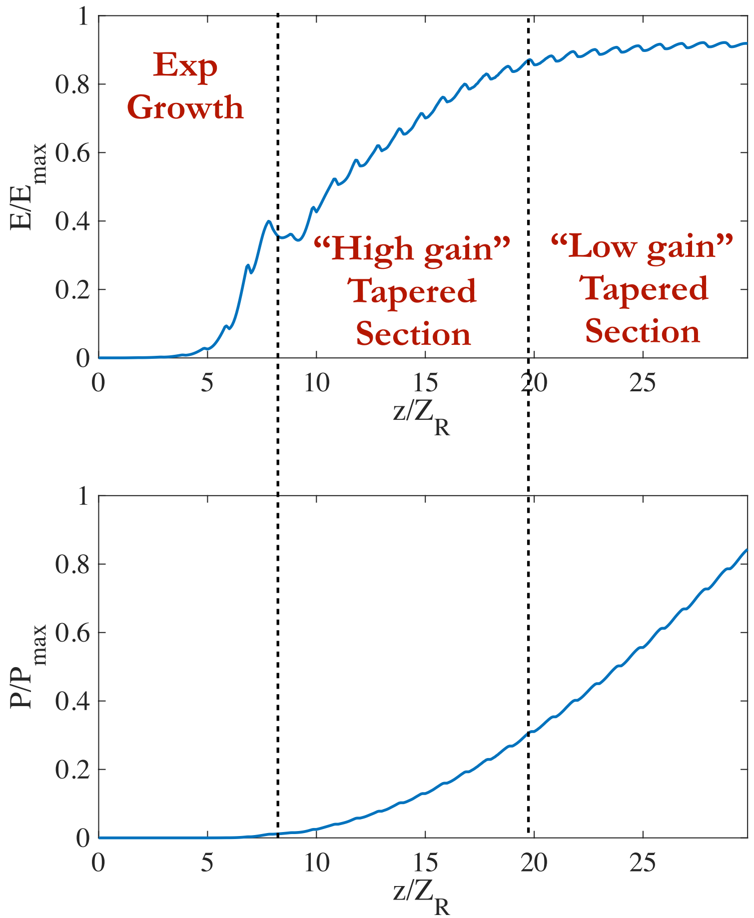
Growth of field reduces guiding sets limit on max. E field

Microbunching and trapping must be kept high to maintain good guiding

$$E_{max}\approx\frac{Z_0 I}{\lambda}\frac{K}{\gamma}\cos\psi_r \qquad P_{rad}=\frac{2\pi}{Z_0}E^2\sigma_r^2$$

D. Prosnitz, A. et al, Phys. Rev. A 24, 1436 (1981)   Scharlemann, T. et al, Phys. Rev. Lett. 54, 17 (1981)

Fawley W.., NIMA 375 (1996)   Yiao, J., PRSTAB. **15**, 050704 (2012)   Schneidmiller, et al., PRSTAB. **18**, 030705 (2015)



Take home messages from 3-D theory

Limit on field and radiation growth region **in contrast with 1-D theory**

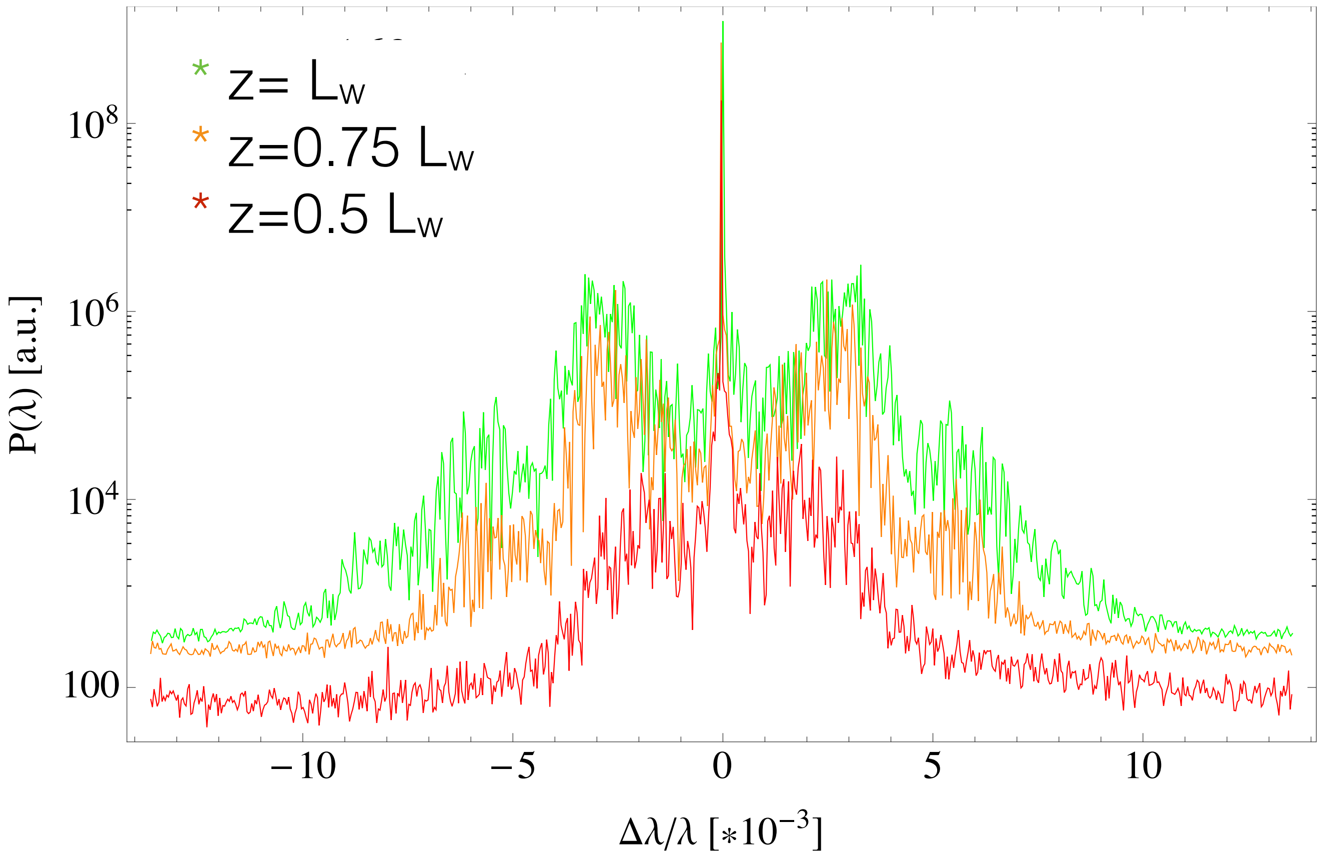
Needs to be considered for long undulators $L_u >> Z_R$

Want to extract energy (taper) as fast as possible to outrun diffraction limit

Time Dependent effects: limits to the 1 frequency model

Electron beam shot noise and synchrotron motion

$$E'(z,t) \propto \boxed{I(t)} \left\langle \frac{\sin\psi(z,t)}{\gamma(z,t)} \right\rangle \qquad \phi'(z,t) \propto \frac{I(t)}{\boxed{E(z,t)}} \boxed{\left\langle \frac{\cos\psi(z,t)}{\gamma(z,t)} \right\rangle}$$



"…the electron motion in a FEL will become chaotic when the sideband amplitude exceeds a certain threshold. This, in turn, will result in significant electron detrapping. Since it is the deceleration of the trapped electron bucket that provides the energy for the radiation in the case of tapered wigglers, detrapping will cause loss of amplification for the FEL signal"

Amplitude and phase modulations of the radiation field

↓

Resonance between sideband radiation and synchrotron motion

↓

Radiation field saturation from reduced optical guiding gives ~ constant L_{synch}

↓

Sideband Instability

S. Riyopoulos, C.M. Tang, Phys. Fluids (1988) "*Chaotic electron motion caused by sidebands in free electron lasers*"

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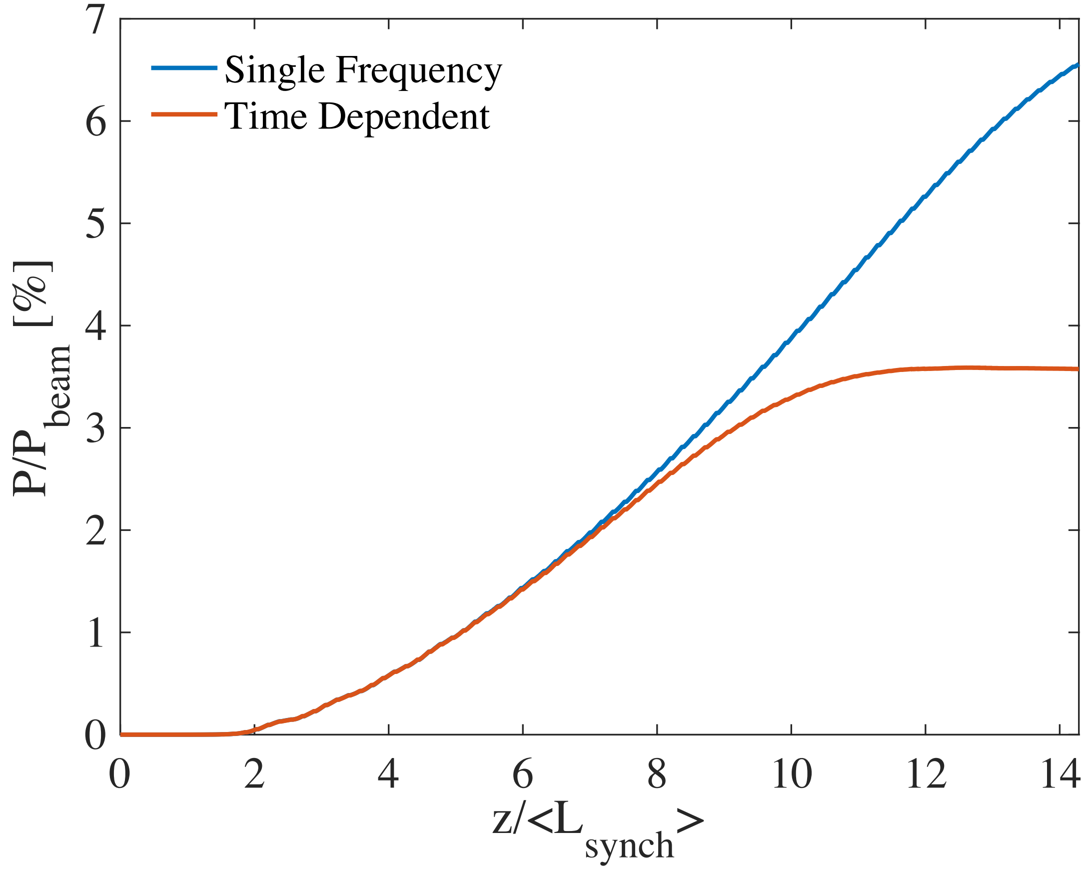

Take home messages from TDP theory

Sideband instability can cause second saturation of radiation power in tapered FEL

Want to reduce the sideband growth along tapered undulator to continue extracting power

Amplitude and phase modulations of the radiation field

↓

Resonance between sideband radiation and synchrotron motion

↓

Radiation field saturation from reduced optical guiding gives ~ constant L_{synch}

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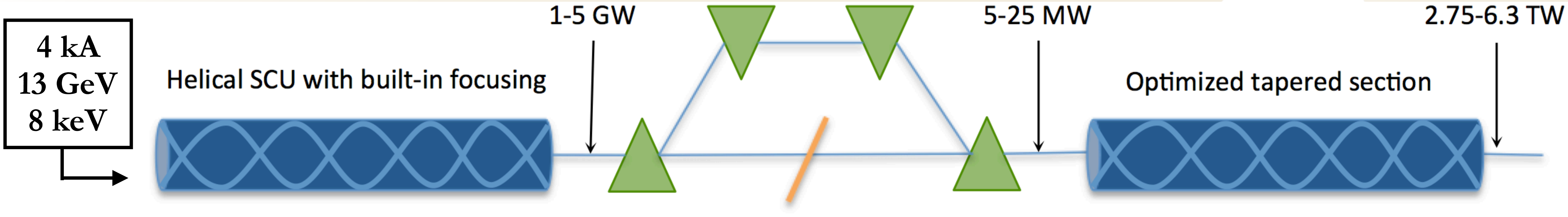
2.2.1. Fresh-bunch self-seeding - experiment

2.2.2.Pre-bunching - simulation

2.2.3.PWFA-FEL for TW-attosecond pulses - simulation

3. Conclusions

Simulation example:
Multi-TW XFEL with an Advanced Gradient Undulator



4 kA
13 GeV
8 keV

Helical SCU with built-in focusing

1-5 GW

5-25 MW

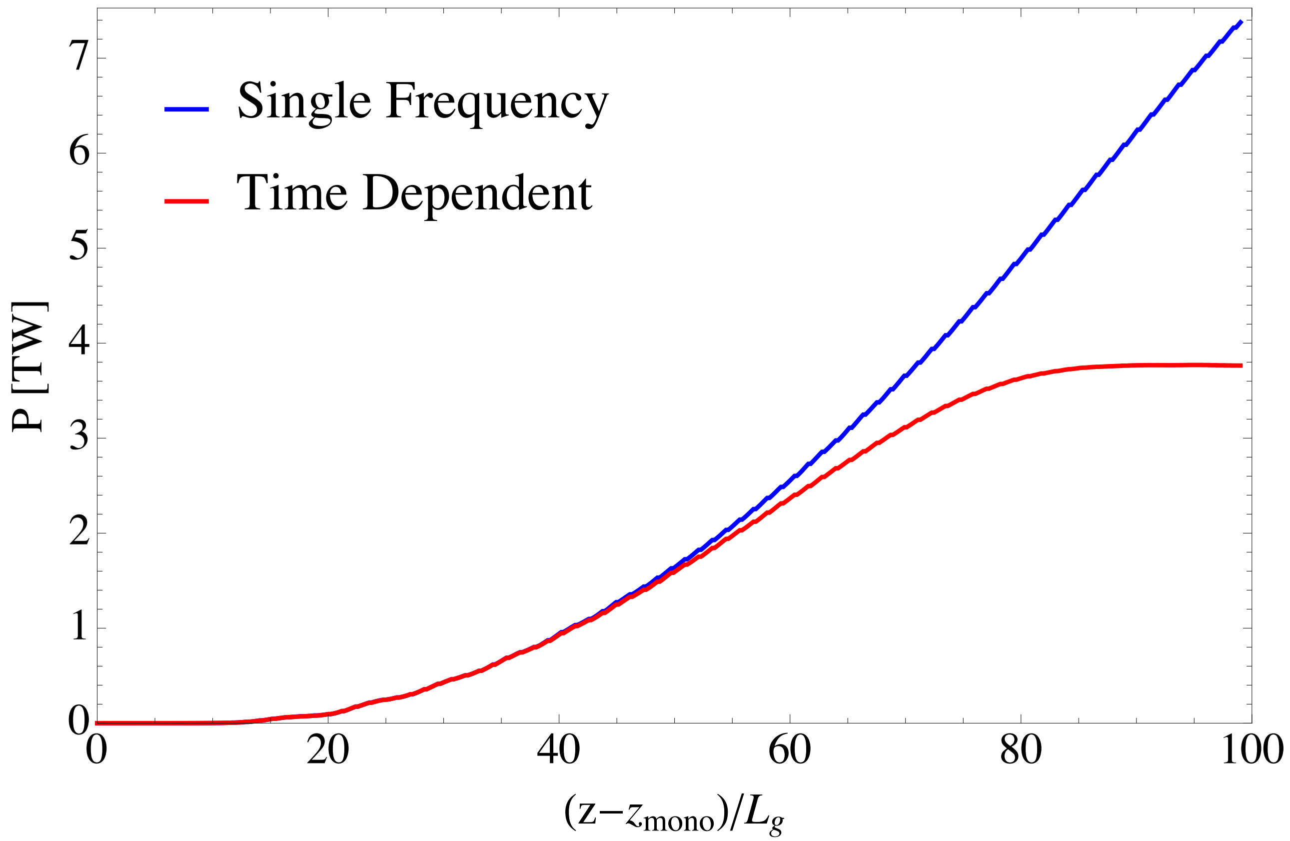
Optimized tapered section

2.75-6.3 TW

Self-seeding monochromator

See F. O'Shea talk tomorrow

Design Feature	Performance Advantages
Superconducting Undulator	- High peak field K=3 - Short period λ_w=2 cm - Improved resistance to wakefields/radiation damage
Short Break Sections	- Maximizes undulator fill factor - Reduces diffraction of radiation - Reduces phase mixing due to energy offset δ $\Delta\theta_i \approx L_{break}\delta_i/\gamma^2$
Distributed Focusing	- Reduces FODO length and supports small β function - Reduces transverse beam envelope oscillation $\Delta\beta^2/\beta_{av}^2 = \beta_{av}L_{fodo}/(\beta_{av}^2 - L_{fodo}^2)$

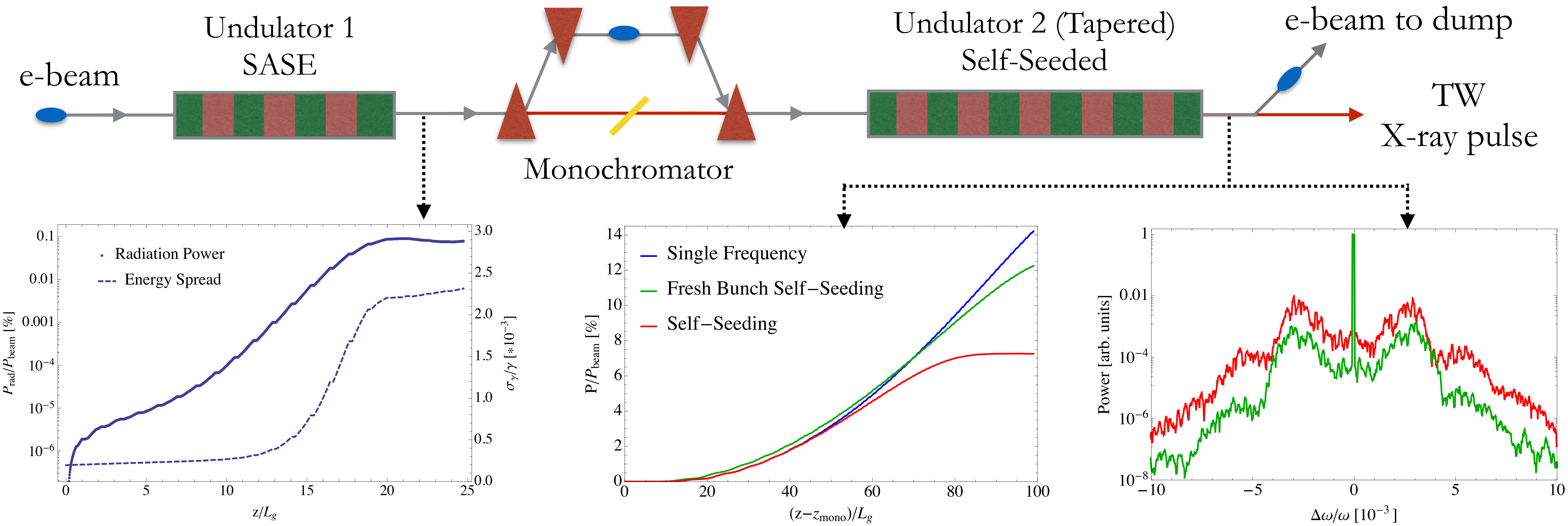


Multi-TW possible in ~100 m undulator.

Sideband instability causes second saturation of power

C. Emma et al., "High efficiency, multi-TW X-ray free electron lasers", PRAB **19,** 020705 (2016)

Overcoming the sideband instability with fresh bunch self-seeding



e-beam

Undulator 1
SASE

Monochromator

Undulator 2 (Tapered)
Self-Seeded

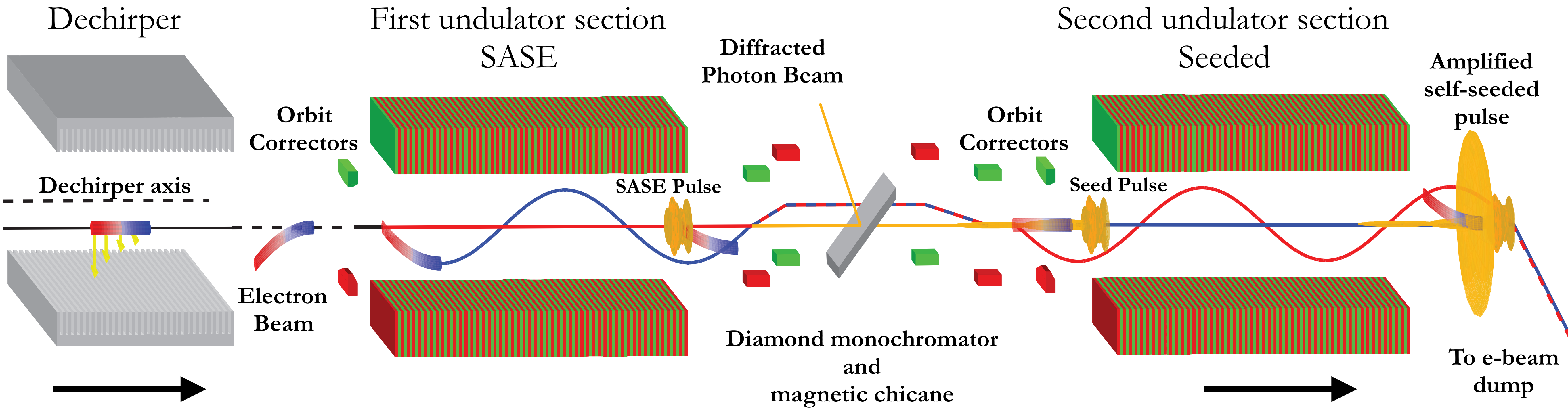
e-beam to dump

TW
X-ray pulse

C. Emma et al., PRAB **19**, 020705 (2016)

- GENESIS simulations show time dependent losses from sideband instability can be overcome using a large seed ($P_{seed}/P_{noise} \sim 10^3$).
- In a self-seeded FEL having a large seed comes at the expense of a large energy spread at the start of the seeded section.
- Escaping the trade-off between seed power and energy spread requires **fresh bunch self-seeding.**

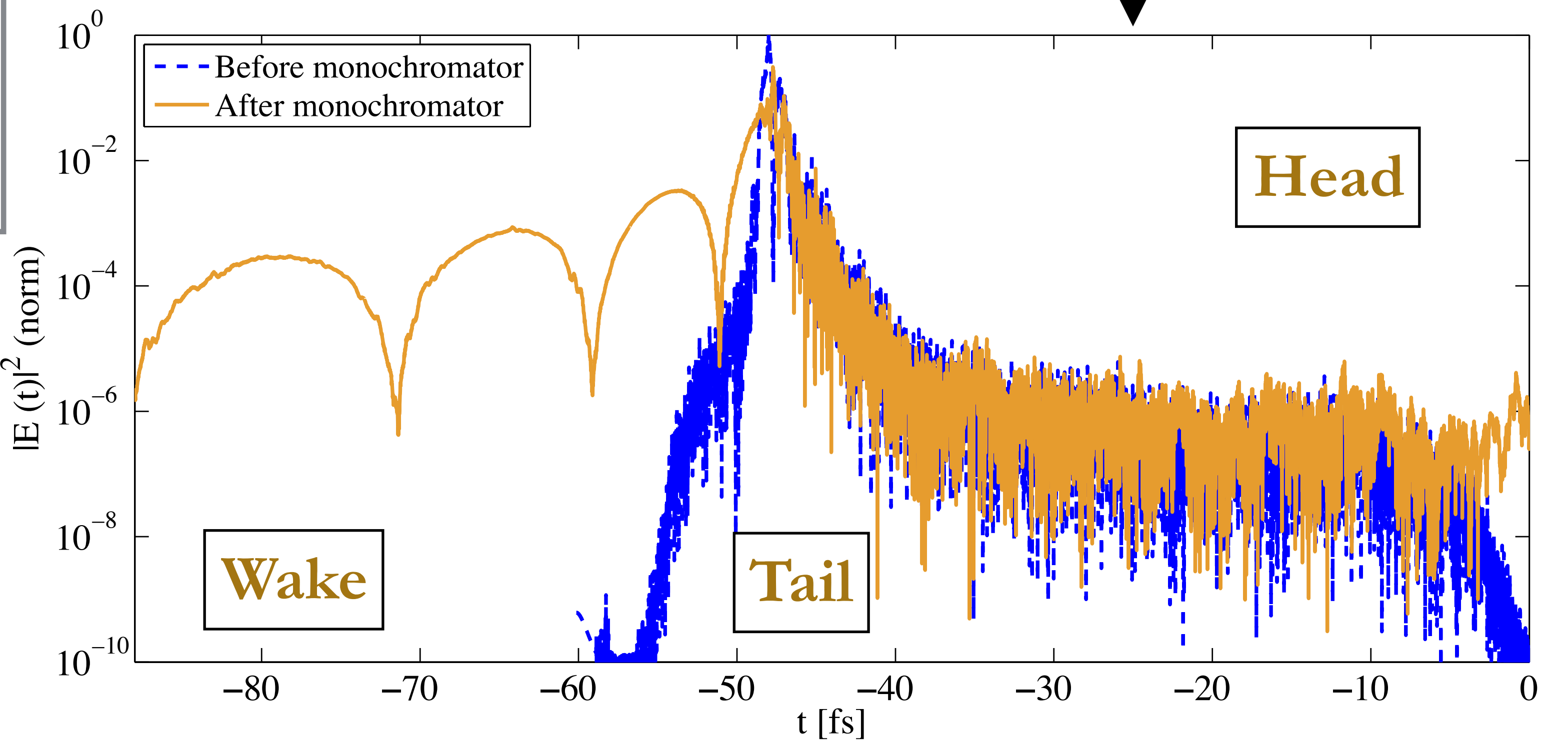
Fresh slice self seeding experiment at LCLS



E-beam

I_{pk}= 4 kA
E= 11 GeV
Q= 180 pC

$E_{\text{X-Ray}}$ = 5.5 keV



Diagnostics

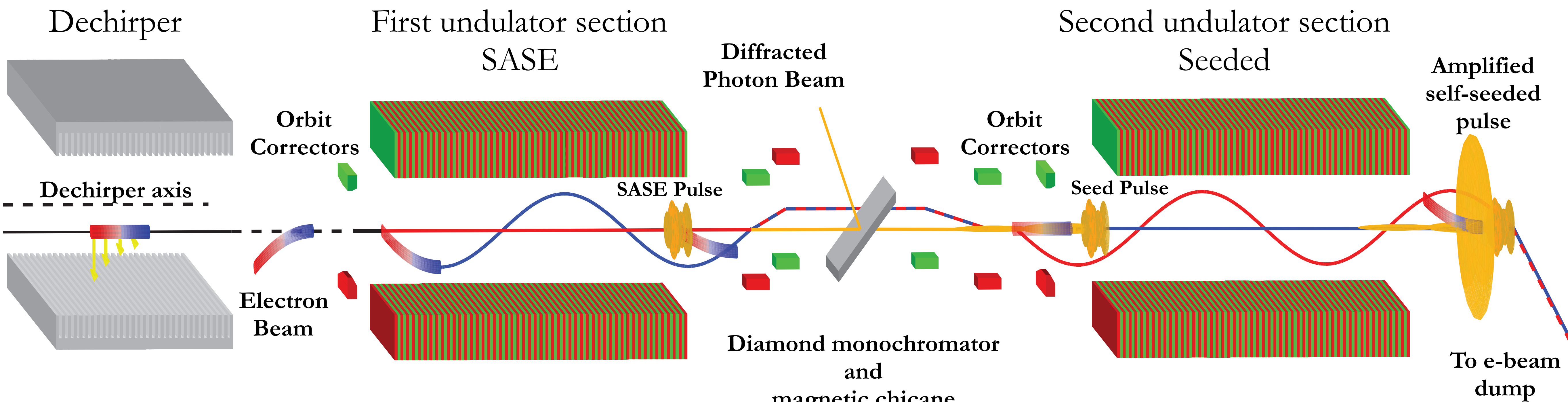
1) **Transverse deflecting cavity**
Electron beam energy loss
(time resolved)

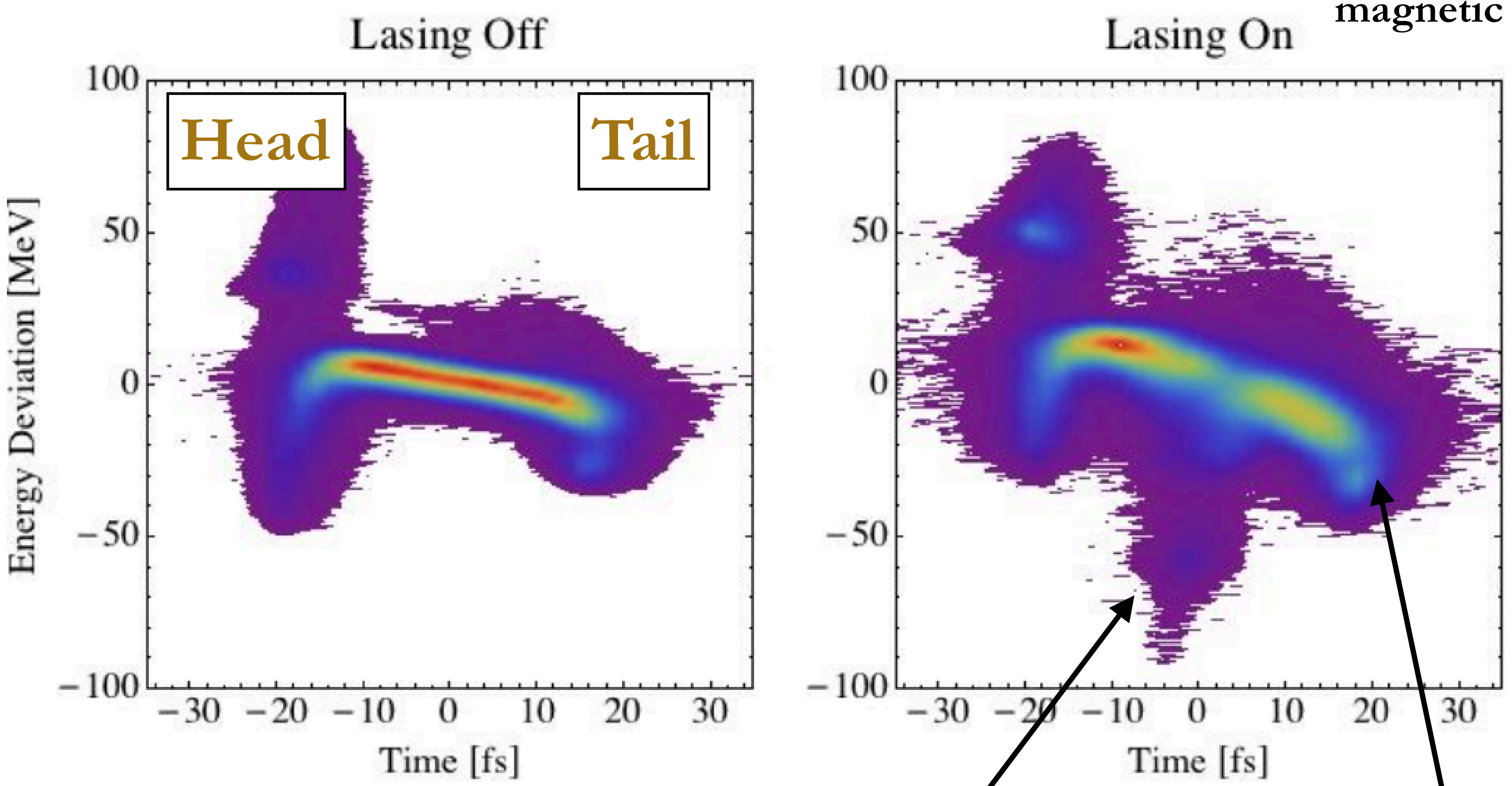
2) **Gas detector**
X-ray intensity

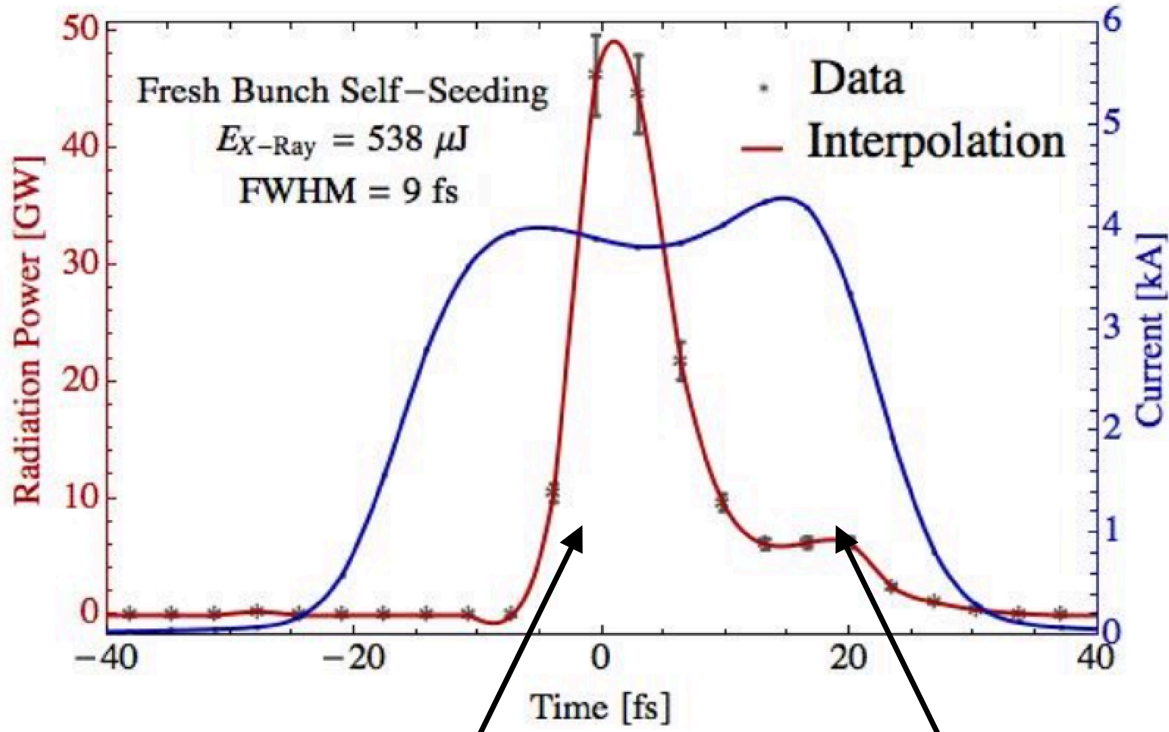
3) **X-ray spectrometer**

C. Emma *et. al.* App Phys. Lett. **110**, 154101 (2017)

Fresh slice self seeding experiment at LCLS







Seeded core

SASE lasing slice

Seeded core

SASE lasing slice

C. Emma *et. al.* App Phys. Lett. **110**, 154101 (2017)

Fresh slice self seeding experiment at LCLS

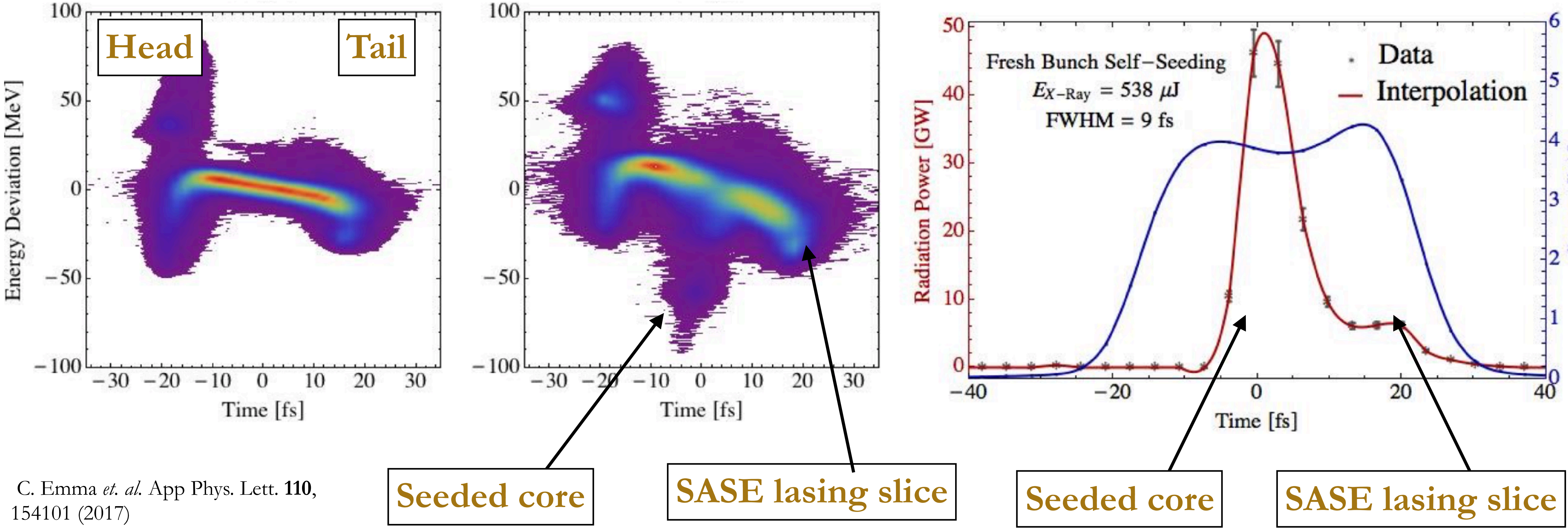
Brightness ratio	Average	Average filtered on e-beam energy	Peak
B_{FBSS}/B_{SASE}	12.5	15.5	35.4
$B_{FBSS}/B_{self-seeding}$	2.4	2.1	2.3

Table 6.1: Comparison between the average and peak brightness of the FBSS scheme with SASE and self-seeding at the same photon energy. The left column is an average without filtering the data based on the incoming electron beam energy. The middle column is an average of the data within the energy jitter window $\Delta E/E_0 = 0.5\%$. The right column is calculating using the best shot for each of the three schemes.

Scientific Achievements

Short ~ 10fs pulses with 50 GW power and $<10^{-4}$ b.w.

~ 2* increase in X-ray power / brightness compared to self-seeding

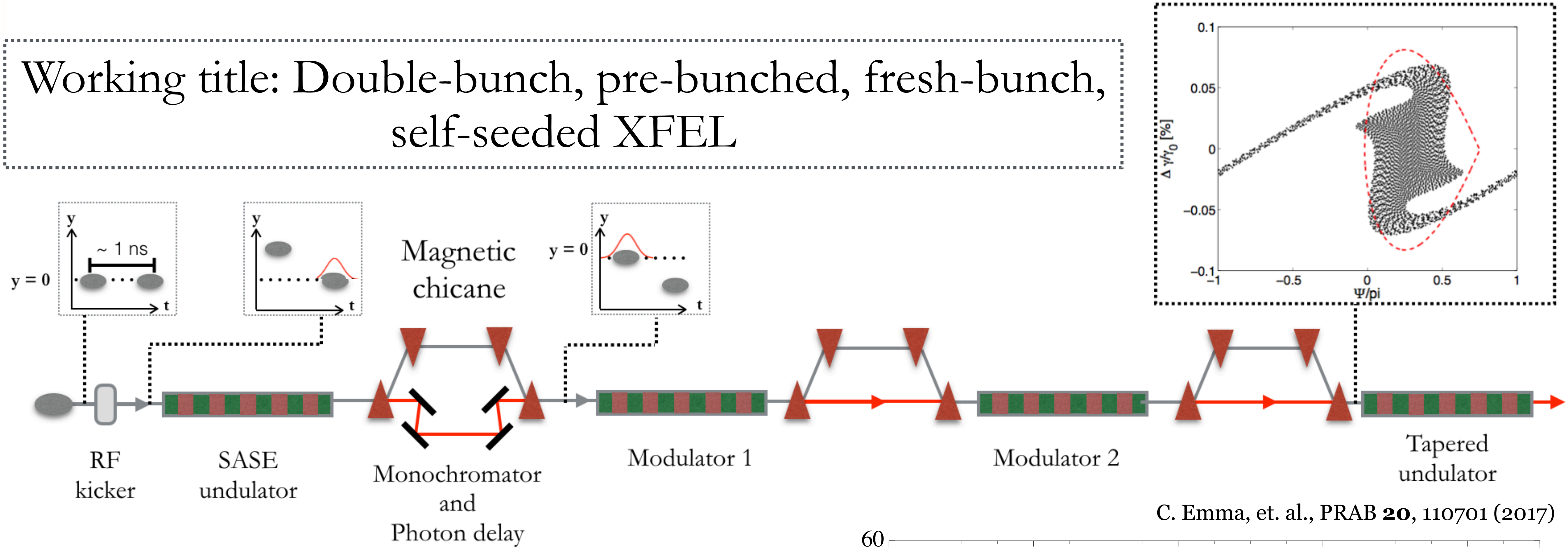


C. Emma *et. al.* App Phys. Lett. **110**, 154101 (2017)

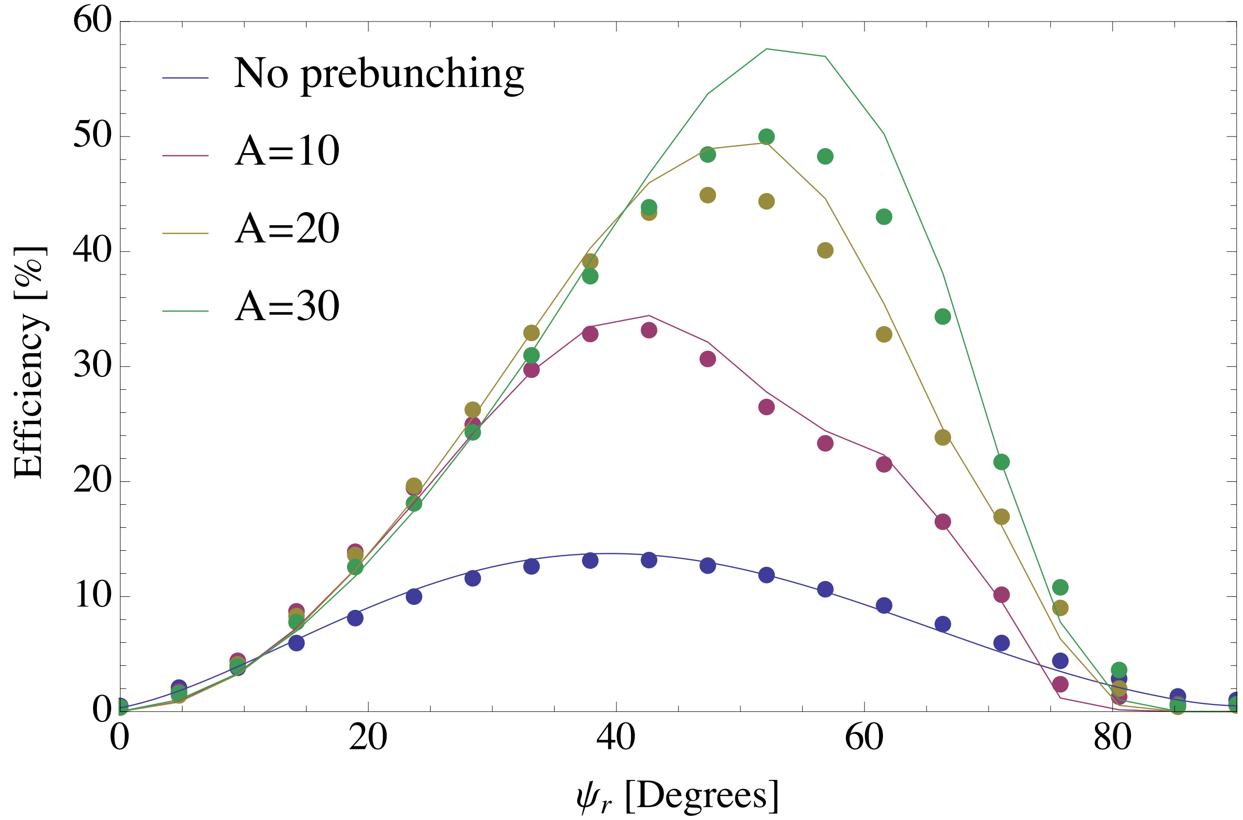
http://pbpl.physics.ucla.edu/Computing/Code_Development/Perave/

Tapered FELs with pre-bunched beams

Working title: Double-bunch, pre-bunched, fresh-bunch, self-seeded XFEL

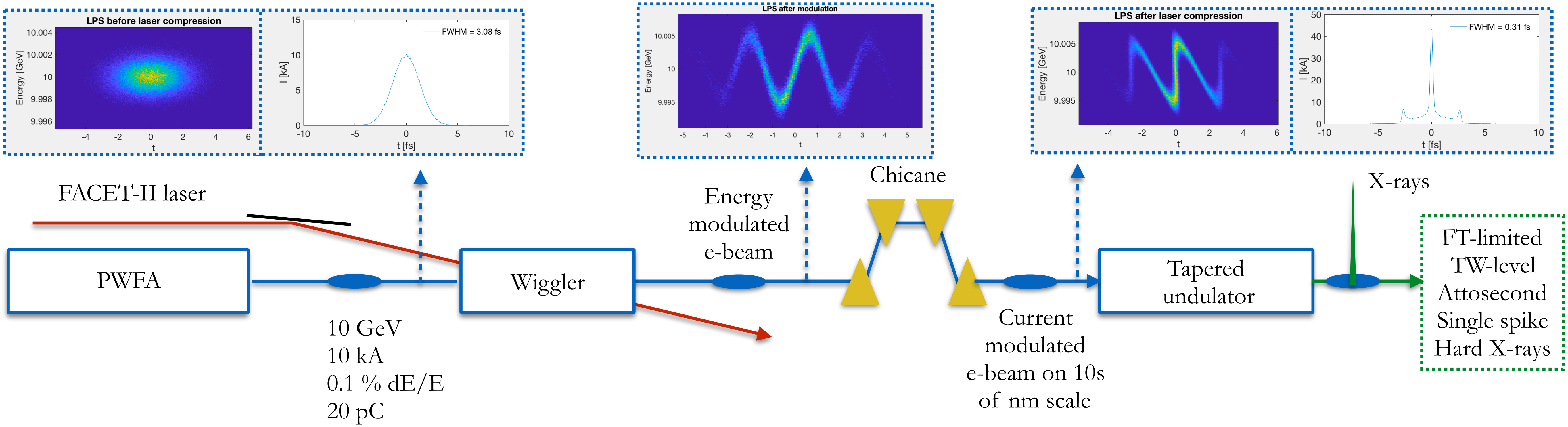


C. Emma, et. al., PRAB **20**, 110701 (2017)



- Pre-bunching with a strong seed (10-30 * the electron energy spread) can increase efficiency to 30-50 % (1-D sims)
- The second advantage is the peak efficiency occurs at larger resonant phase. This allows faster energy extraction, countering the effects of diffraction and sideband instability.
- Would be nice to do the experiment!

Future studies: TW-Attosecond pulses from PWFA-FEL + eSASE



FACET-II laser

PWFA

Wiggler

Energy modulated e-beam

Chicane

Tapered undulator

X-rays

FT-limited
TW-level
Attosecond
Single spike
Hard X-rays

10 GeV
10 kA
0.1 % dE/E
20 pC

Current modulated e-beam on 10s of nm scale

For single spikes you want $\sigma_z \sim L_{coop}$

For FACET-II PWFA case we have $L_{coop} = \lambda_r/\lambda_u\, L_G \sim (1\ \text{nm}/1\ \text{cm}) * 30\ \text{cm} = 100$ as

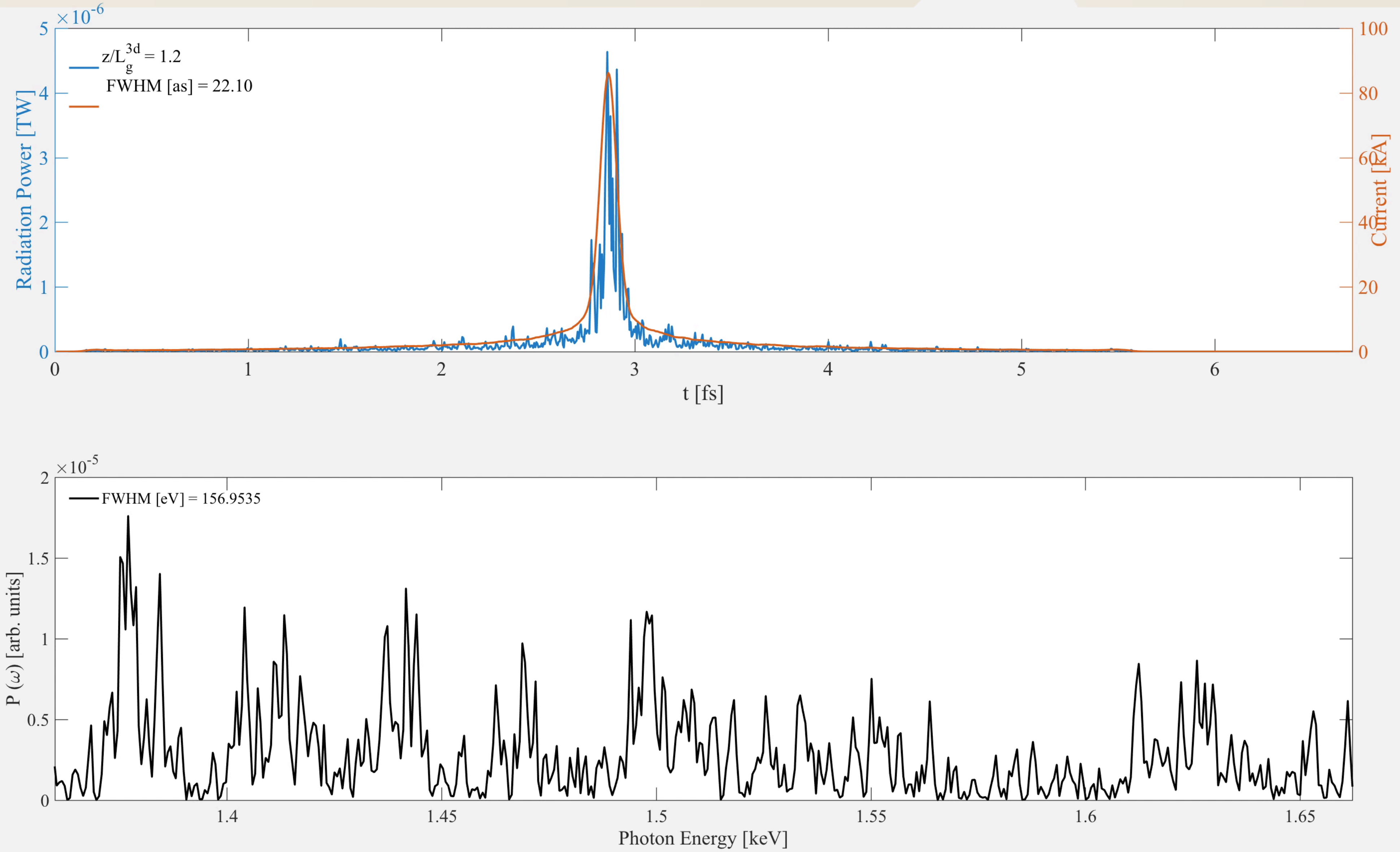
Coming out of the PWFA we have $\sigma_z \sim 800$ as so we need laser-based compression to give factor 8 reduction in spike length.

Modulation (delta gamma) scales like sqrt(laser power) see Zholents PRSTAB

See J. Duris talk tomorrow

GENESIS SIMULATION

Electron Beam	Value
Energy	10 GeV
Peak Current	10 kA
Emitttance (x,y)	50 nm
Energy Spread (before laser compression)	10^{-3}
Beta Function	10 m
Undulator	**(LCLS-II SXRU)**
Period	3.9 cm
Peak K (planar)	5.5
FEL parameters	
Photon Energy	1.5 keV
Pierce Parameter (80 kA after compression)	10^{-2}
Gain Length	25 cm



- Simulation assumes current profile from slide before. The undulators are from LCLS-II SXR.
- Power reaches 2 TW in 5 m (1.5 undulators) with FWHM 42 as and 46 eV bandwidth. The time-bandwidth product is 1.93 eV*fs, very close to the Fourier limit (1.8 eV*fs). After super radiant spike saturates the SASE from the shoulders keeps growing exponentially and eventually broadens the pulse.
- Adding more undulators SASE will grow behind the leading spike spoiling the coherence. Maybe this can be suppressed with faster tapering, studies are ongoing.

Conclusion

(1) We studied **undulator tapering strategies** to increase the efficiency of XFELs and reach TW peak power levels.

(2) **Diffraction** and the **sideband instability** were identified as the fundamental processes which limits the efficiency of tapered XFELs.

(3) We presented the design of an **advanced superconducting undulator** for maximal energy extraction (> 10 %) in the shortest possible undulator length (100 m) to overcome diffraction limits.

(4) We presented a solution to the sideband problem, the **fresh bunch self-seeding method**, and demonstrated it experimentally at the LCLS.

(5) Our demonstration of FBSS shows a **brightness increase** of 12/2 times compared to SASE / regular self-seeding.

(6) We have studied a combination of pre-bunching and FBSS as a sort of **“ideal system”** for a TW level tapered XFELs. Results from 1-D sims are encouraging, 3-D sims to come.

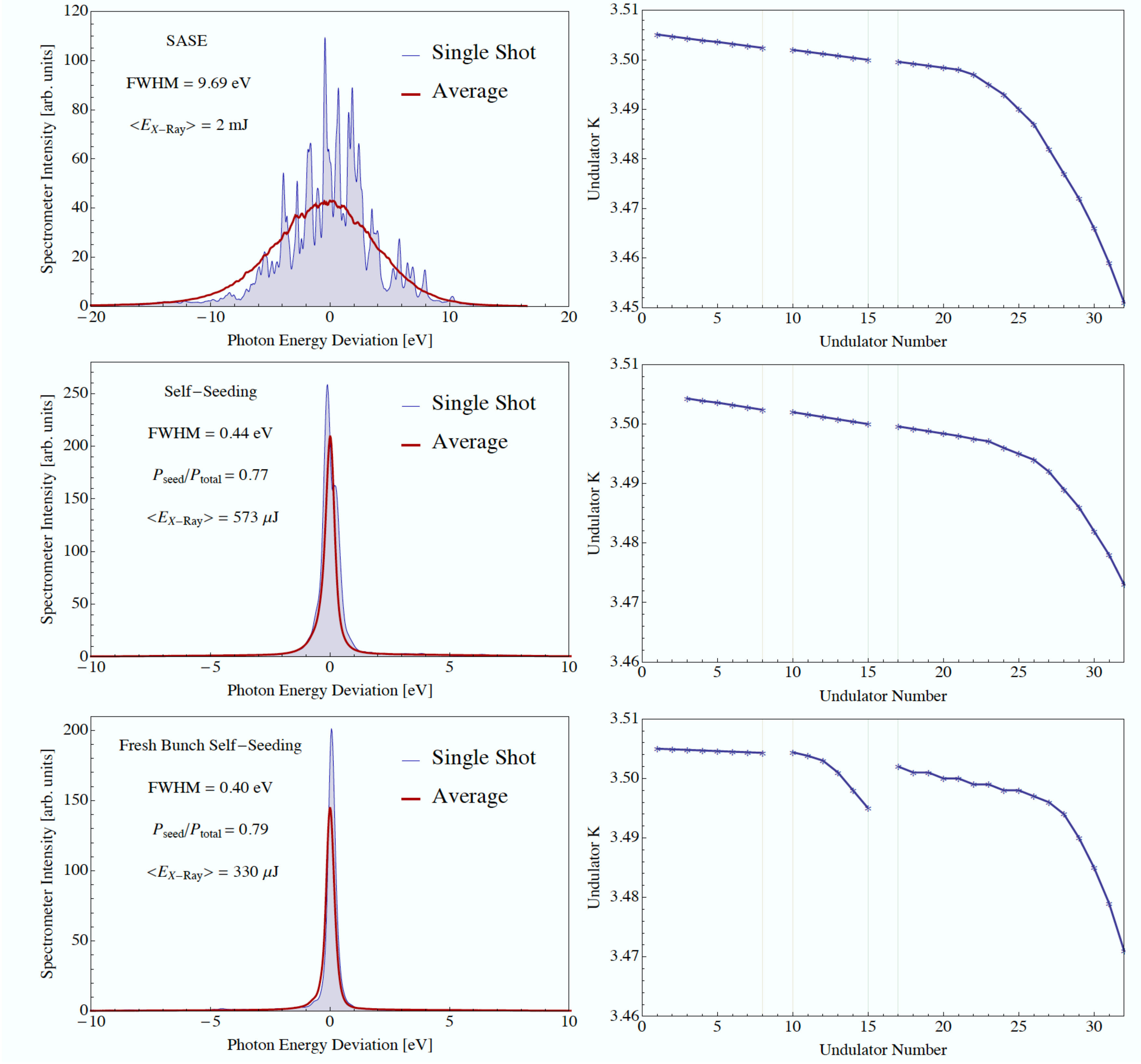
What Next?

(1)Detailed studies of high efficiency/tapered FELs with advanced accelerator beams.

(2)More exploratory studies of advanced schemes: e.g. tapered eSASE, superradiance, tailored beam profiles, pre-bunching…

Backup slides

Fresh slice self seeding experiment at LCLS



Sideband suppression via gain modulation

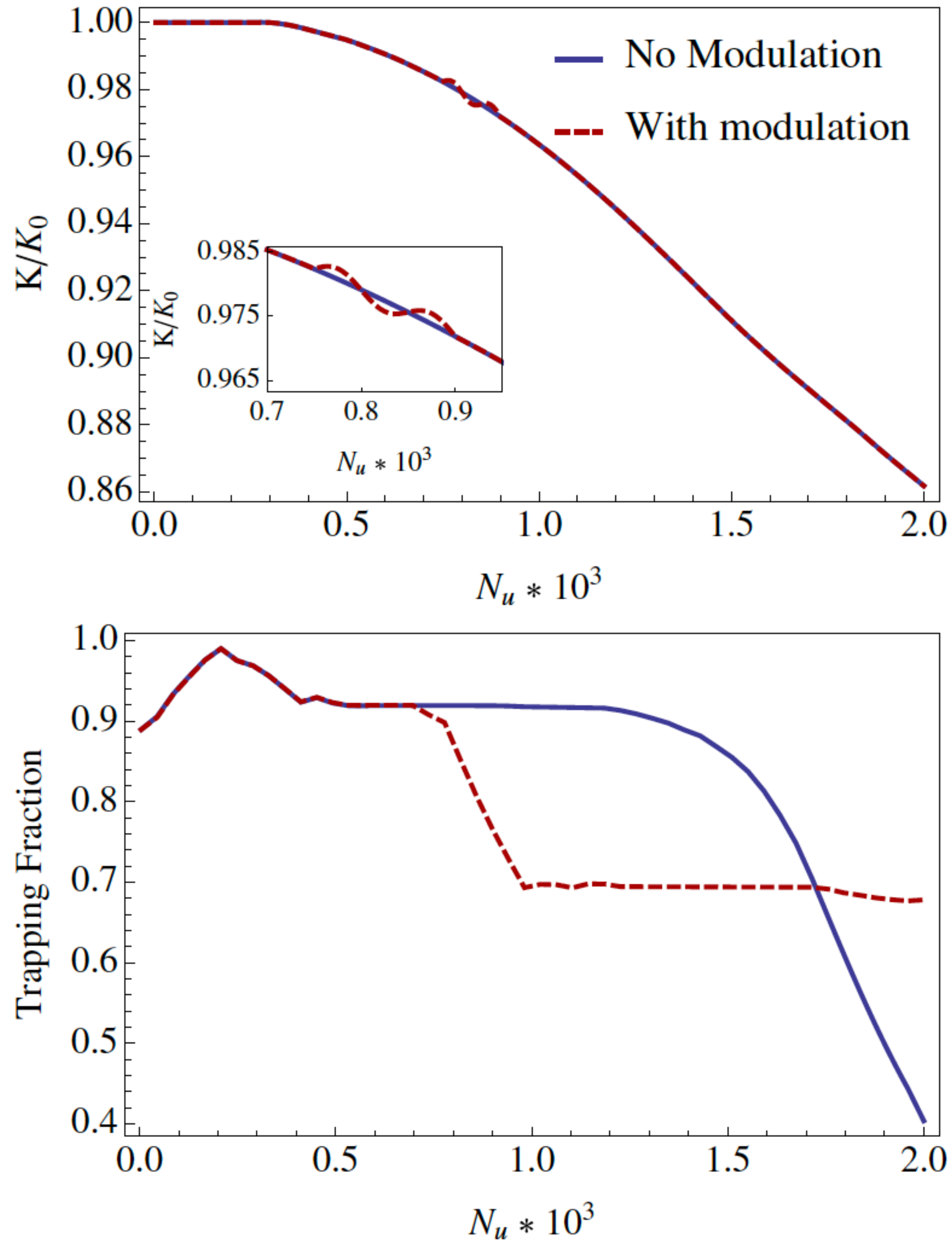


FIG. 5. (Top) Undulator taper profile for a gain modulated tapered FEL. The modulation section at $N_u = 750$ changes the synchrotron frequency and damps the sideband growth (see Fig. 6). (Bottom) The trapping fraction drops after the modulation section but remains constant compared to the unmodulated case which suffers from severe sideband-induced detrapping after $N_u = 1500$.

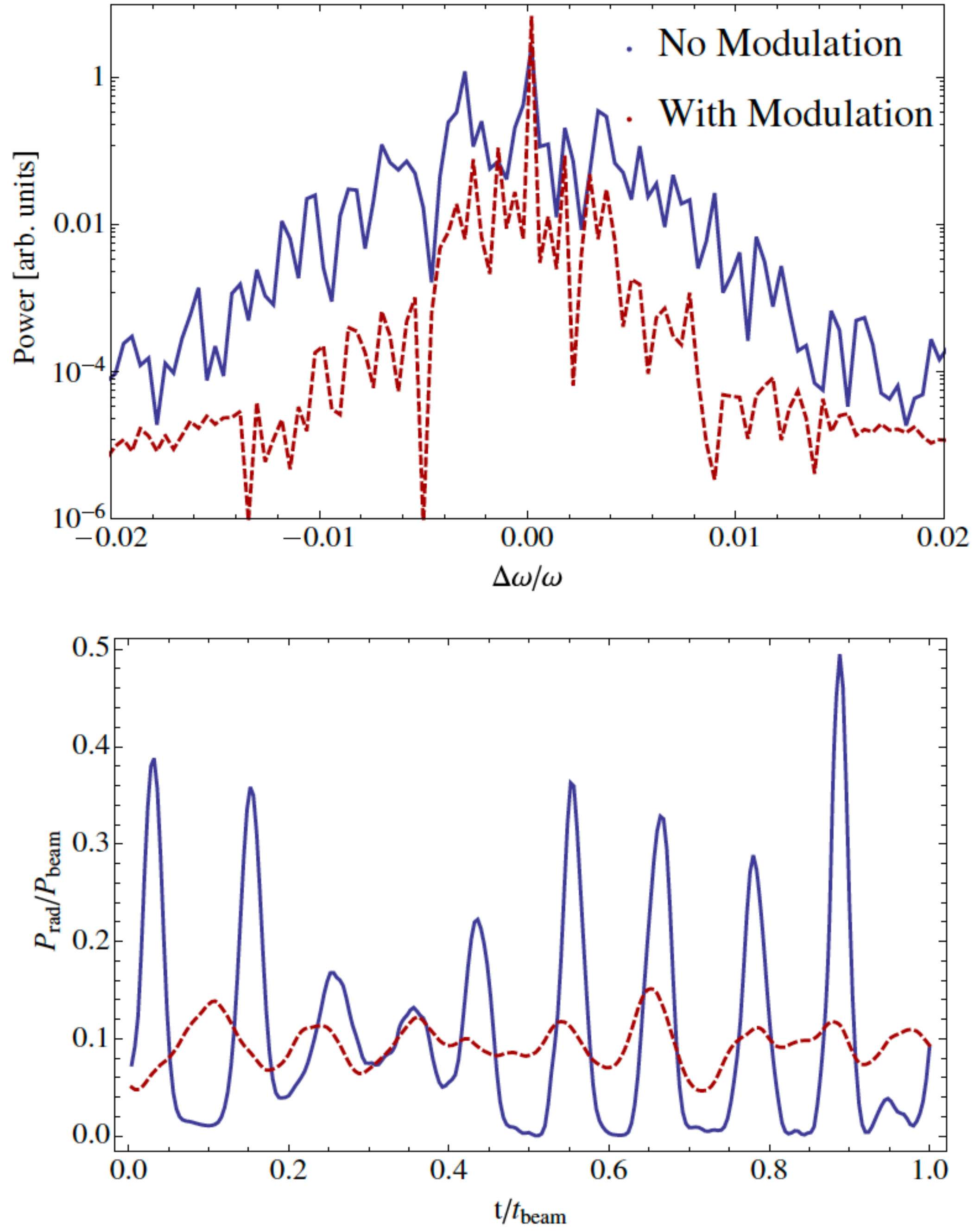


FIG. 6. Radiation spectrum (top) and temporal profile (bottom) with and without gain modulation showing sideband reduction for a gain modulated high efficiency FEL. The ratio of sideband to total power is 55% in the unmodulated case and 4% in the modulated case.