High efficiency free electron lasers

C. Emma

IOTA/FAST Collaboration meeting

May 10, 2018

Fermilab

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Presentation Outline

1. Physics of tapered FELs

1.1. Motivation

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

2. Experimental studies

2.1. Past

2.1.1. Fresh-bunch self-seeding experiment (SLAC)

2.1.2. NOCIBUR experiment (BNL-ATF)

2.2. Present

2.2.1. TESSA-266 (Argonne)

2.3. Future

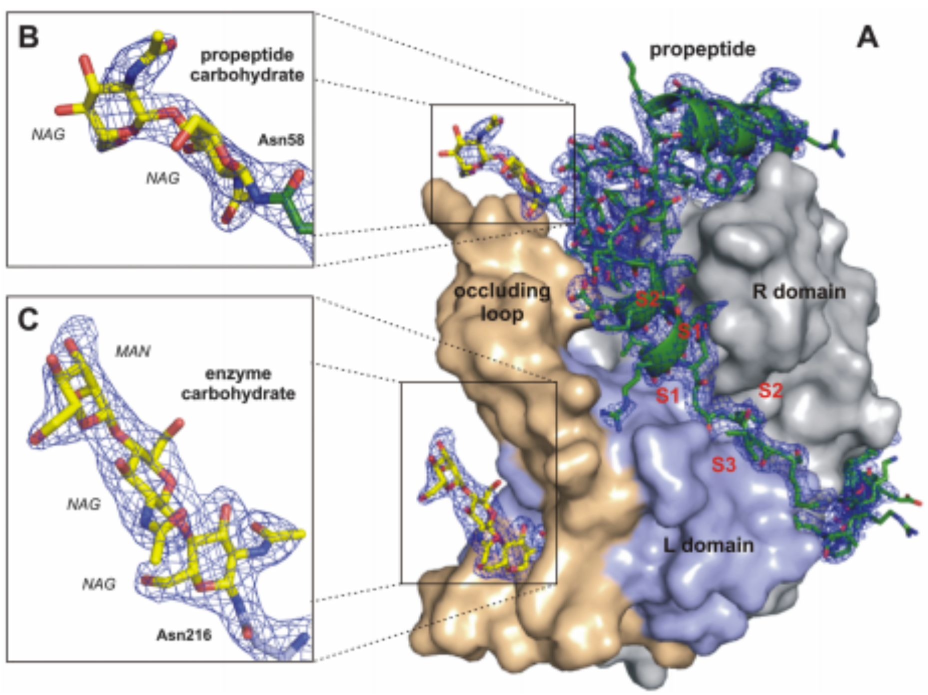
2.3.1. Opportunities at FAST

3. Conclusions

Motivation for high efficiency FEL

Imaging single molecules via "diffraction before destruction"

Redecke et al., Science 339, 6116, (2012)



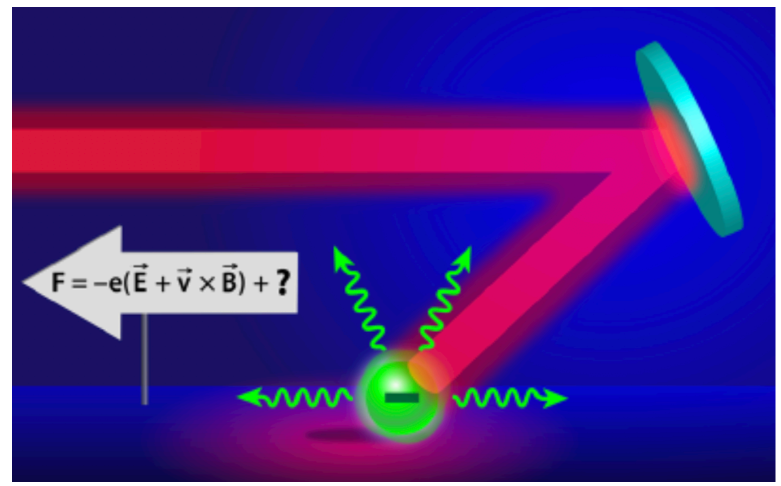
2.1 A resolution

Trypanosoma brucei cysteine protease cathepsine B

Single Molecule Imaging Goal
10 fs - 10 mJ - 2020

Aquila et al., "The LCLS single particle imaging roadmap" Stuct. Dynam. **2**, 041701

High field electrodynamics



From Phys. viewpoints, A. Macchi, Physics 11, 13 (2018)

Unexplored physics phenomena e.g. radiation reaction occur when electrons interact with an E-field close to the Schwinger critical field

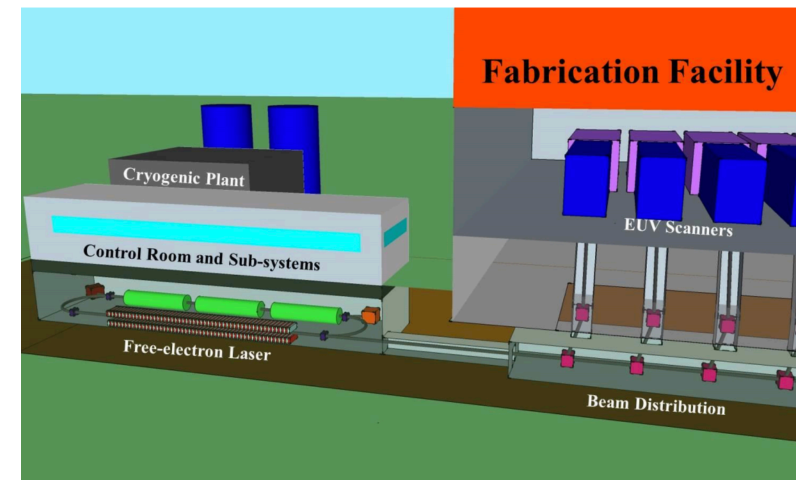
$$E_{Schwinger} = \frac{m_e^2 c^3}{\hbar^3 e} = 1.3 \times 10^{18} \mathrm{V/m}$$

Is being pursued actively at the moment using PW lasers and LWFA e-beams with *interesting* results e.g.

Cole *et al*, Experimental evidence of radiation reaction in the collision of a high-intensity laser pulse with a LWFA electron beam PRX 8, 011020 (2018)

Poder *et al* "Evidence of strong radiation reaction in the field of an ultra-intense laser", arXiv:1709.01861

Industrial FEL for EUV lithography



From Hosler, Wood "Free electron lasers: beyond EUV lithography insertions", Global Foundries

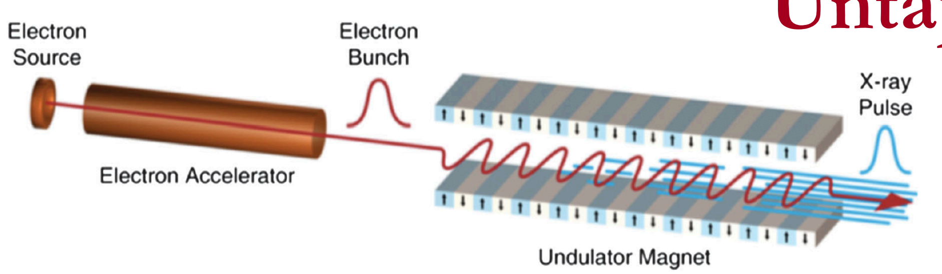
Semiconductor industry is a very large economic driver \$2.0T global electronics maker

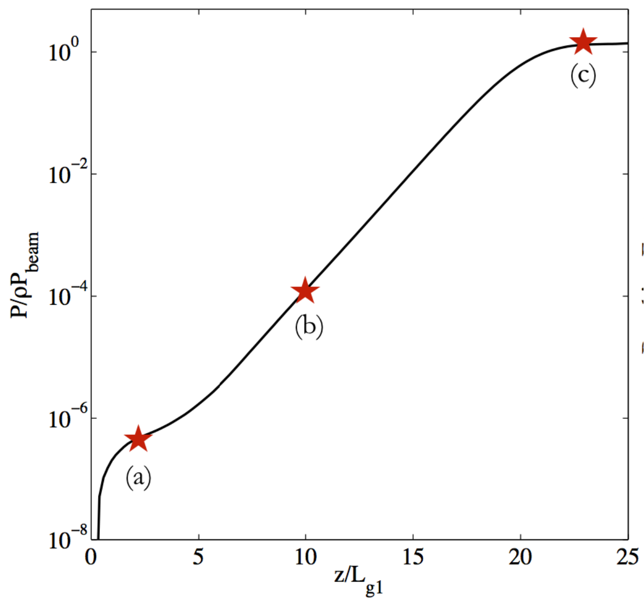
Current technology uses EUV from laser produced plasma sources. Expected cost is \$15-20B for leading-edge fab.

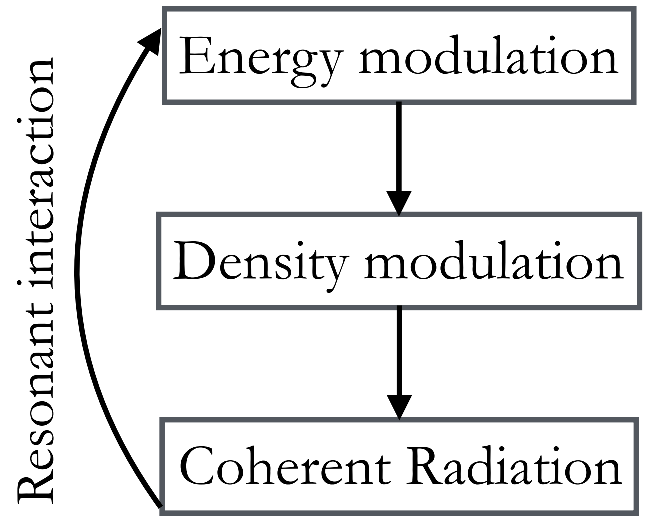
FELs being considered as an alternative but need to fulfill many requirements, one of which is *high efficiency* ~ 10 %

Undulator tapering for high efficiency FEL

Untapered FEL







Resonance condition

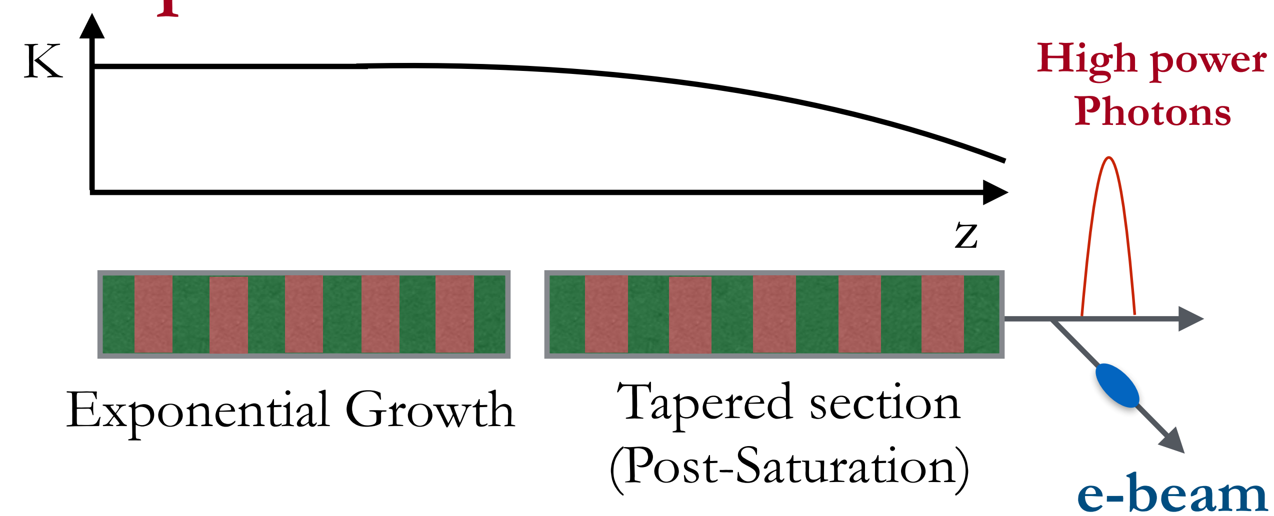
$$\lambda = \frac{\lambda_u}{2\gamma_r^2}(1 + K^2)$$

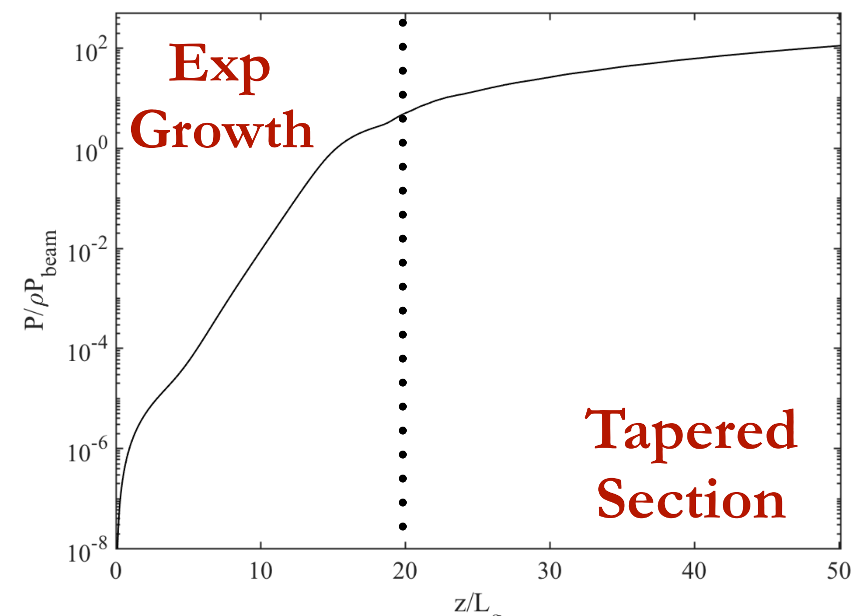
- 1-D physics (BPN Opt Comm. 1984) described by single parameter ϱ.

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

- Some numbers:
  E_e=250 MeV, I = 0.2 kA, λ = 250 nm, ϱ ~ 0.5%
- For high efficiency applications we want > 20x in efficiency to >10 %

Tapered FEL





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

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

Power scaling in post-sat regime

$$P_{rad} = P_0 + P_1 \bar{z} + P_2 \bar{z}^2 \longleftrightarrow K = K_0 - bz - \frac{cz^2}{2}$$

Dominant for short undulators or large seed

Dominant for long undulators

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

Power scaling in post-sat regime

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

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

Dominant for short undulators or large seed

Dominant for long undulators

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

Initial Condition contribution

Tapering contribution

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

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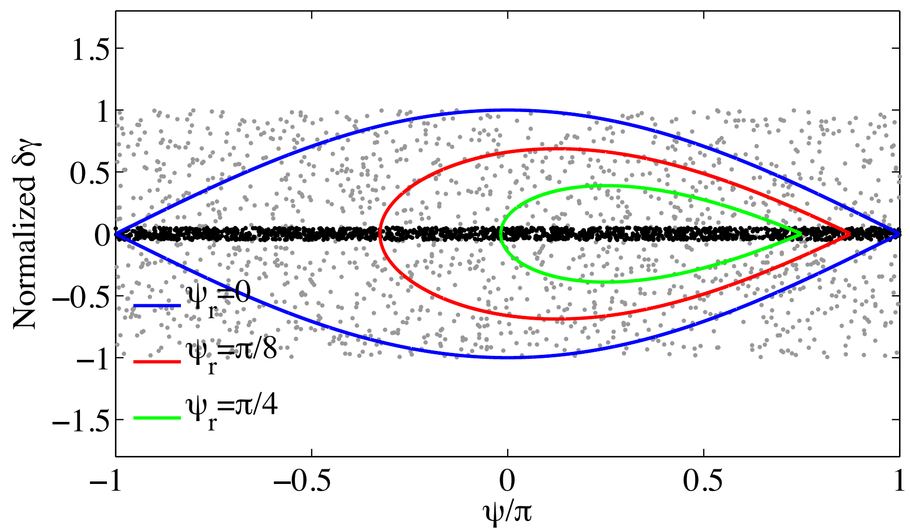

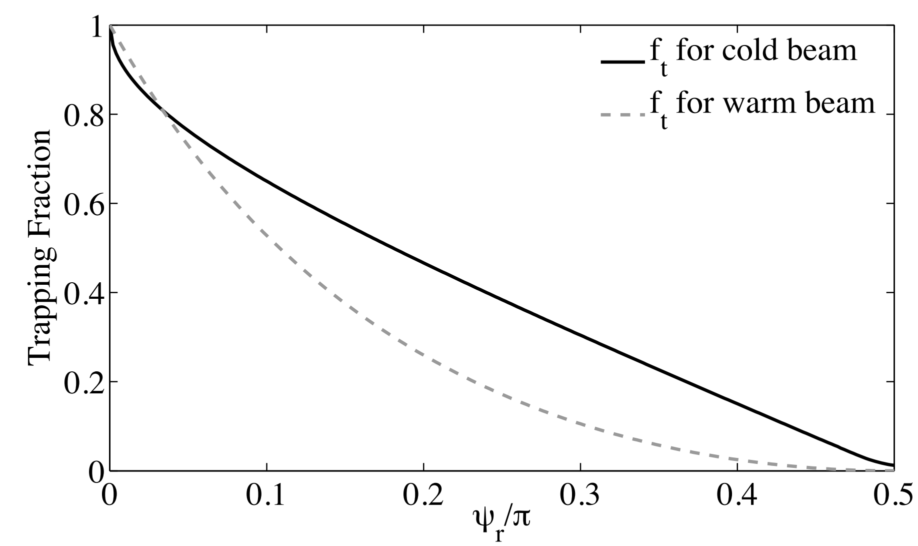

1-D effects: How to choose the taper for max. power

SLAC

Power scaling in post-sat regime

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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**

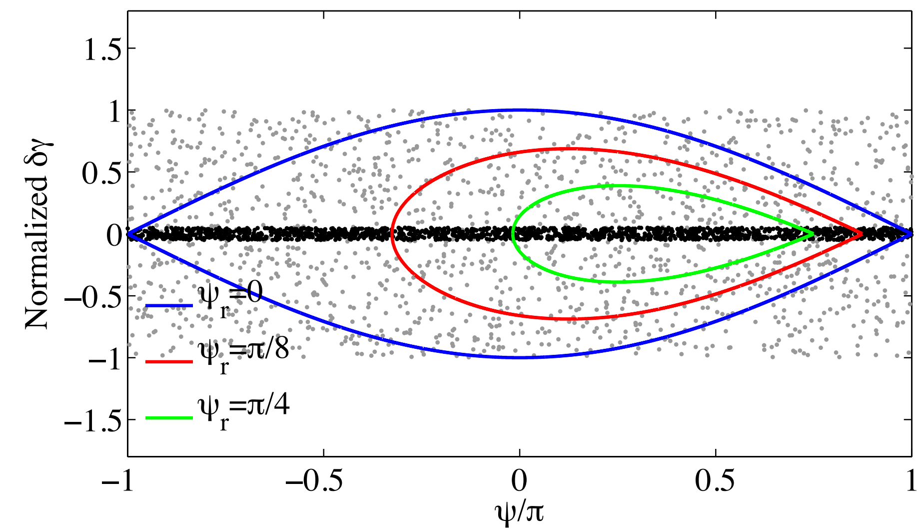
∴ Trade-off between number of electron trapped and how quickly the electrons are decelerated

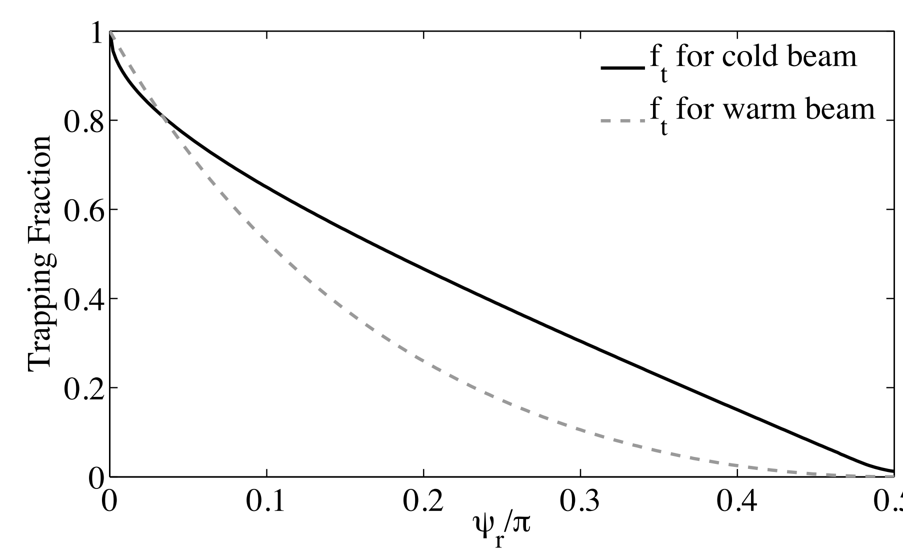
(2) **Power scales like $(f_t \sin\psi_r)^2$**

∴ 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: trade-offs and design considerations

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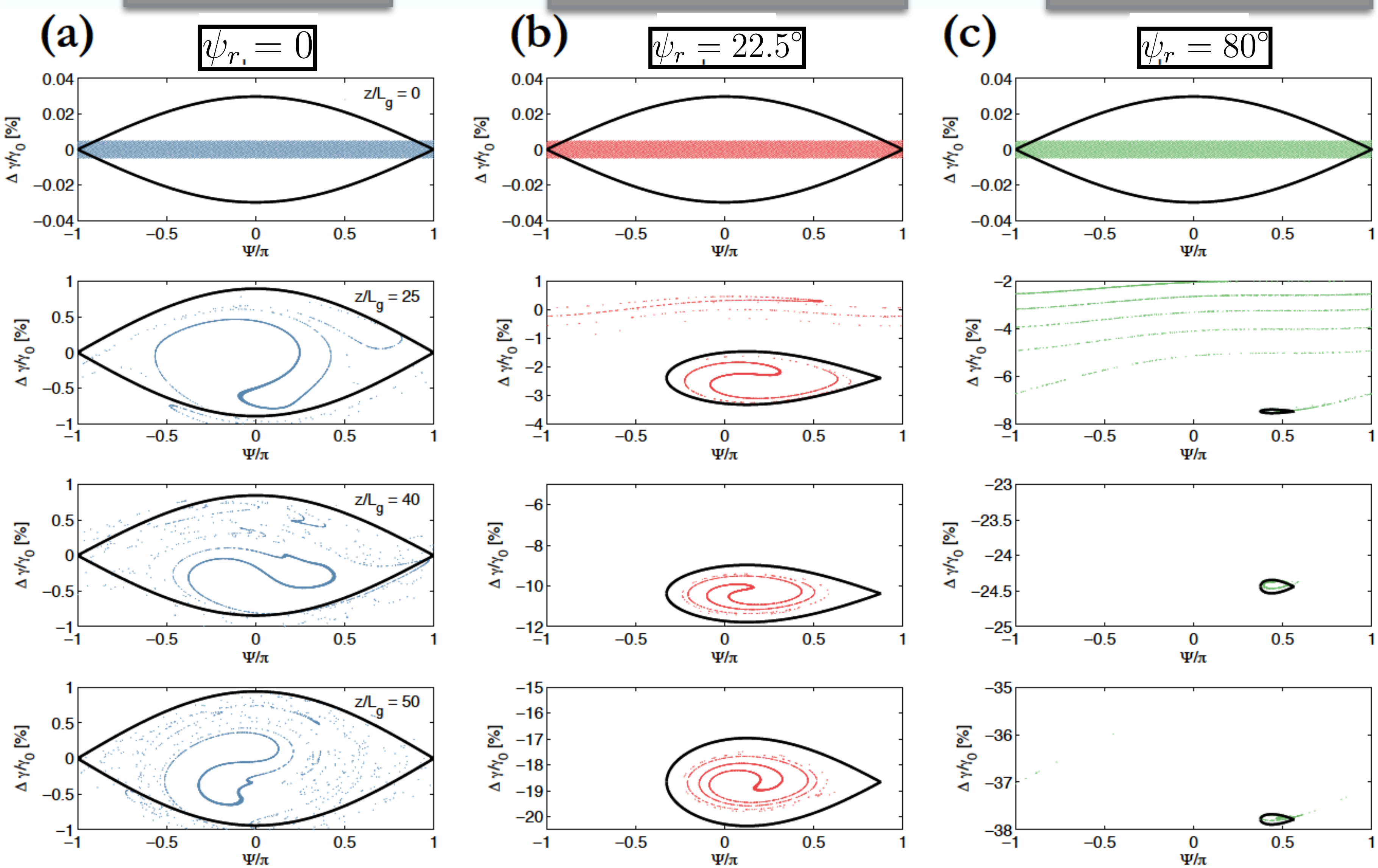
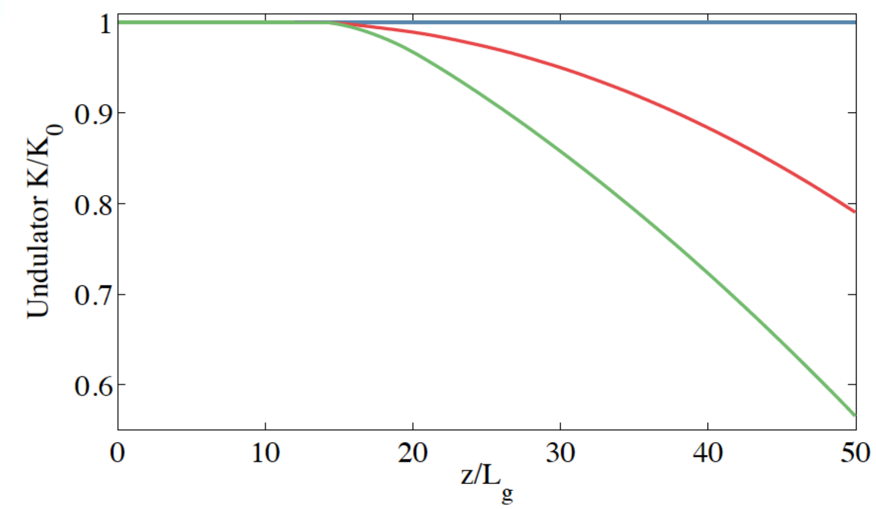
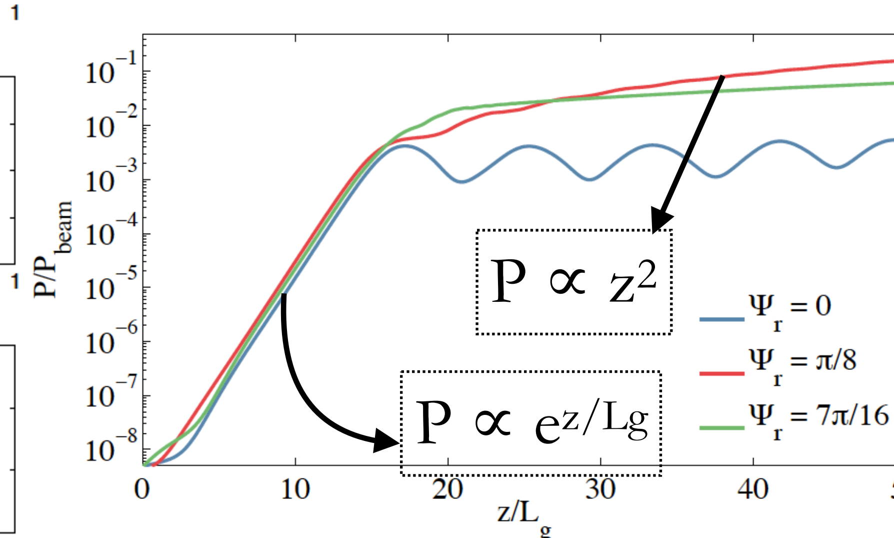
No tapering | "Slow" tapering | "Fast" tapering







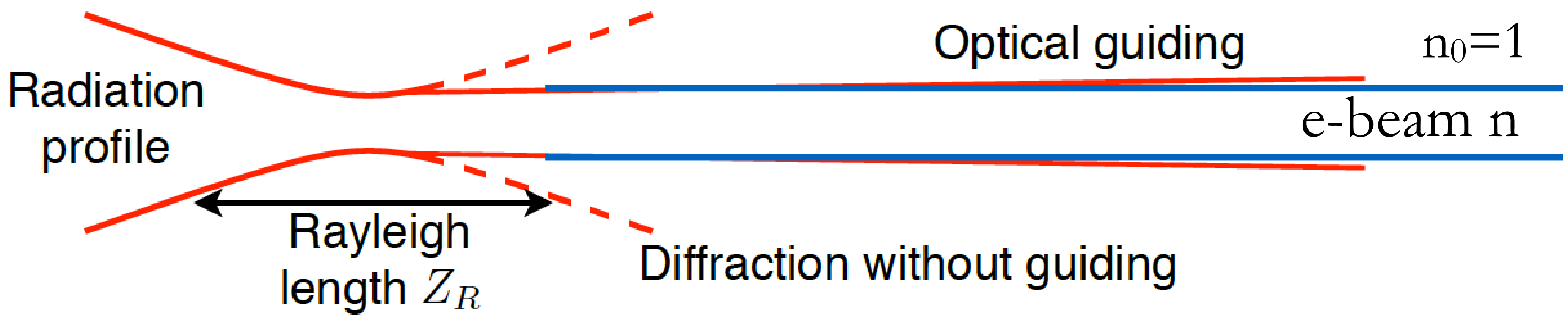
No tapering efficiency is the same as saturation

"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

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



E-beam refractive index

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

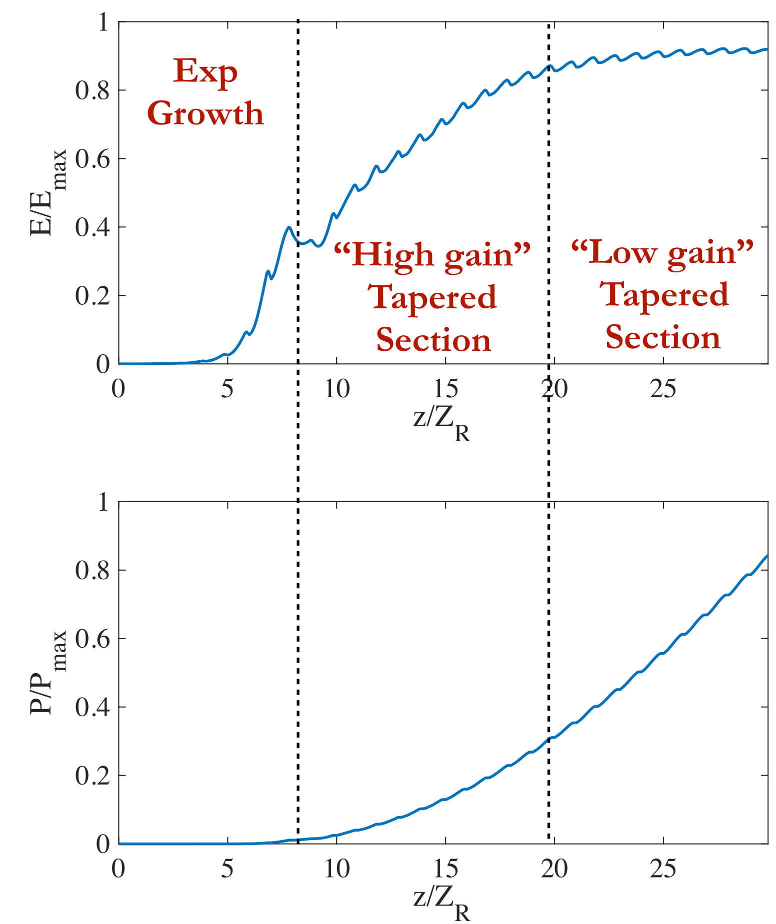
Growth of field reduces guiding sets limit on max. E field

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)



<u>Take home messages from 3-D theory</u>

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

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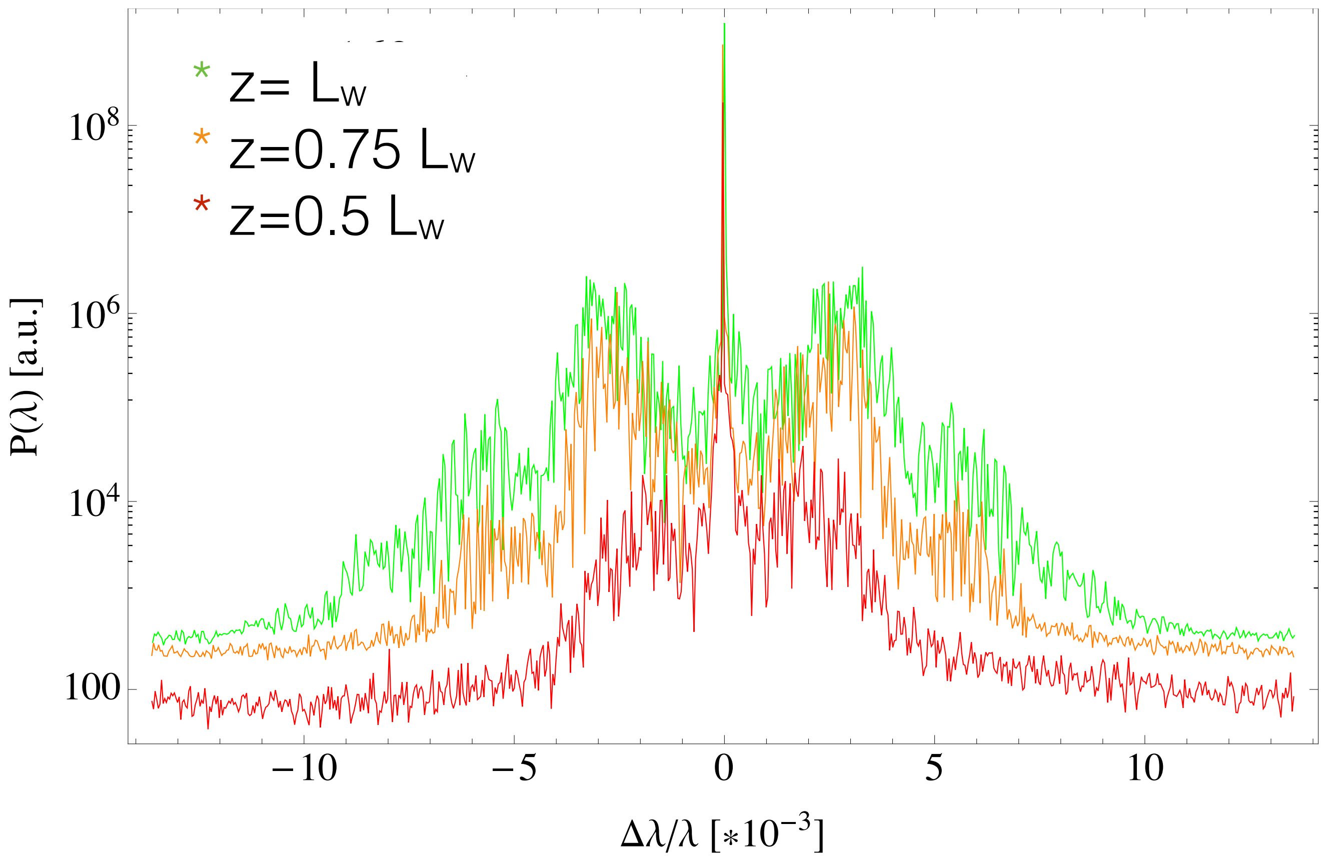
Electron beam shot noise and synchrotron motion

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



"…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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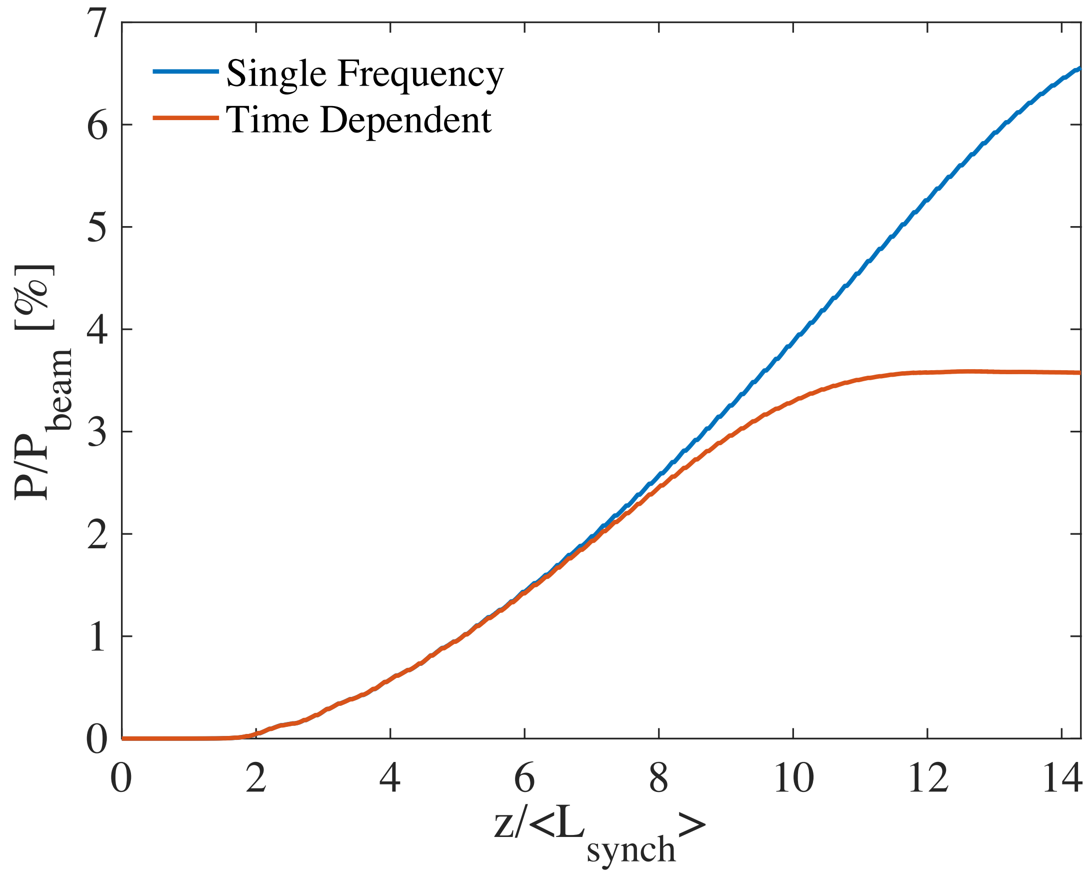

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Sideband Instability

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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

Presentation Outline

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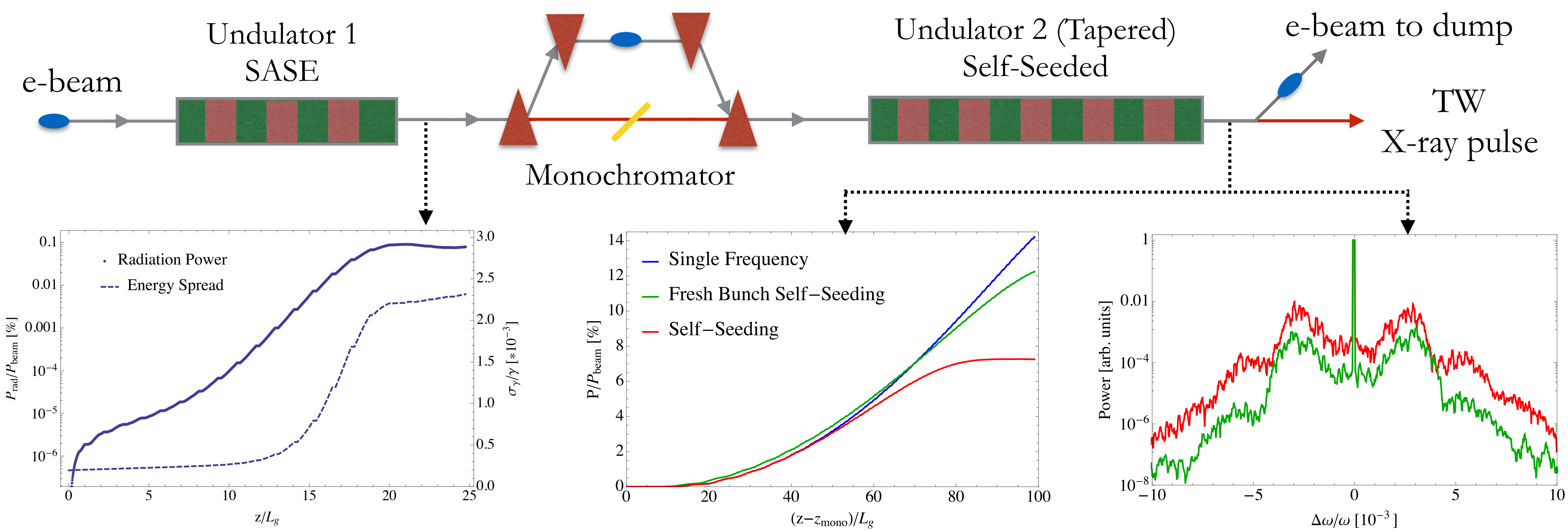
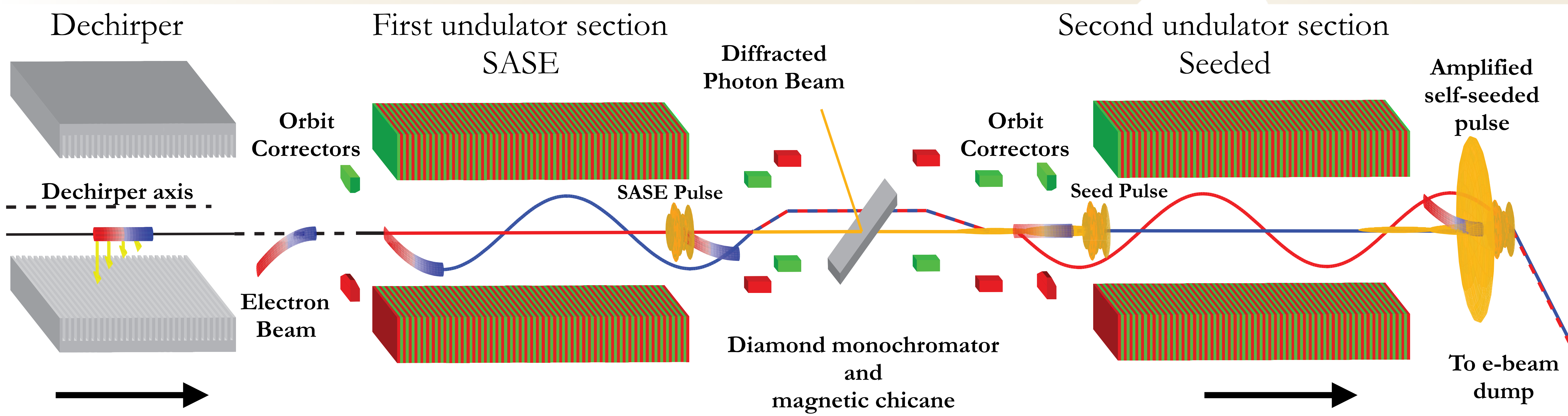
Fresh bunch self-seeding experiment - simulations



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.**

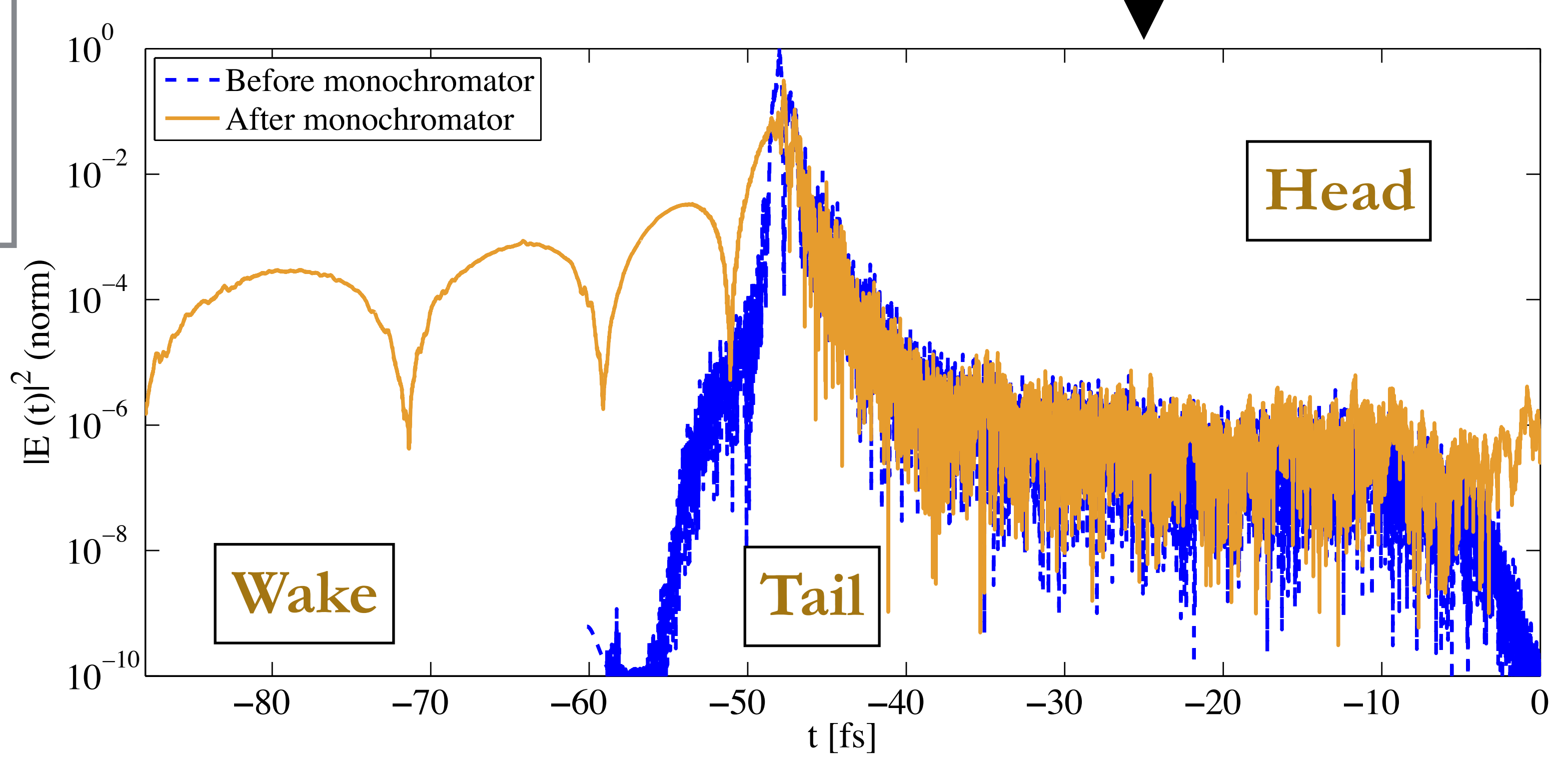
Fresh slice self seeding experiment at LCLS



E-beam

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

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



Diagnostics

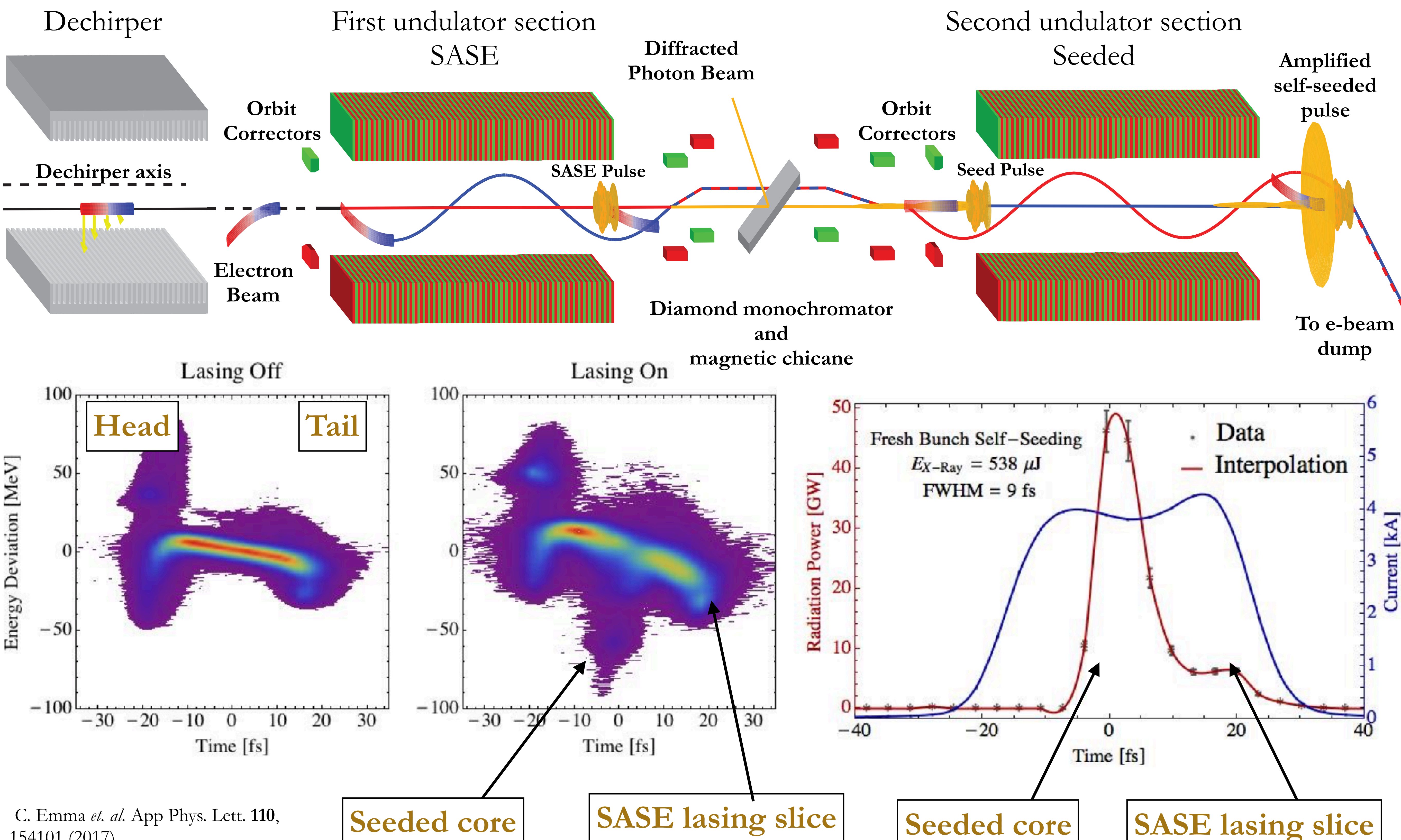
1) **Transverse deflecting cavity**
Electron beam energy loss
(time resolved)

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



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

Fresh slice self seeding experiment at LCLS

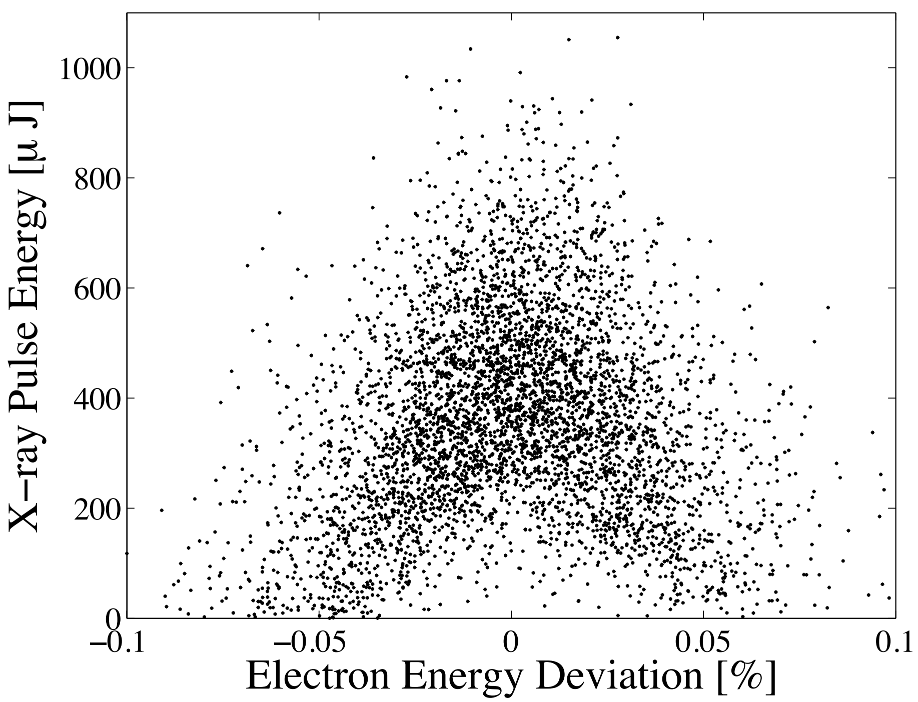
Brightness ratio	Average	Average filtered on e-beam energy	Peak
B_{FBSS}/B_{SASE}	12.5	15.5	35.4
$B_{FBSS}/B_{self-seeding}$	2.4	2.1	2.3

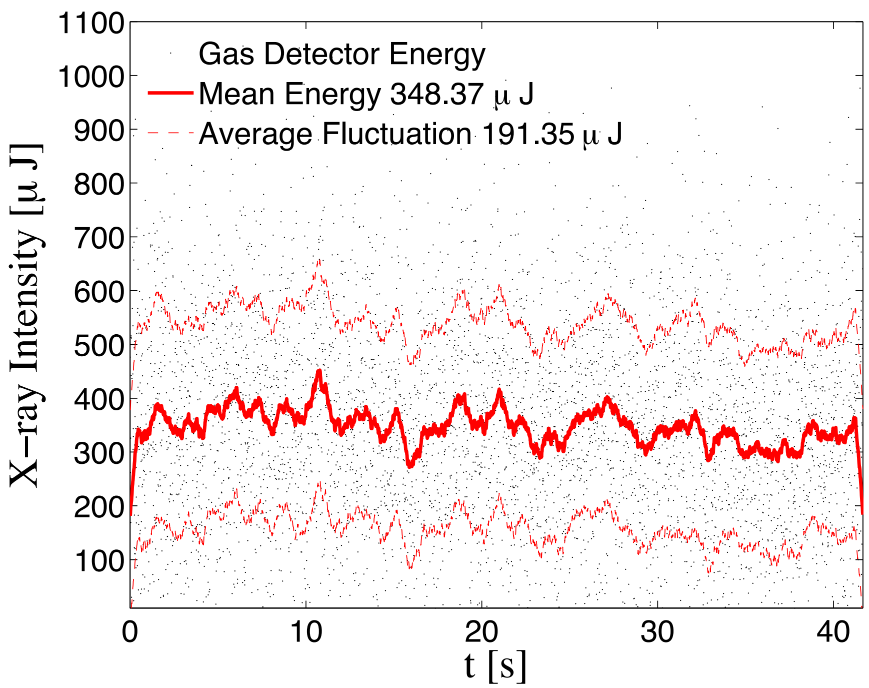
Table 6.1: Comparison between the average and peak brightness of the FBSS scheme with SASE and self-seeding at the same photon energy. The left column is an average without filtering the data based on the incoming electron beam energy. The middle column is an average of the data within the energy jitter 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





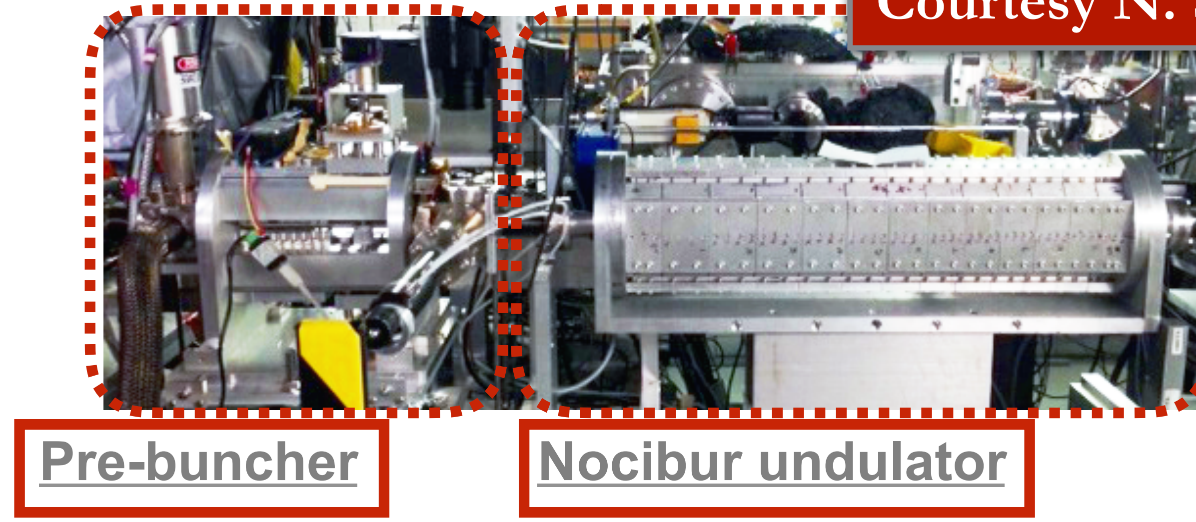
Issues to work on

Large shot-to-shot intensity fluctuations due to:

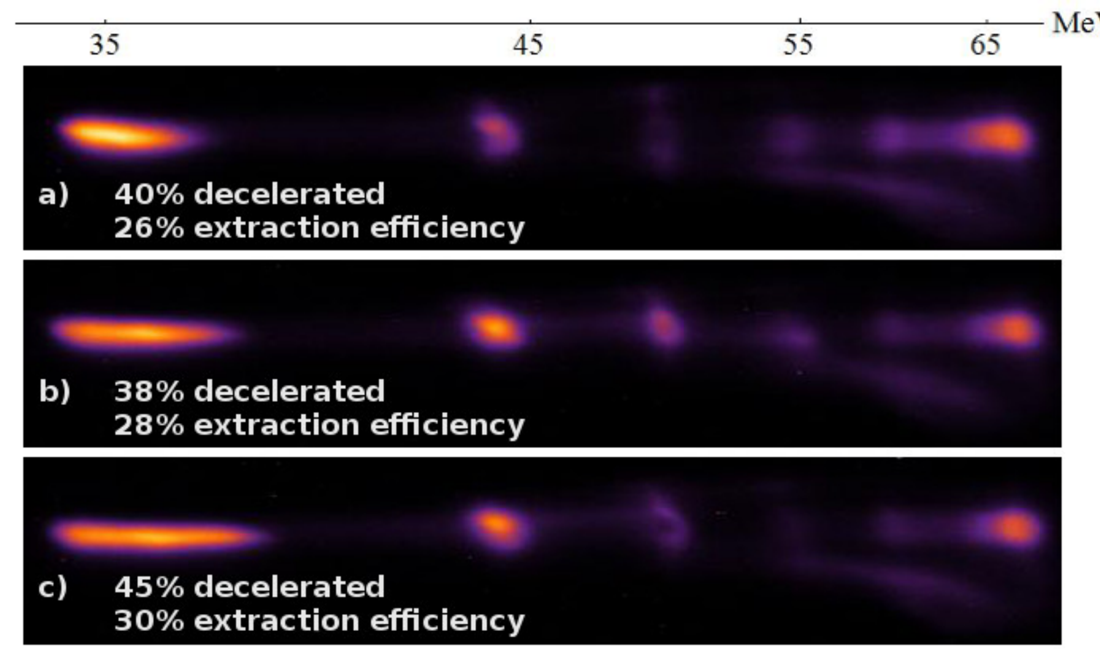
i) Energy jitter
ii) Seed power fluctuations from self-seeding monochromator

TESSA demonstration **NOCIBUR** experiment

Courtesy N. Sudar

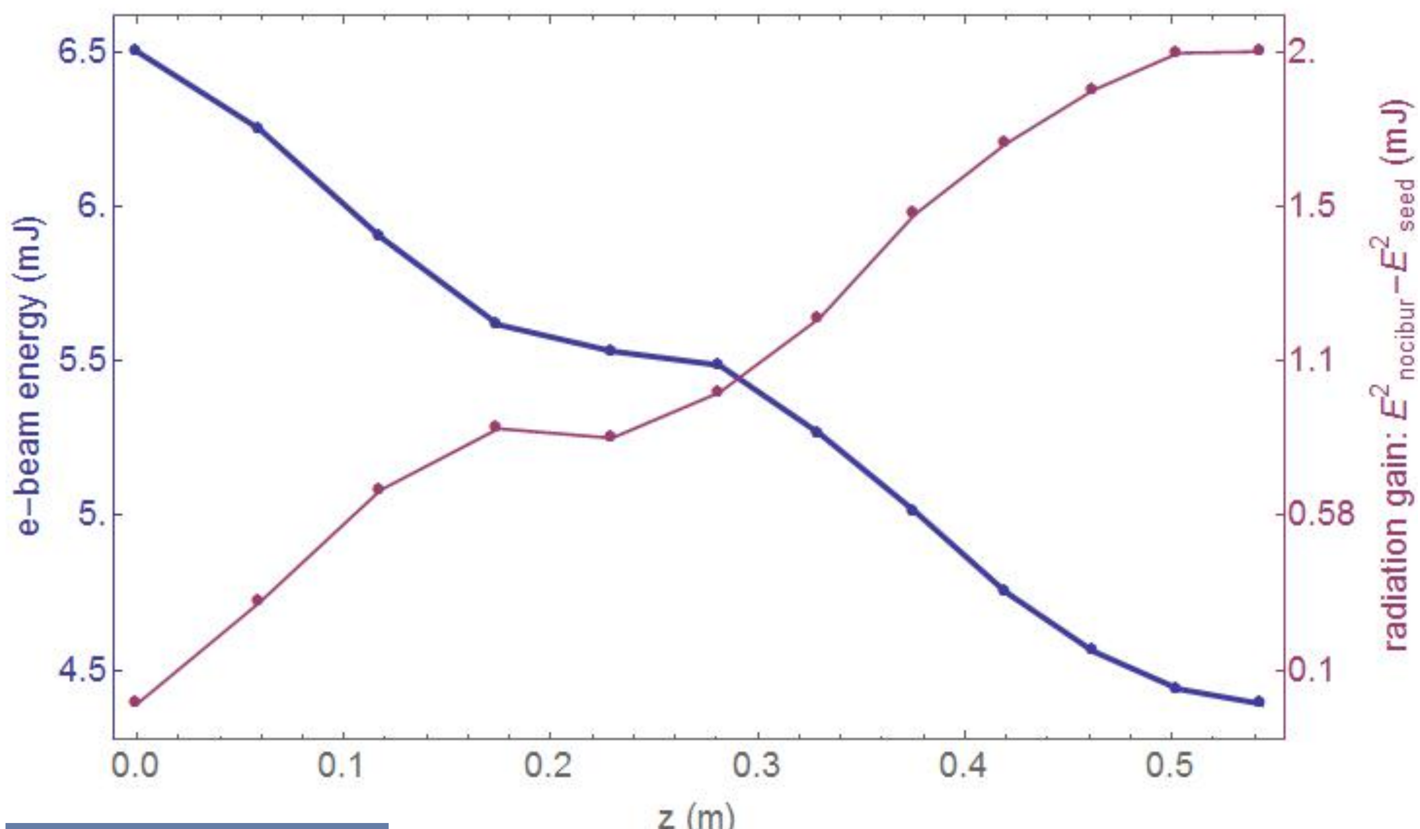


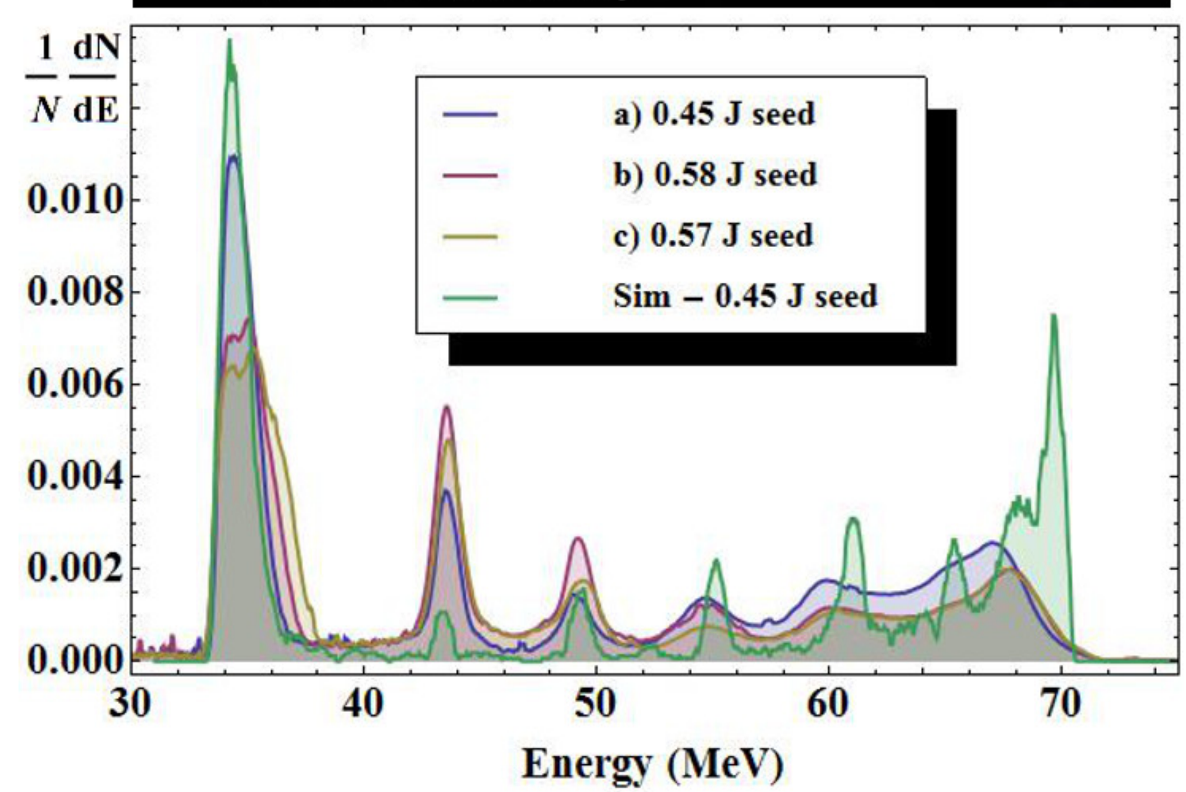
- strongly tapered helical undulator (decelerating)
  - λw: 6 - 4 cm, K: 2 – 1.2, $\Psi r = \pi/4$
- pre-bunched electron beam
- 200 GW, 10.3 μm CO_2 laser seed
- 45% of particles decelerated from 65 → 35 MeV (Lu=0.54m)
- 30% conversion efficiency
- good agreement with GPT simulations
- Genesis simulations show expected radiation growth for electron beam energy loss



Issue to work on

Very large external seed laser necessary. Would like a self-contained system



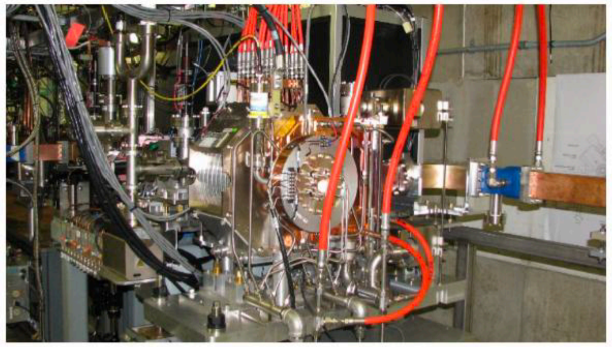


UCLA

N. Sudar et al. Phys. Rev. Lett. 117, 174801 (2016)

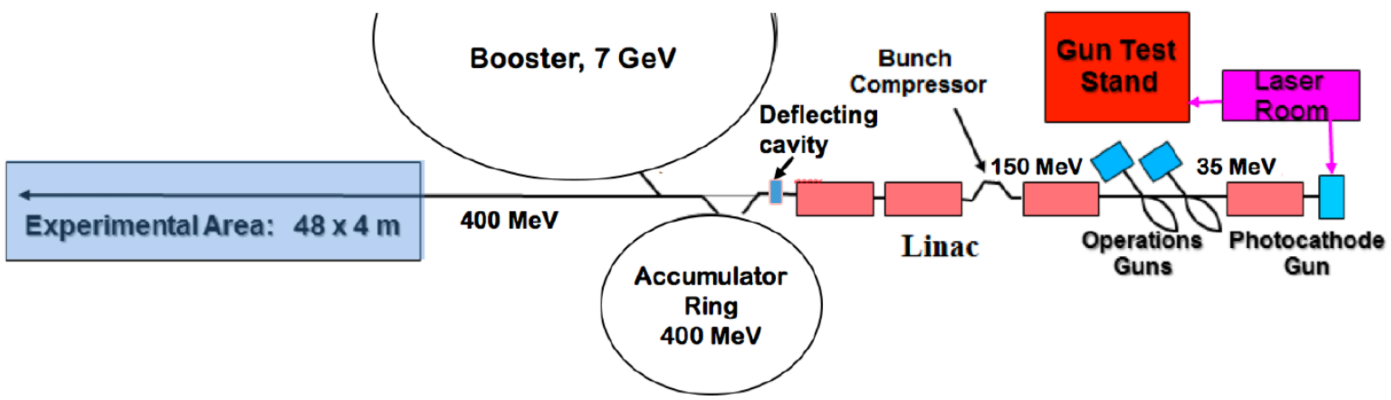
Presently ongoing experimental work

Courtesy
P. Musumeci, Y. Park



TESSA-266

- Higher gain and higher current for radiation measurement
- Injector Linac at Argonne National Laboratory will operate at 375 MeV, 1kA and provide injection for 1.5 minutes in every 2 minutes
- decelerate ebeam for ~10% efficiency in 4 m undulator.
- Significant improvement from <1% efficiency in previous short wavelength FEL.

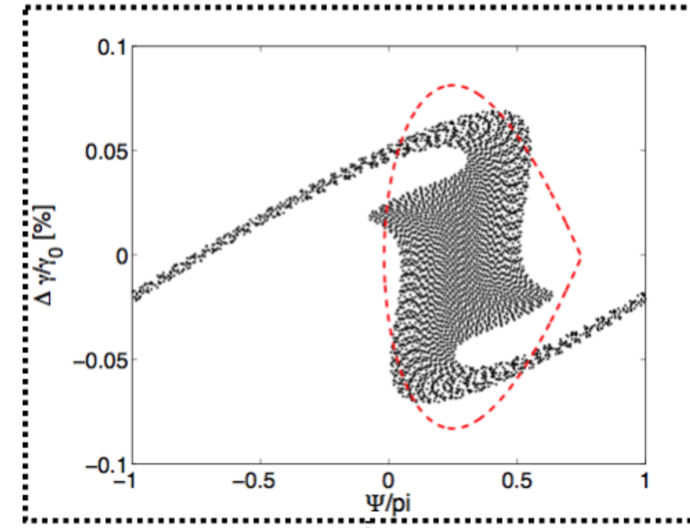


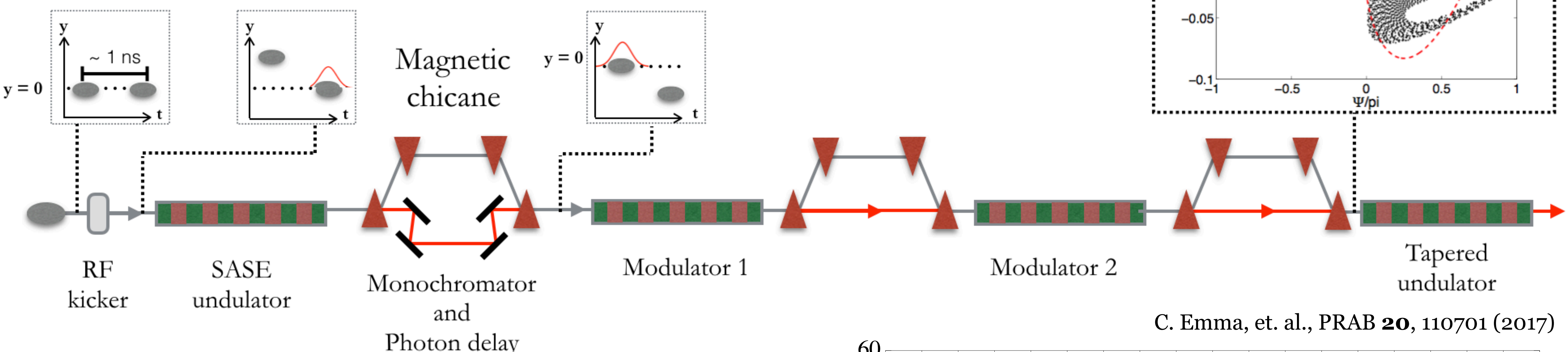
E-beam Energy	375MeV
Radiation Wavelength	266nm
Emittance	2 um
Seed Power	< 1GW
Energy spread	~.1%?
Peak Current	1 kA
Bunch length (RMS)	50um?

SBIR·STTR America's Seed Fund
radiabeam TECHNOLOGIES
UCLA
radiasoft
Argonne NATIONAL LABORATORY

Future advanced schemes to be tested #1

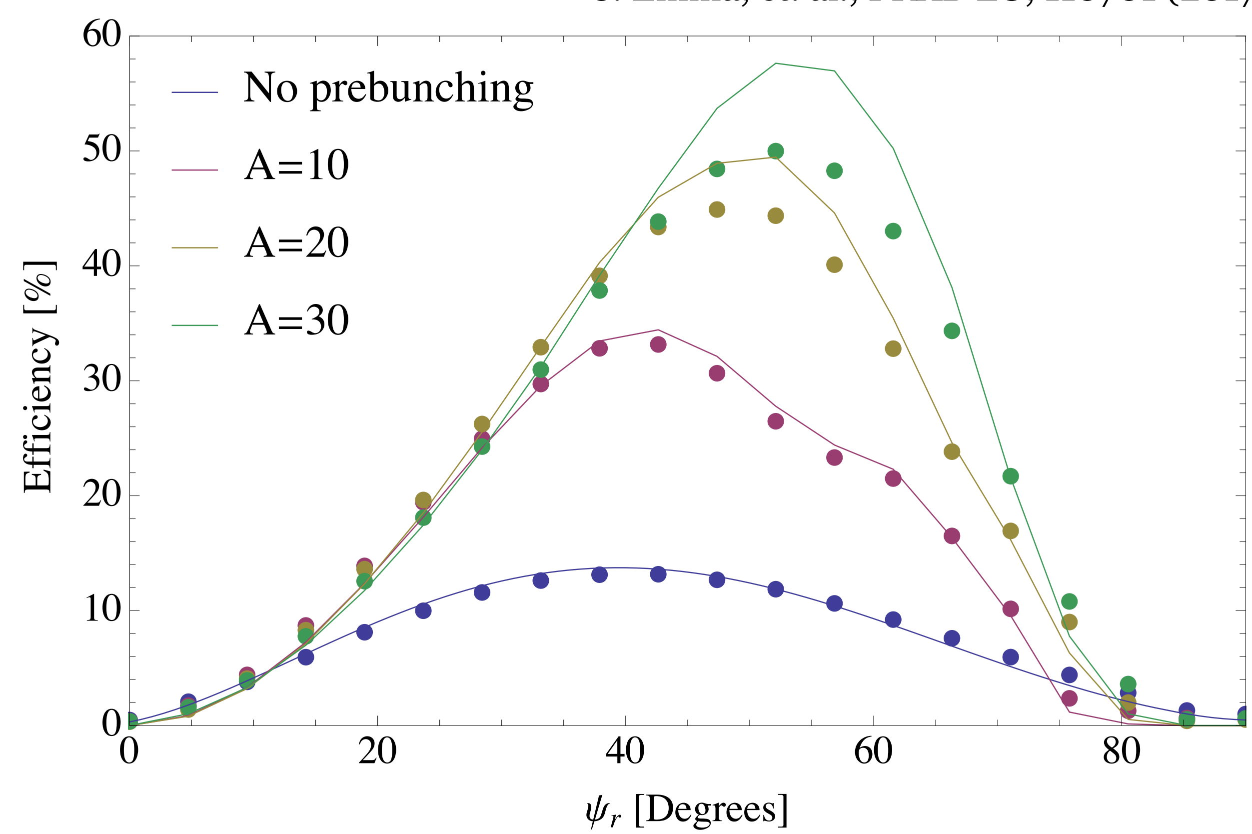
Working title: Double-bunch, pre-bunched, fresh-bunch, self-seeded XFEL





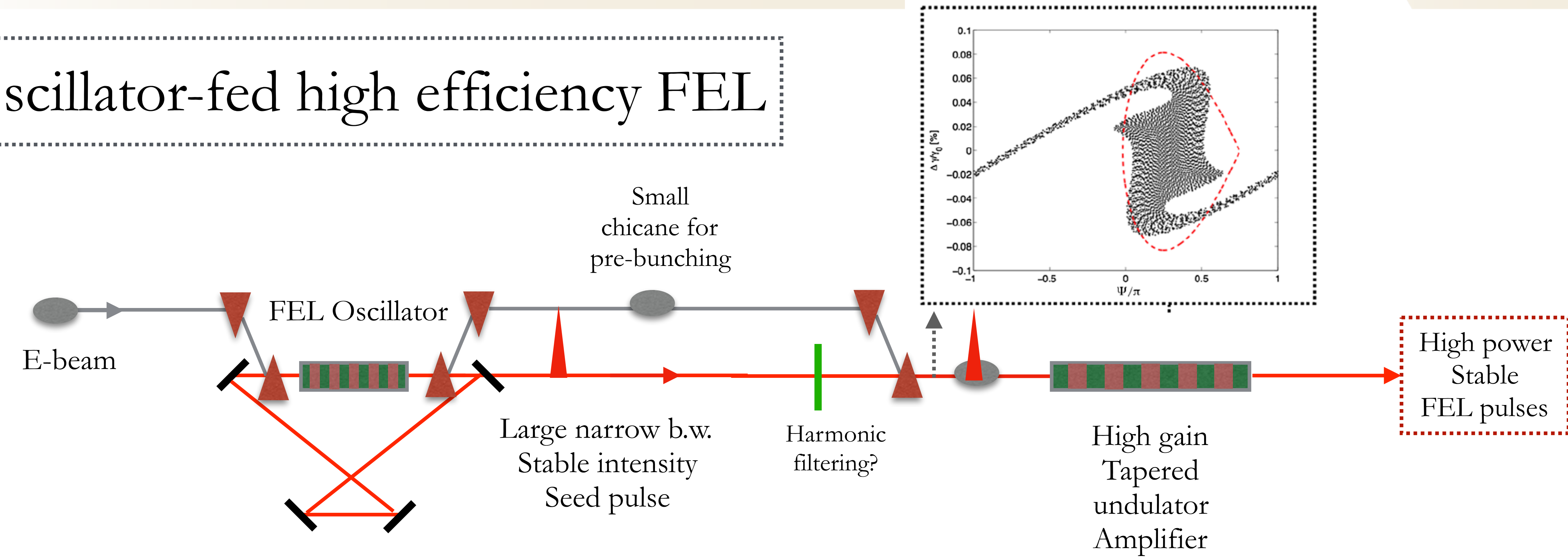
C. Emma, et. al., PRAB **20**, 110701 (2017)

- 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. Still suffers from intensity fluctuations.
- Has not been tested: would be nice to do the experiment!



Future advanced schemes to be tested #2

Oscillator-fed high efficiency FEL



- Oscillator-fed tapered FELs have two advantages over fresh-bunch seeding:
  - Narrow bandwidth seed
  - Stable intensity, no shot-to-shot fluctuations
- Pre-bunching with a small chicane can yield the ideal set of initial conditions
- Harmonic filters and appropriate thing of the high gain tapered section can extend the scheme to shorter wavelengths.
- Oscillator-fed high efficiency/harmonic FEL has not been tested experimentally but has received recent theoretical interest e.g. J. Duris *et al.*, https://arxiv.org/pdf/1704.05030.pdf , K. Kim, "A Harmonic X-ray FEL Oscillator," in High-Brightness Sources and Light-Driven Interactions

Conclusion

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

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

(3) We determine that a **large, stable seed** and a **pre-bunched** electron beam are the **ideal initial conditions** for high efficiency FEL.

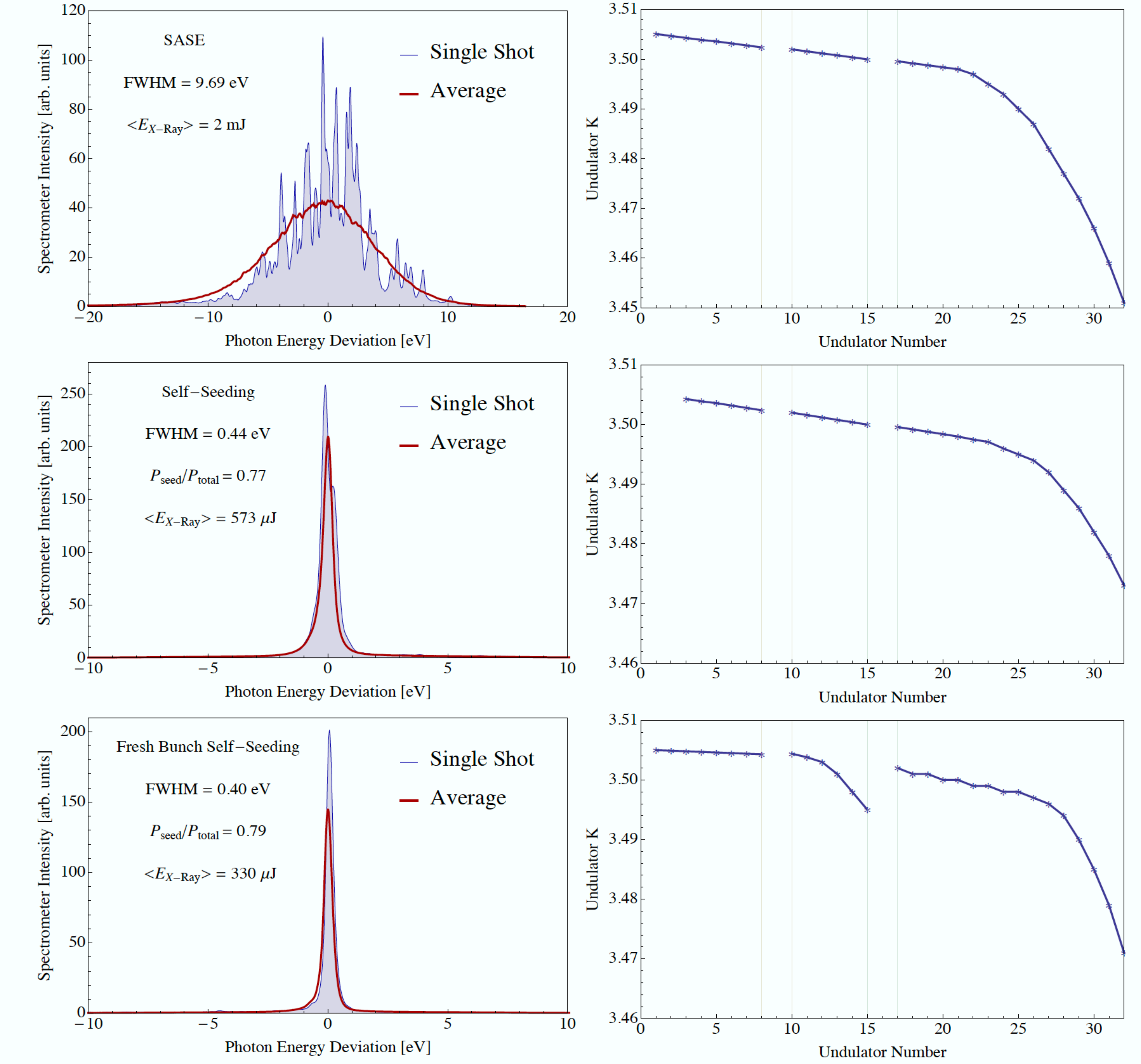
(4)We have studied this combination of pre-bunching and large seed as a in simulation. Results from 1-D sims are encouraging, 3-D sims to come.

(5) The above situations have been investigated separately in experiment **but not yet together**…

(6)Given recent interest in the FEL/science community/industry and limited FEL R&D time at large user facilities, a facility for testing advanced concepts for high efficiency FELs would be a welcome development for the field.

Backup slides

Fresh slice self seeding experiment at LCLS



Sideband suppression via gain modulation

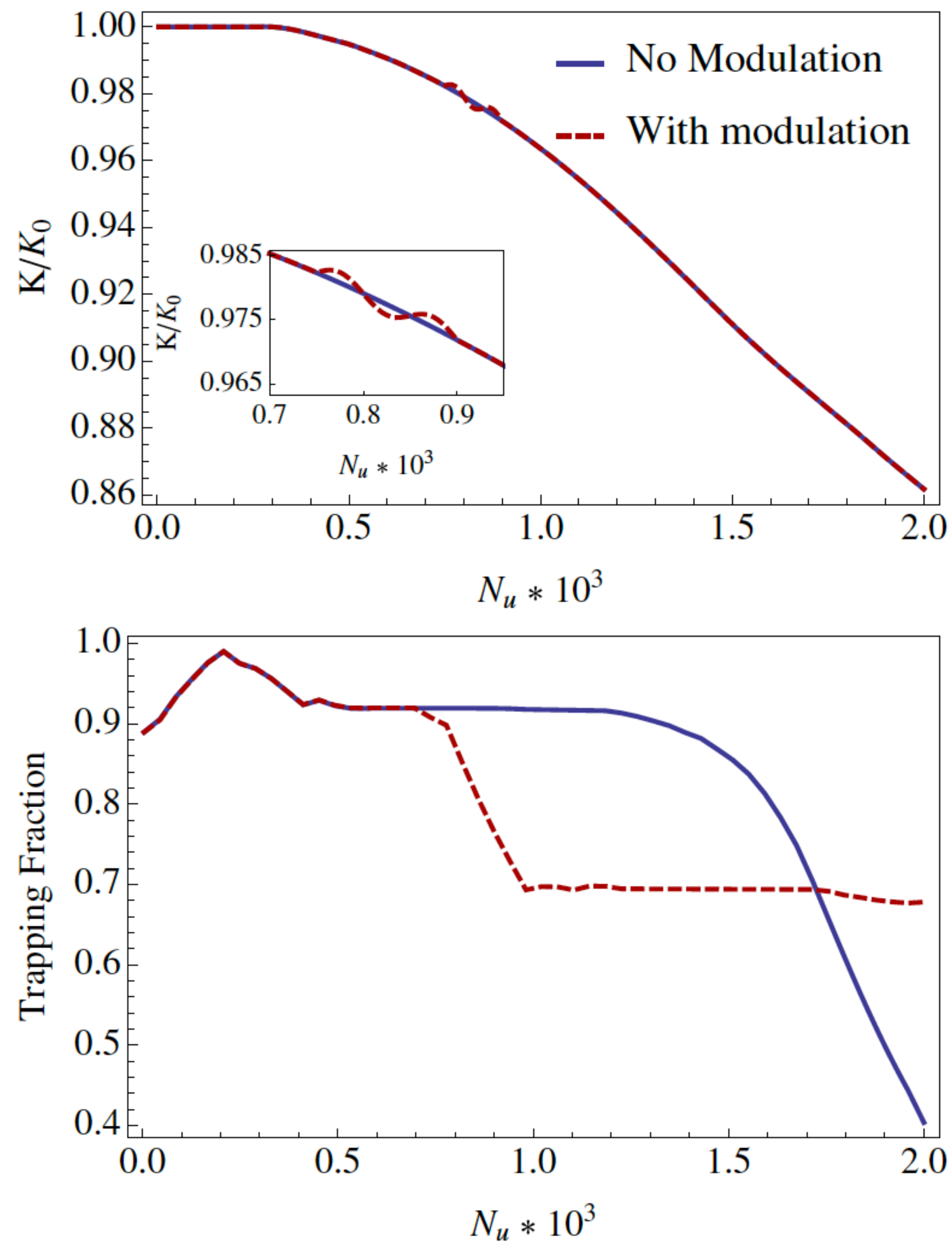


FIG. 5. (Top) Undulator taper profile for a gain modulated tapered FEL. The modulation section at $N_u = 750$ changes the synchrotron frequency and damps the sideband growth (see Fig. 6). (Bottom) The trapping fraction drops after the modulation section but remains constant compared to the unmodulated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

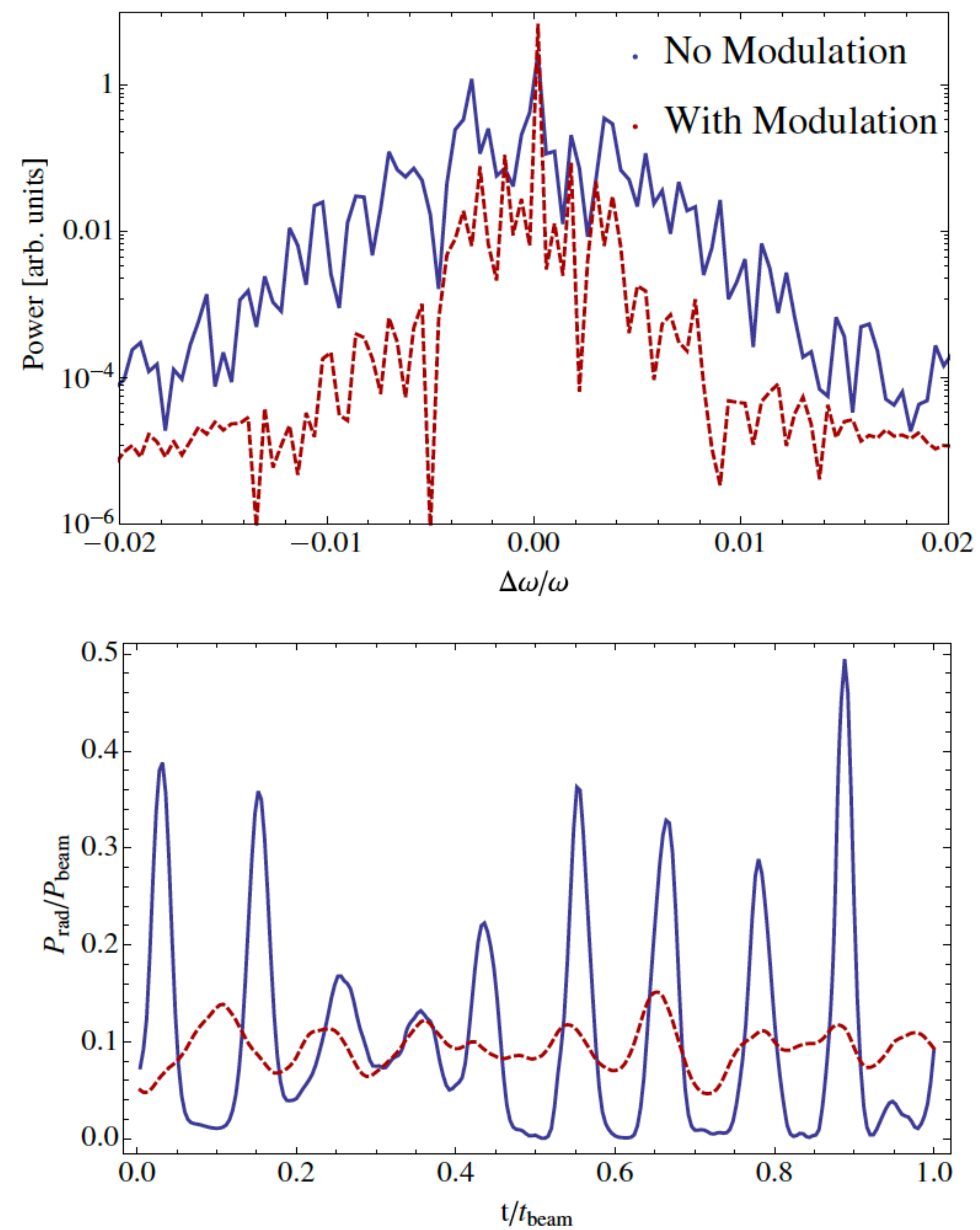


FIG. 6. Radiation spectrum (top) and temporal profile (bottom) with and without gain modulation showing sideband reduction for a gain modulated high efficiency FEL. The ratio of sideband to total power is 55% in the unmodulated case and 4% in the modulated case.