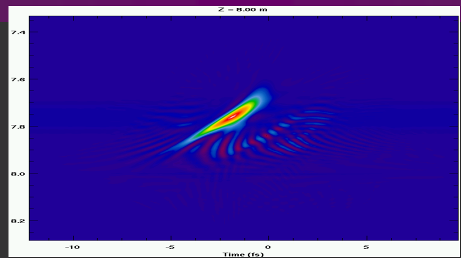
Use of Few-Cycle, Optical Energy Modulation + Undulator Tapering to Produce High Power, Ultrashort FEL Radiation Pulses at Soft X-Ray and EUV Wavelengths



William M. Fawley
Center for Beam Physics, LBNL

"Frontiers in FEL Physics and Related Topics"
Elba, September, 2007

The "Bottom Line": A (relatively) simple method to produce synchronized, fs-duration pulses in the XUV

- Ingredients: few-cycle optical pulse + reasonable e-beam (1 kA, 1-2 GeV, ~1 mm-mrad) + 10-20 m of *taperable* undulator
- 0.5 - 1 GW output pulses with τ_{FWHM}~ 2 fs or less
- Output temporally synchronized with optical pulse
- Scales smoothly from 2 to 32 nm
- Works with both SASE and external seeded input (multi-MW class)
- Contrast extremely good --- output is redshifted by 2% or more -> spectral filtering will give more contrast
- Interesting wavelength chirp over ultrashort pulse
- Both shift and chirp are adjustable (including sign)
- Easy to make a pulse train with uniform separation

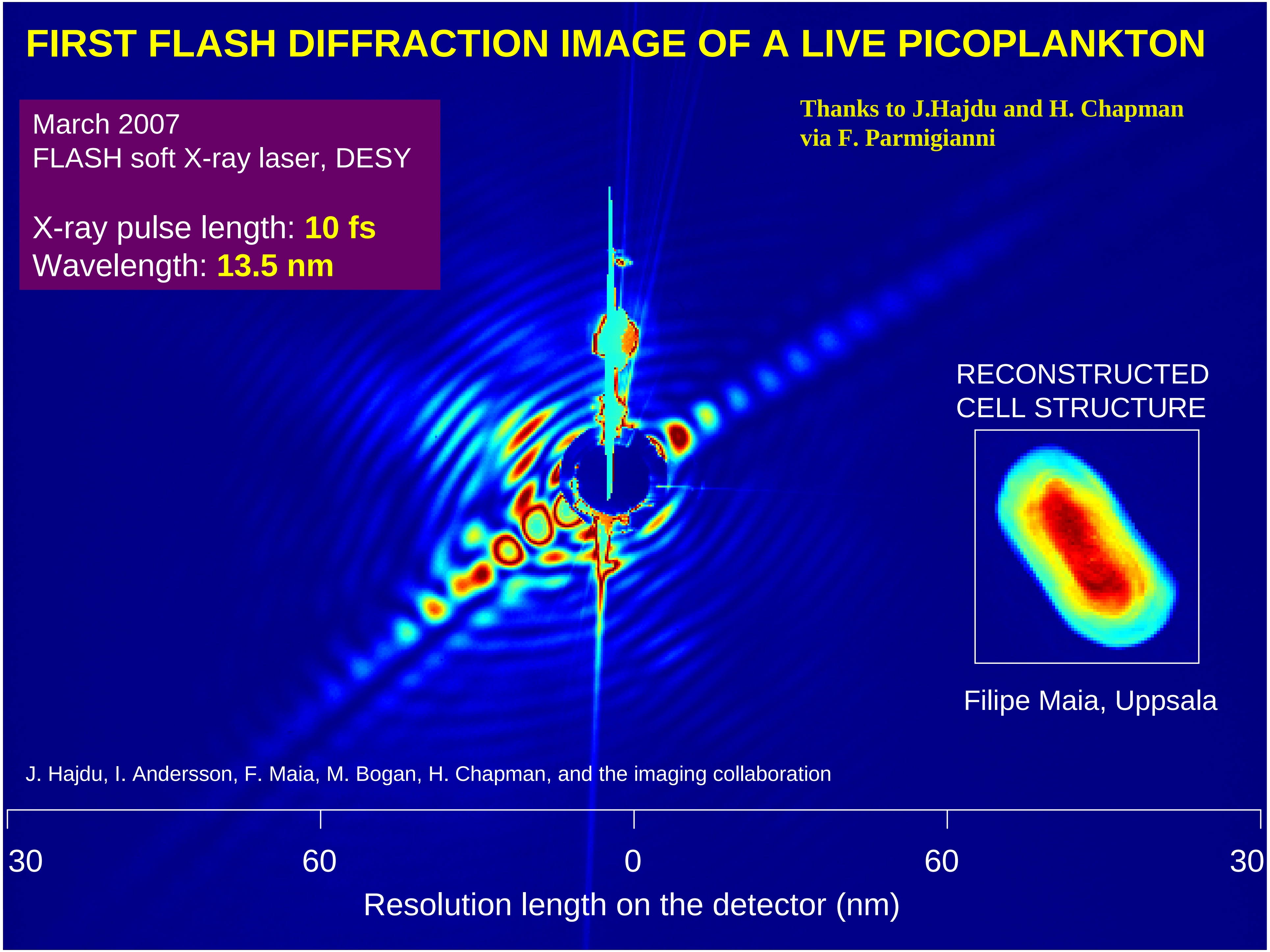
The Usefulness of XUV/Soft X-ray Short Pulses

- Proclaiming the usefulness of short pulses for many applications is like praising apple pie and motherhood

  Nonetheless, some examples include:

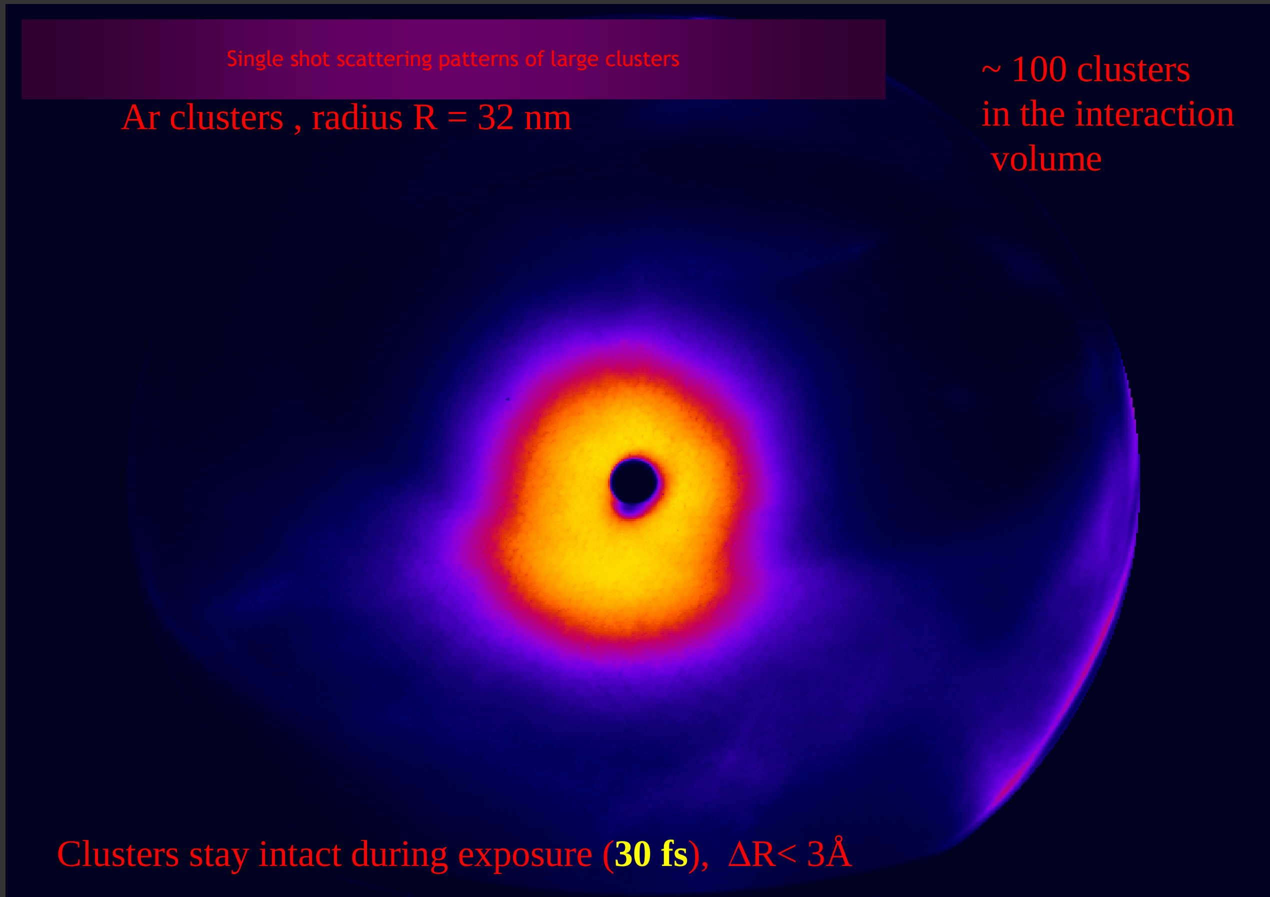
- Coherent XUV imaging --- works better at 2 fs than 15 fs (less hydro expansion)
- Time-domain dynamics of inner shell e- (absorption, fluorescence, Auger processes) of Co, Mn, Fe at 1-keV
- Pump-probe investigations of materials with “long” timescales (> 1 fs) (but still short relative to 100 fs)
- Time-resolved studies of the dynamics and reaction rates of chemical radicals

Thanks to F. Parmigianni


FIRST FLASH DIFFRACTION IMAGE OF A LIVE PICOPLANKTON
March 2007
FLASH soft X-ray laser, DESY
X-ray pulse length: 10 fs
Wavelength: 13.5 nm
Thanks to J.Hajdu and H. Chapman
via F. Parmigianni
RECONSTRUCTED
CELL STRUCTURE
Filipe Maia, Uppsala
J. Hajdu, I. Andersson, F. Maia, M. Bogan, H. Chapman, and the imaging collaboration
30
60
0
60
30
Resolution length on the detector (nm)

Ultrafast processes and imaging of gas phase clusters and nanoparticles

Spokespersons: **T. Möller, C. Bostedt (TU-Berlin)**
Co-proponents: P. Milani, University of MilanoJ.
Hajdu, University of Stanford and University of Uppsala H.N. Chapman, LLNL, Livermore



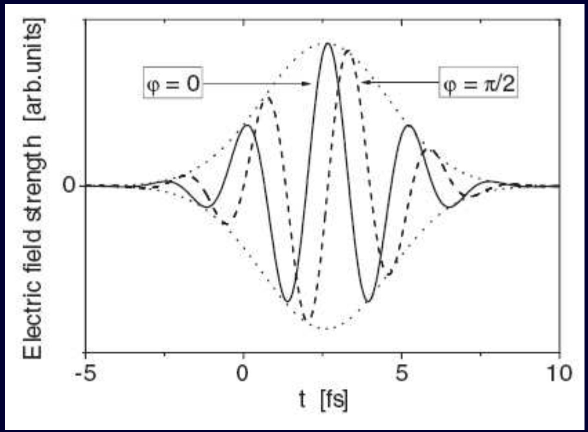
February 2006

Courtesy F. Parmigianni, U. Trieste & FERMI

Many Short Pulse FEL Schemes rely upon Rapid $\gamma(t)$ Variation

- **As A. Zholents explained in his talk on Tuesday, there are numerous schemes to exploit the high power and short duration of few cycle, intense optical pulses via interaction with an e-beam in a short undulator (e.g., energy modulation, tilt modulation)**

- **Saldin, Yurkov, and Schneidmuller** (PRSTAB **9**, 050702 (2006)) **published a particularly clever scheme to use both $\gamma(t)$ variation together with "reverse" undulator tapering to produce "attosecond" duration pulses in the hard x-ray regime**



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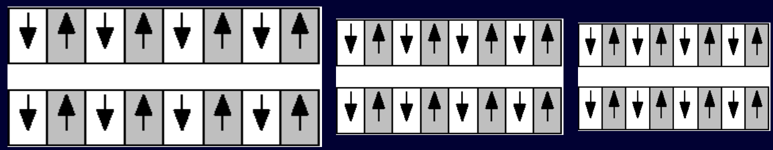


Saldin *et al.* reverse taper scheme applied to SASE XFEL

l time). The energy chirp parameter

$$\hat{\alpha} = -\frac{d\gamma}{dt}\frac{1}{\gamma_0\omega_0\rho^2}$$

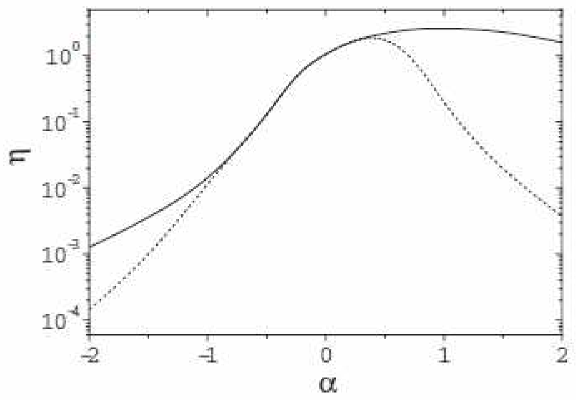


FIG. 2. Normalized output power versus parameter $\hat{\alpha}$. Solid: $\hat{z} = \hat{z}_{sat}(\hat{\alpha})$ (see Fig. 1); dashed: $\hat{z} = \hat{z}_{sat}(0) = 13$.

Note asymmetry w.r.t. α for power at z/L_G=13 with negative *dγ/dt* giving more power and max P at α =+0.2

Previously found by H.-D. Nuhn and rediscovered/explained by Huang and Stupakov

Layout & Components

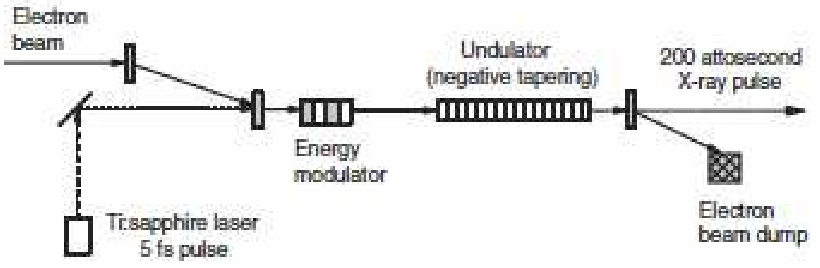


FIG. 4. Schematic diagram of the attosecond x-ray source. The energy modulator performs slice energy modulation of the electron bunch (see Fig. 6). The undulator tapering leads to complete suppression of the amplification process in the largest fraction of the electron bunch, and the output x-ray pulse has 200 attosecond pulse duration.

Saldin et al. Results @ 0.15 nm

XFEL: 12 kA, 15 GeV, 1 MeV σ_E, 1.4 mm-mrad, λ_w=3.65 cm

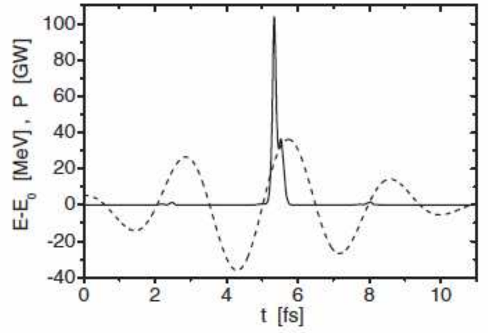


FIG. 6. Energy modulation of the electron beam at the exit of the modulator undulator (dotted line) and a profile of the radiation pulse at the undulator length 100 m.

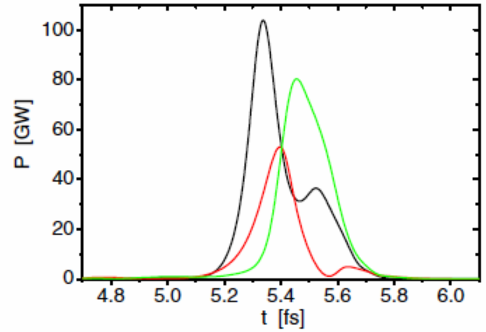


FIG. 7. (Color) Temporal structure of the radiation pulse (three different shots) at the undulator length 100 m.

Underlying Principles of Scheme

- FEL gain curve narrow at a given ω: $\Delta\gamma/\gamma \sim \rho$
- If γ (or a_w) vary too rapidly with z, gain can be suppressed
  - A slight positive $d\gamma_R/dz$ (*e.g.*, from wakefields) can enhance SASE gain (Nuhn, Huang & Stupakov, Saldin et al.)
  - External energy losses (e.g., wakefields, spontaneous emission) can be balanced by a negative $d\,a_w / dz$

- As seen by a radiation "spike", slippage converts a z-derivative in undulator property to a time-derivative of the properties of the e-beam gain media

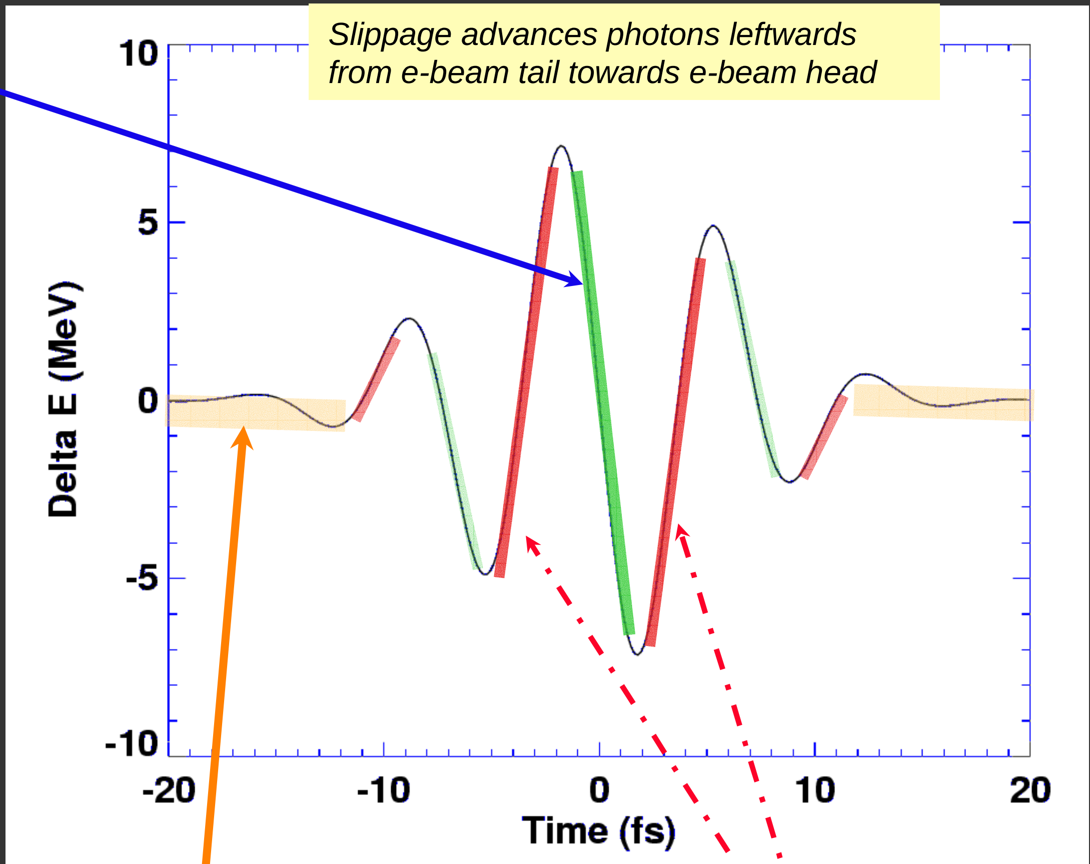
- "Upstream" energy modulation by a few cycle optical laser can create a very large $d\gamma/dt$ locally in time

- Balancing local $\frac{d\gamma}{dt} \times (c - v_{beam})$ by proper $d\,a_w / dz$ maximizes gain locally in t; condition is $\frac{d \ln a_w}{dz} = \frac{1}{c}\frac{d \ln \gamma}{dt}\left(\frac{1+a_w^2}{a_w^2}\right)\frac{\lambda_s}{\lambda_w}$

Only a small portion of e-beam has the correct energy chirp

Good $d\gamma/dt$ match to $+dK/dz$ taper, very strong gain

- Normalized width of FEL gain curve in γ is ~ $\rho\gamma$
- ρ typically 1-2 $\times$ 10^{-3}
- Change with z of resonant γ by ~0.5 $\rho\gamma$ in one gain length strongly suppresses gain
- Gain suppression (absorption at some *t*) is somewhat antisymmetric: best either if actual γ is reduced with z via external field ***OR*** *K* (and thus γ_R) is increased with *z*



No match to taper, little gain, some absorption

Completely unmatched to $+dK/dz$ taper, strong absorption

E-beam, Optical Laser, Undulator Parameters

- E-beam: 2 GeV, 1 kA, matched β=4 m, σ_E=200 keV, ε=0.5 mm-mrad
  (parameters used in LBNL future light source investigations)
  (low emittance really only needed for shortest λ_S)
  - r_b ~ 30 microns; FEL ρ ~ 2.9E-3 for λ_S = 8 nm

- After some empirical investigation,
  - chose λ_{opt}=2200 nm (helps increase gain by decreasing slippage relative to λ=800 nm possibility)
  - ΔE_{opt} modulation = $\pm$ 7.5 MeV
  - for λ_S = 8nm and λ_w =30 mm, a_w = 2.7 (linear polarization)
  - found "best" undulator taper was 3.5% / 10-m (*simple linear*); balance condition would predict 3.25% / 10-m

- To keep a_w and taper rate constant with λ_S , scaled $\lambda_w \propto \lambda_S$
  - this also keeps slippage rate (*e.g.*, fs/m) and req. ΔE_{opt} constant

- Time-dependent GINGER simulations (2 1/2 D + *t*)
  - Simulation window typical 5 to 9 $\times$ λ_{opt}
  - Temporal resolution ~ 60 to 100 attoseconds

Output power vs. E_modulation

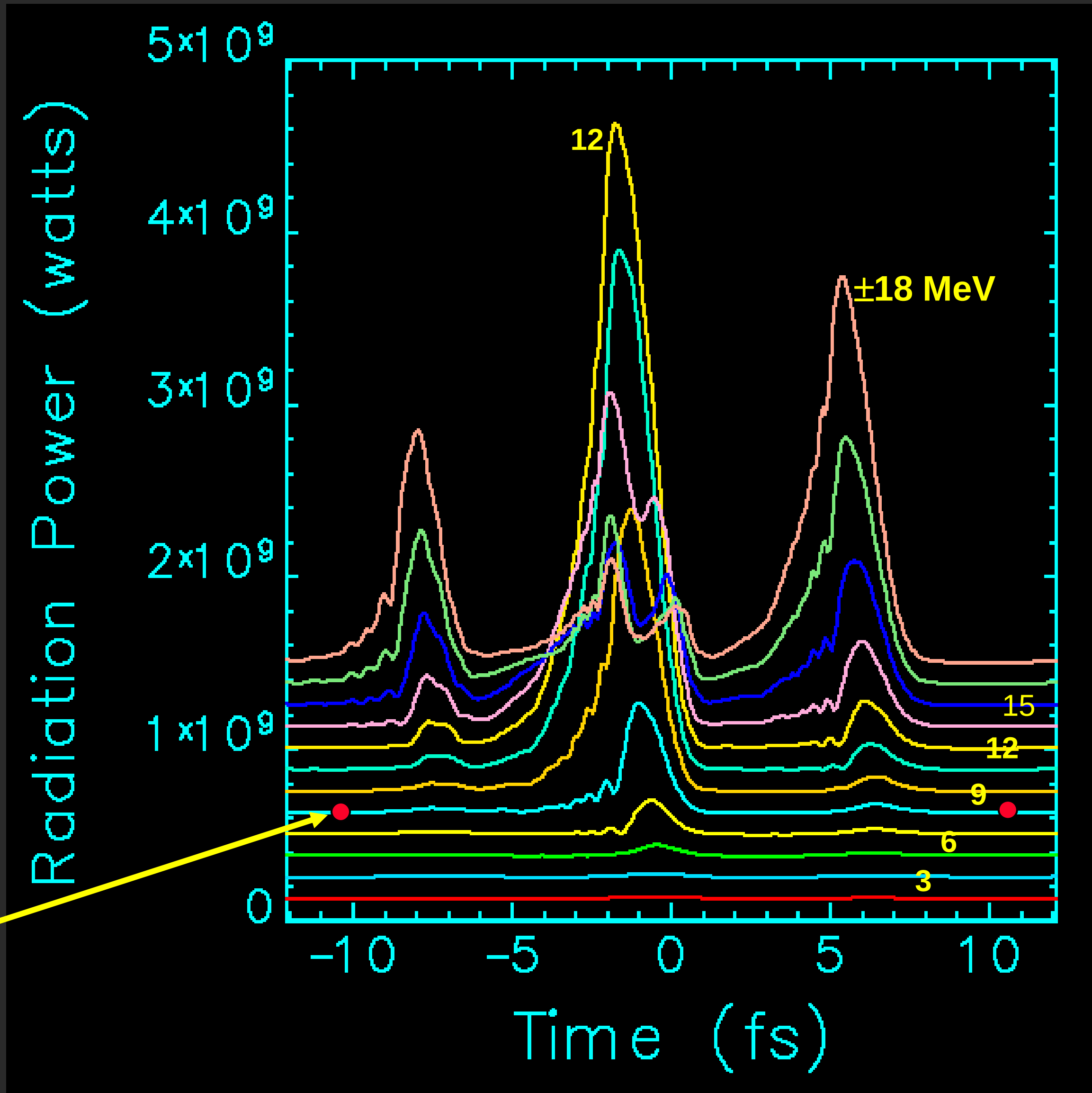
8-nm seeding; 5 MW input
E_{MOD} scanned from 1.5 to 18 MeV in steps of 1.5 MeV

Curves staggered 0.33 GW

Peak output in central spike occurs at E_{MOD} ~ 12 MeV

(but note that contrast not as good as 7.5 or 9 MeV curves)

Design point 7.5 MeV

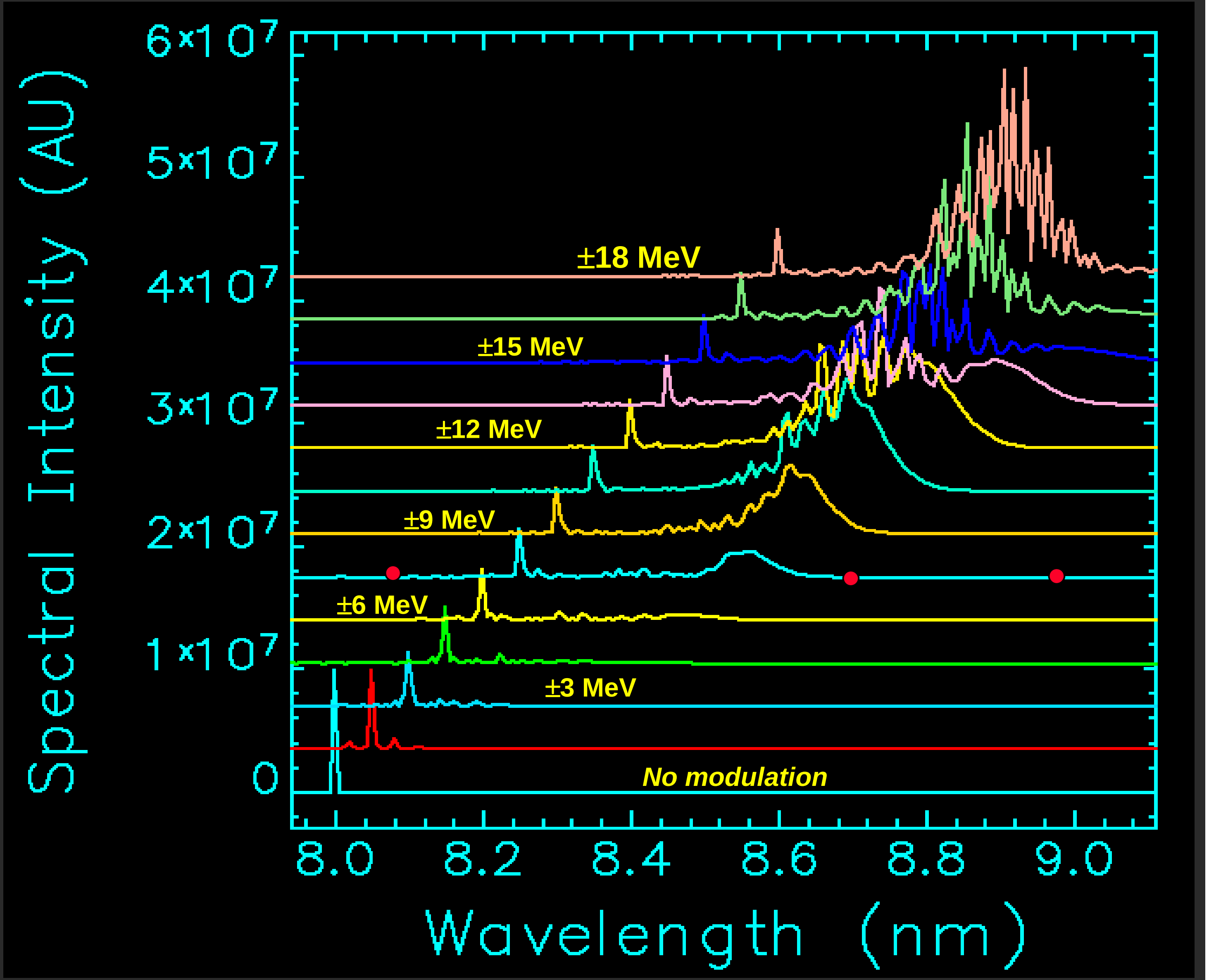


Output Spectra vs. E_mod (seeded at 8 nm)

Near-field spectra

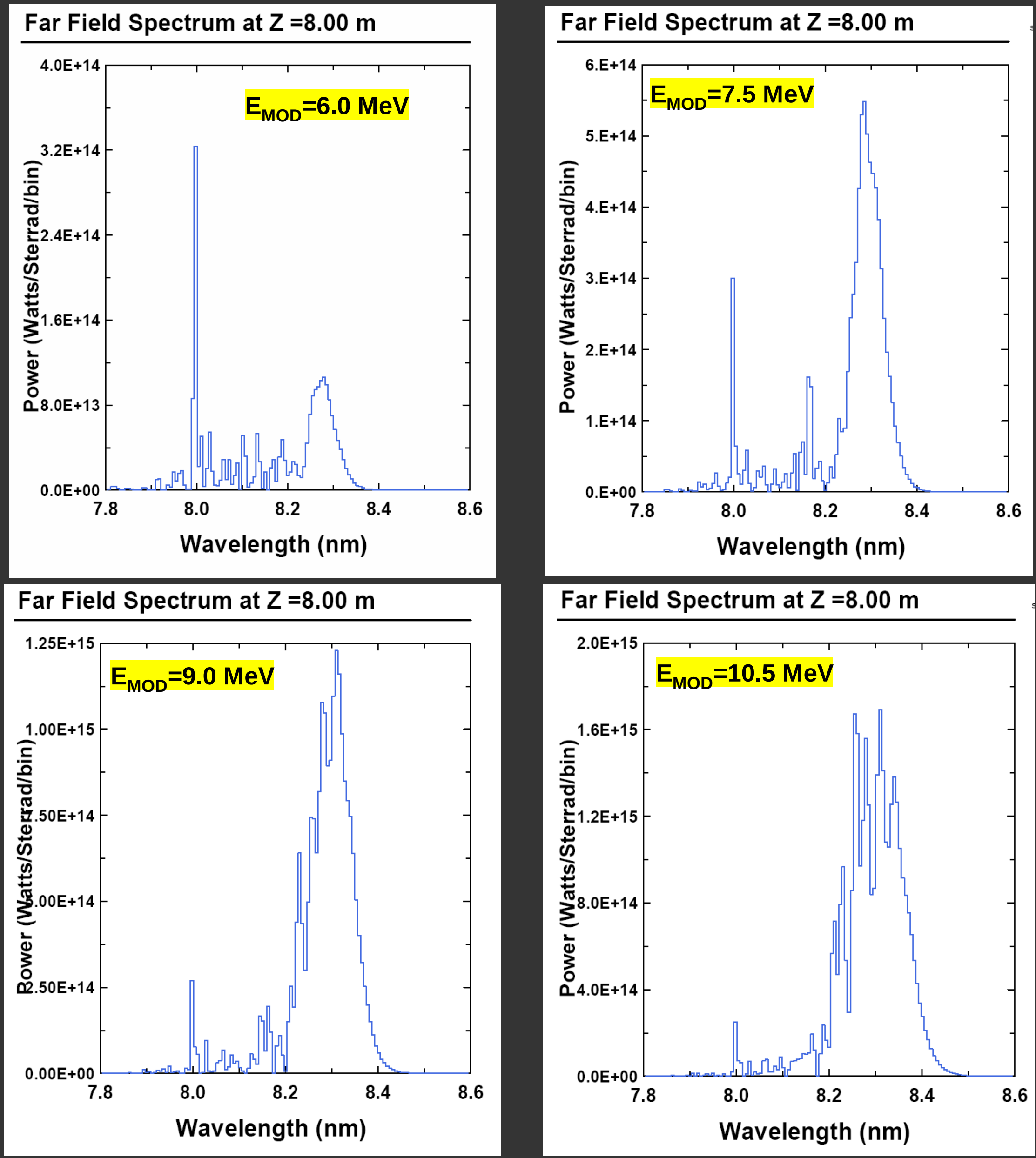
Note that curves with E_{MOD} > 9 MeV have much wider bandwidths; more spiky behavior

Design point chosen to be **7.5 MeV**



Far-field Spectra vs E_{MOD} ; 8 nm Seeding

Far-field spectra indicate that optimization of contrast *AND* peak power suggests working design point of 7.5 MeV

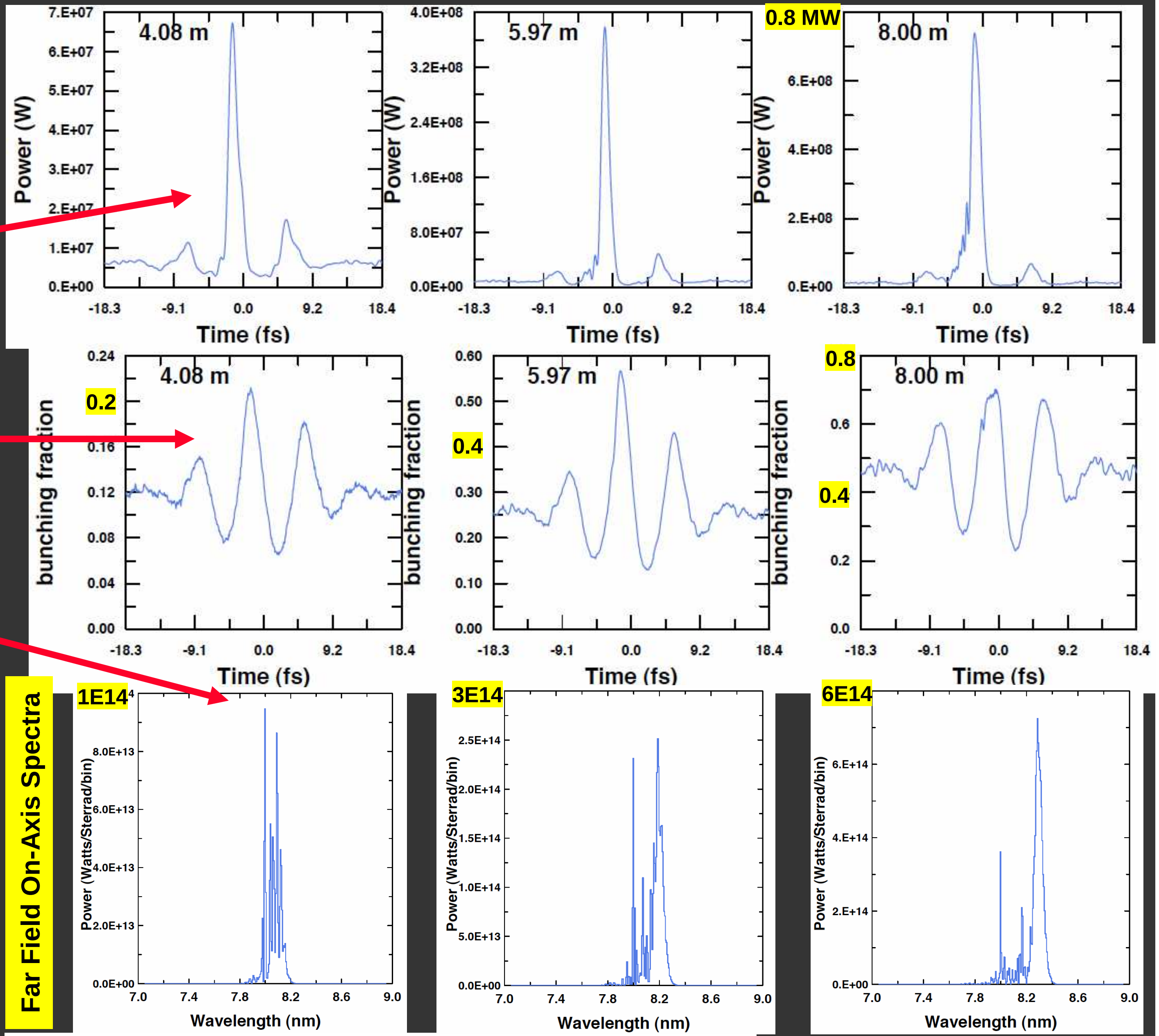


8-nm Case with Ext. Seed: Power, Bunching, Spectra Snapshots

Note that contrast in P(t) increases with z;

Bunching fraction reaches relatively high values nearly everywhere in time;

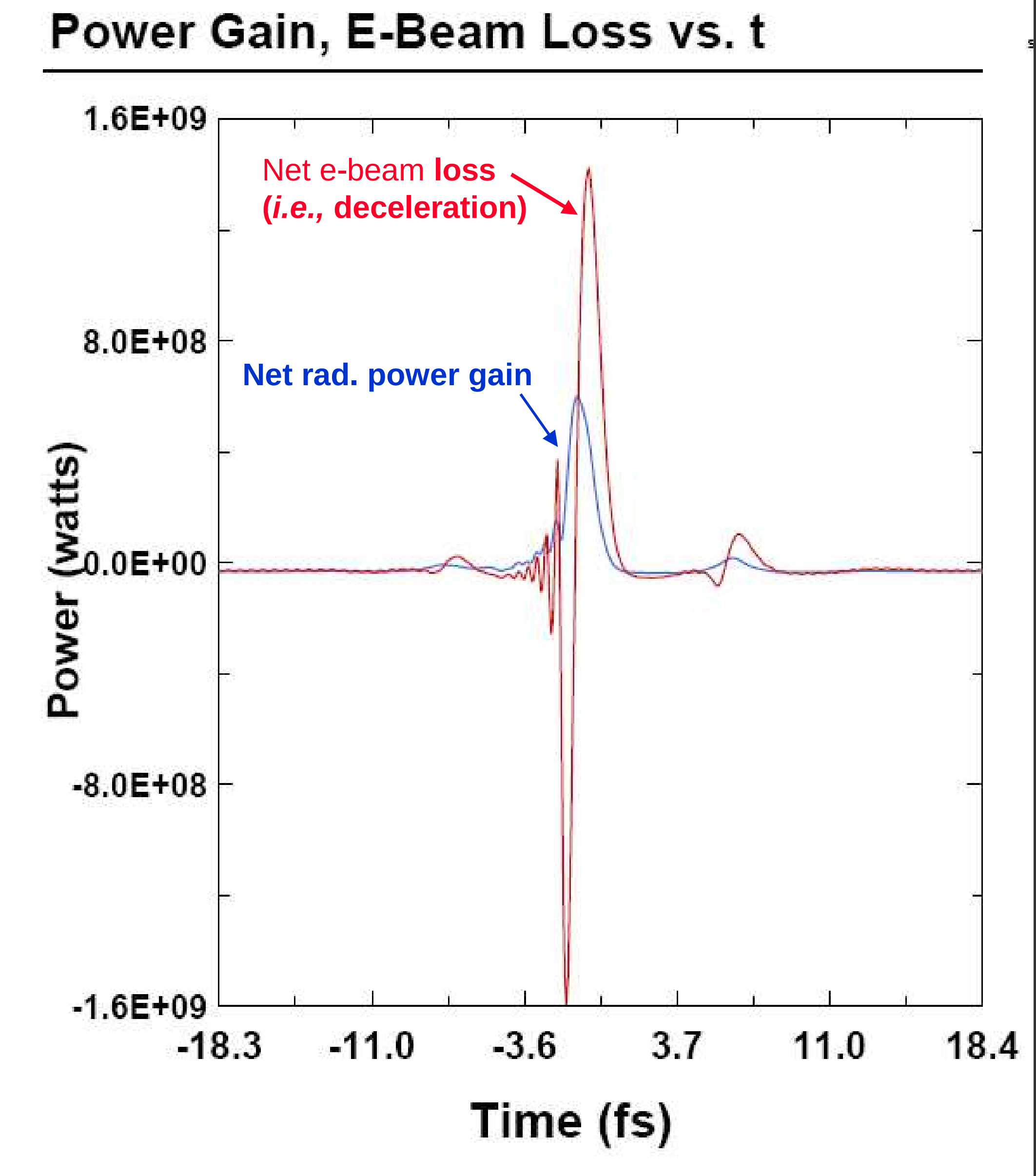
Far field spectrum cleans up with z, moves redward



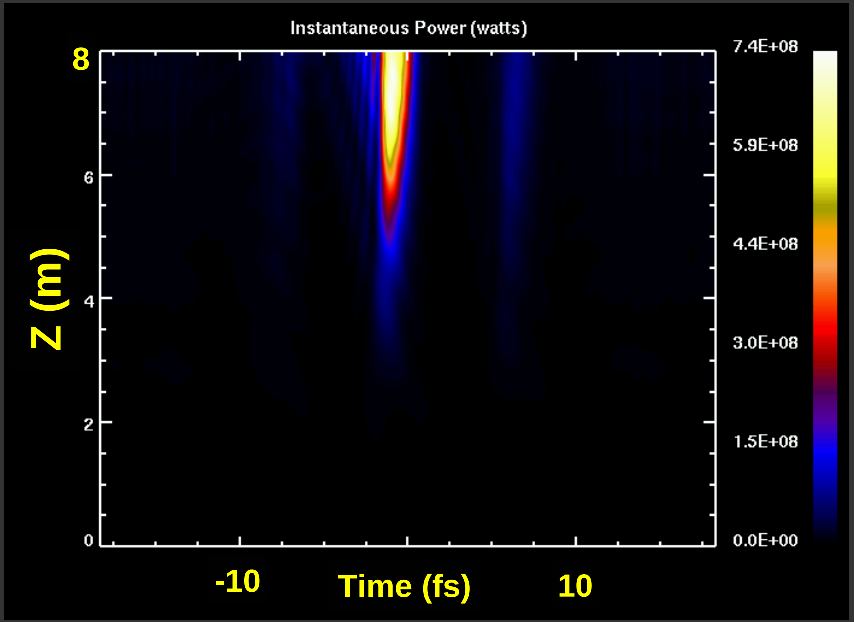
E-beam energy loss, gain t-dependence

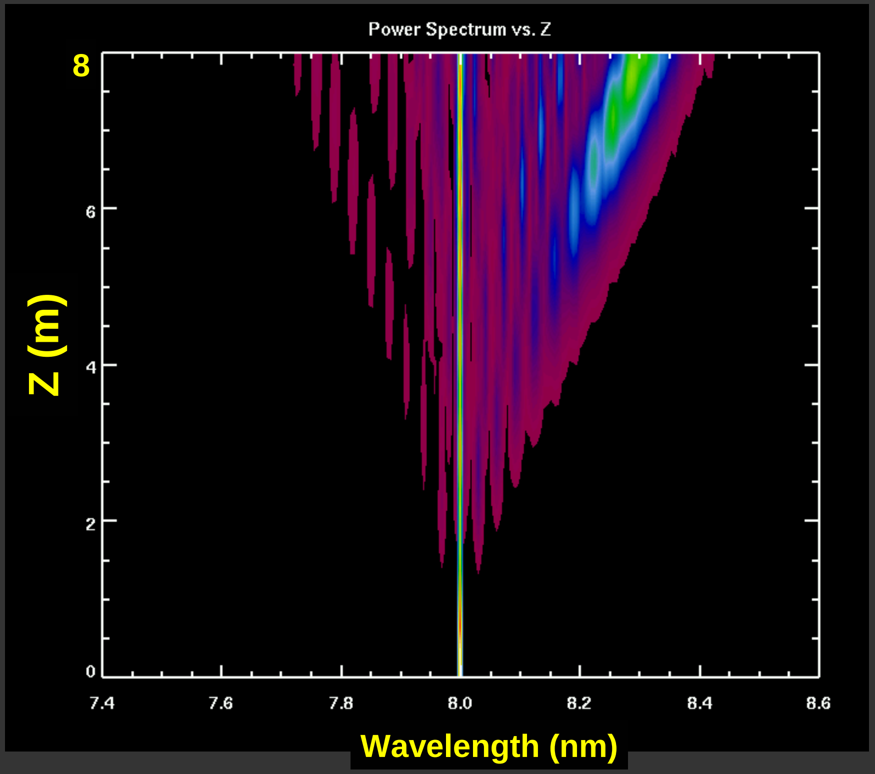
Net radiation power gain is quite smooth with only small amplitude ripples

Net e-beam loss shows extreme oscillations, with large losses at largest negative values of $d\gamma/dt$ and net acceleration at positive $d\gamma/dt$

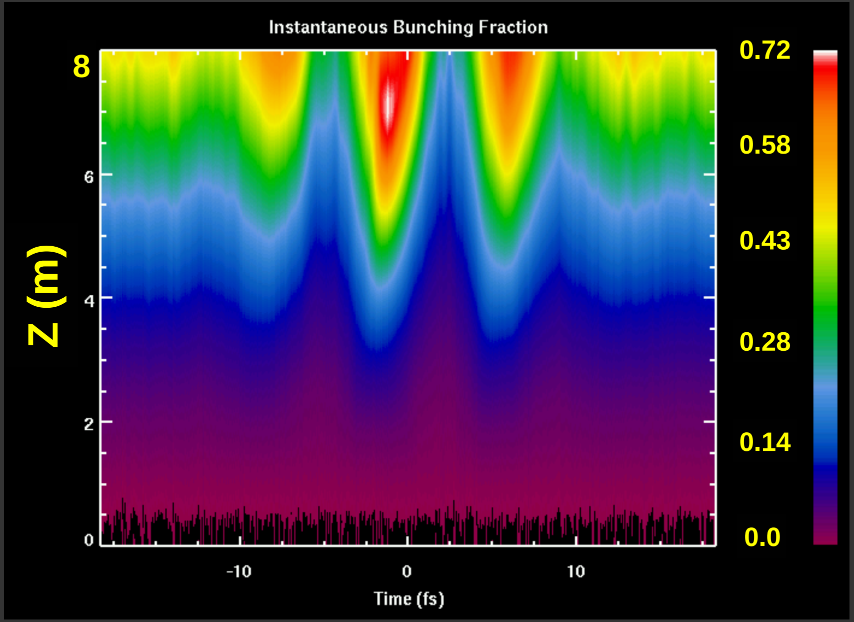


8-nm Seeded Case: Power, Bunching, Spectrum vs. Z





Near-field spectrum



Wigner Transforms of On-axis, Far-Field E: 8-nm Seeded Case

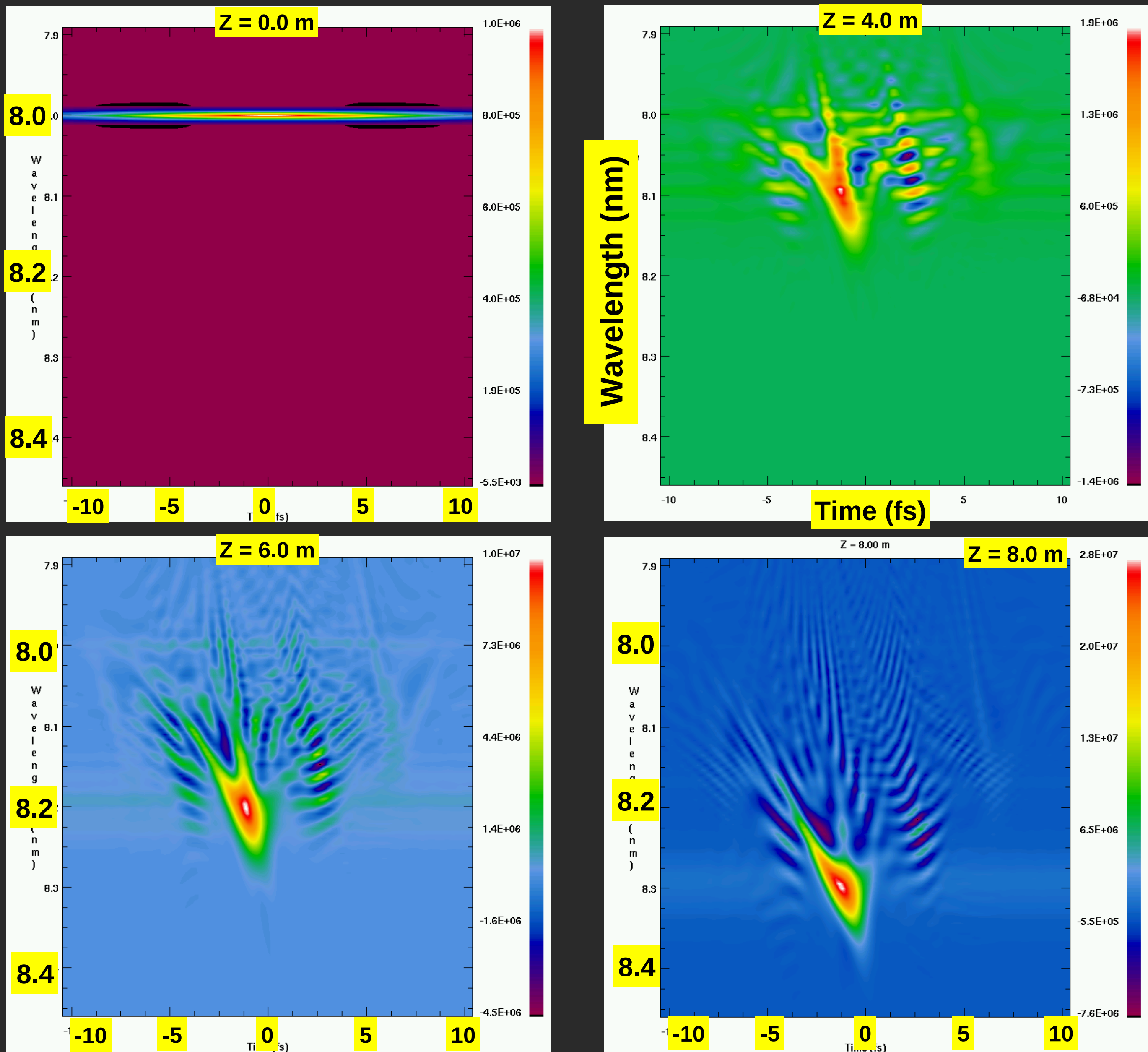
Wigner transform $W(t,\omega)$ of the *complex* electric field can give a 2-dimensional map of intensity as function of time and frequency -- essentially this is the longitudinal phase space of the radiation.

1-D projections give $P(t)$, $P(\omega)$.

As do "FROG" experimental measurements, $W(t,\omega)$ can show underlying frequency chirps and t- ω correlations.

By the end of the simulation at z=8 m, emission peak has shifted redwards to 8.3 nm from the original seed wavelength of 8.0 nm. There is a positive chirp which agrees quantitatively with the value .05 nm/fs predicted by the $d\gamma/dt$ modulation.

In these plots, time is measured relative to a frame moving at the speed of the e-beam; interaction effects lock radiation peak with e-beam modulation
(*i.e.*, $v_{group} = v_{e\text{-}beam}$)



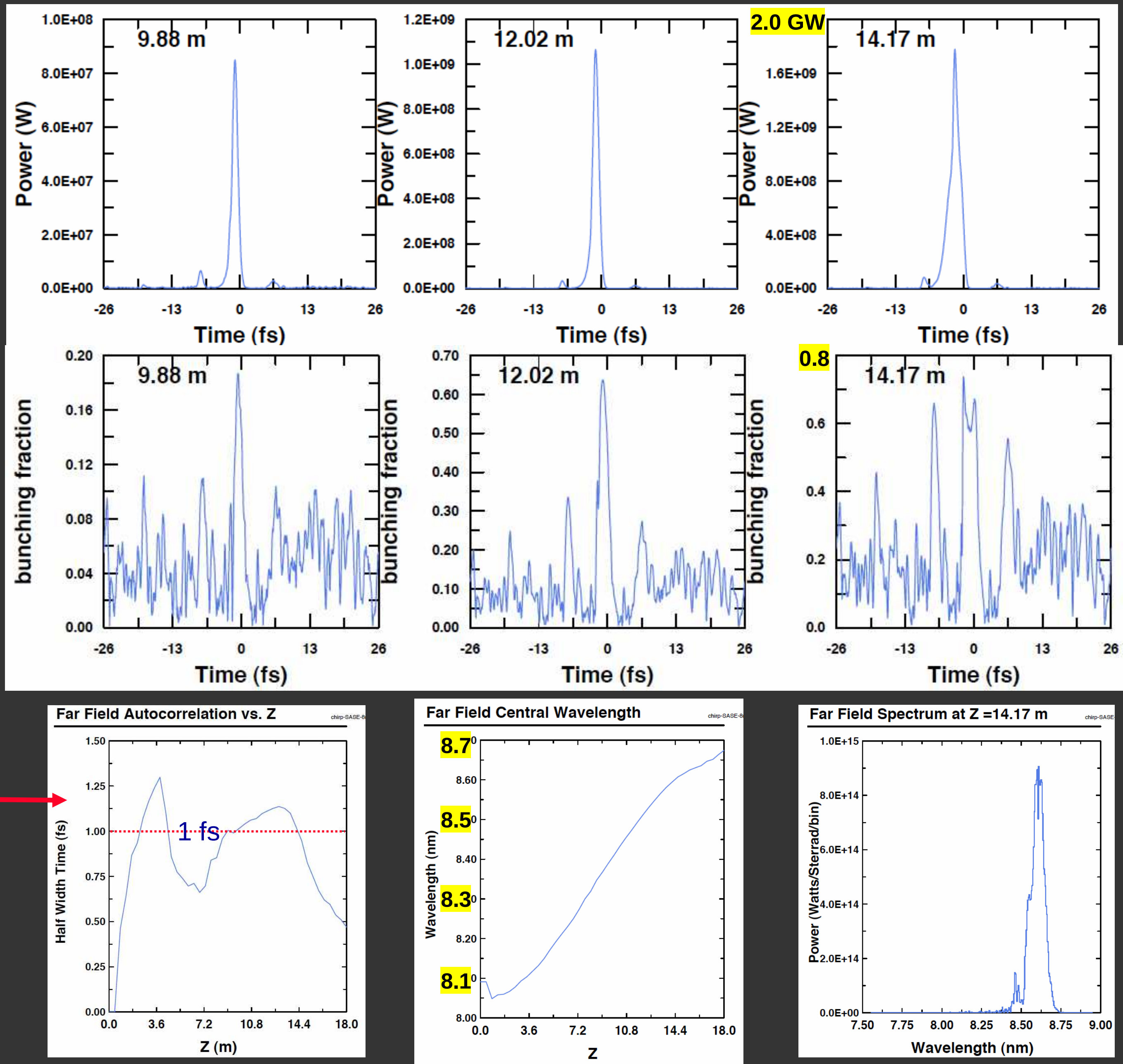
Movie of W(t,λ) for 8-nm seeded bunching, far field…

Wigner transform of complex bunching

Wigner transform of far-field, on-axis E

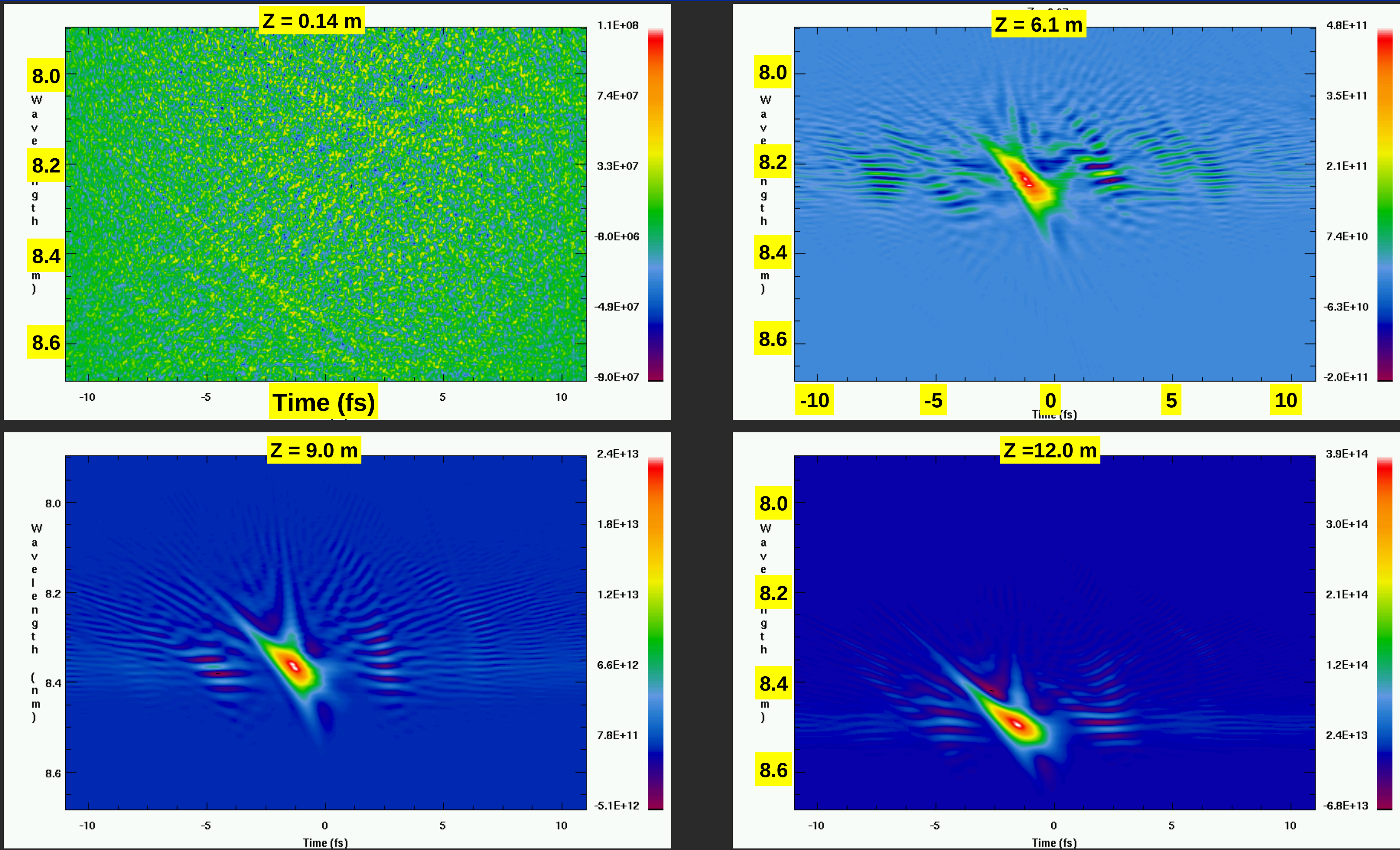
QuickTime™ and a
H.264 decompressor
are needed to see this picture.

8-nm SASE-initiated case – snaphots, etc.



Autocorrelation $C_{1/2}(t)$ of far-field, on-axis E; "half-power" point; Indicative of inverse spectral bandwidth (but can be decreased by underlying chirp)

Wigner Transforms of E_{FF} for 8-nm, SASE-initiated case

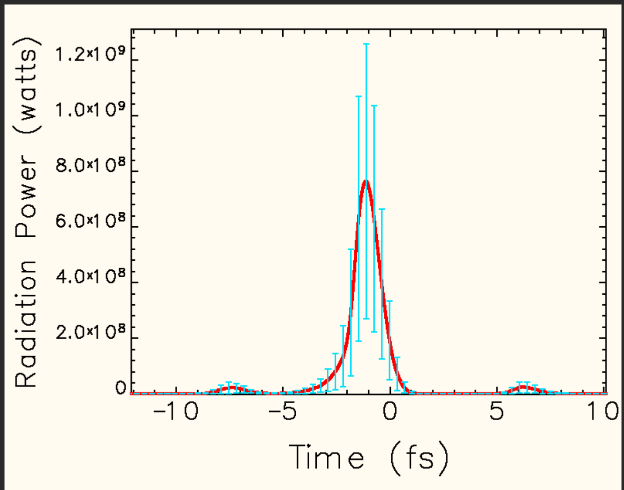


Wigner transform of on-axis far field for SASE-initiated case with a reverse taper. E-beam and undulator parameters are the same as the 8-nm seeded case. Peak instantaneous power ~1.0 GW at z=12 m.

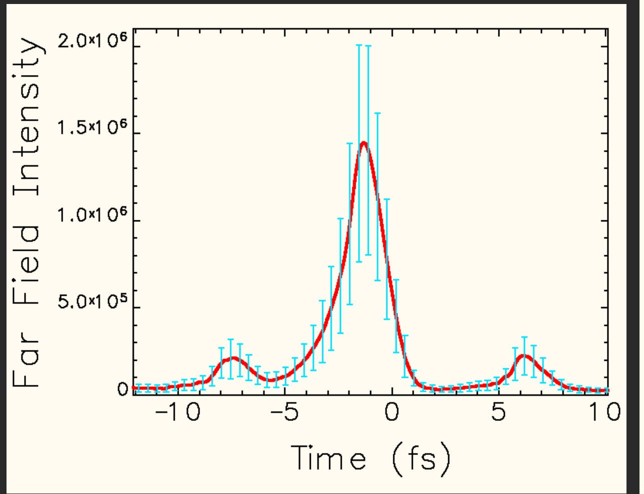
Pulse Shape, Spectra Statistics for 8-nm SASE output

- 64 GINGER runs, identical except for different random number seeds used to initiate shot noise
- SDDS toolkit used to determine RMS statistics of output variations
- Ensemble averages quite smooth;
  - large shot-to-shot variations ($\sigma_P(t)$ / <P(t)> ~ 1)
  - jitter in pulse center-of-mass in (t, λ) < (0.5 fs, 0.05 nm)
  - Near-field *P(t)* has shorter duration in main spike, better contrast, but more amplitude jitter

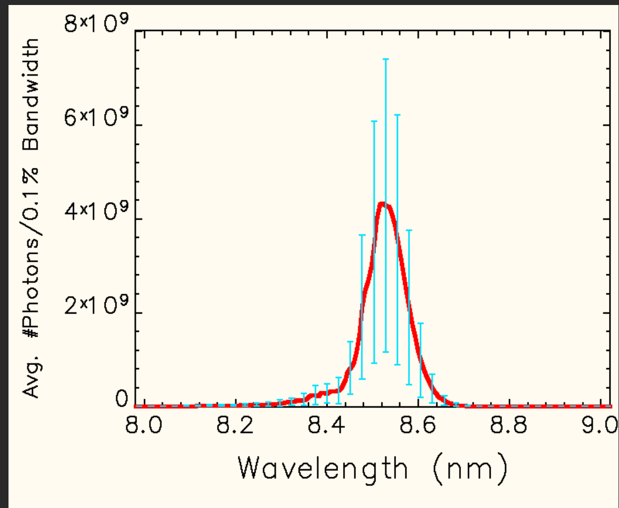
Near-field Power



Far-field Power

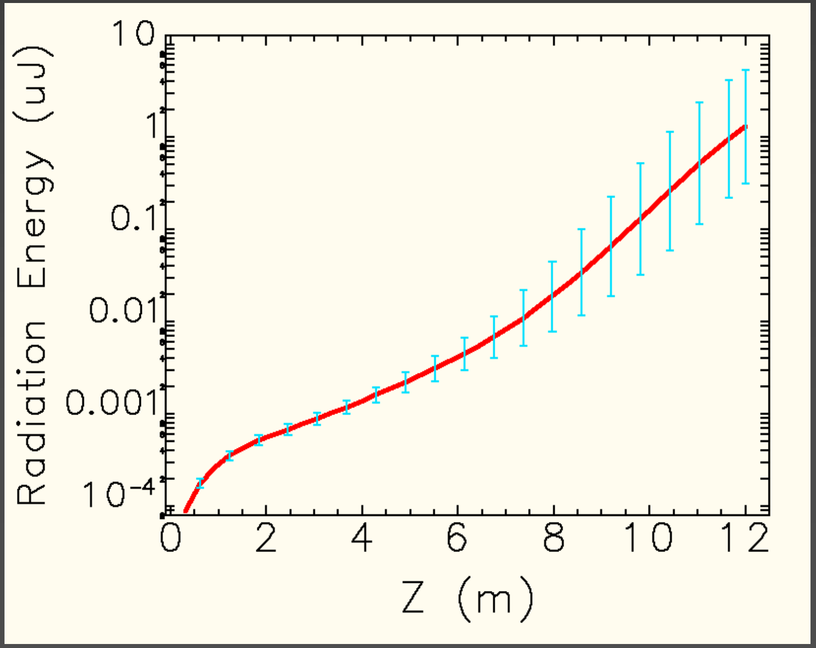


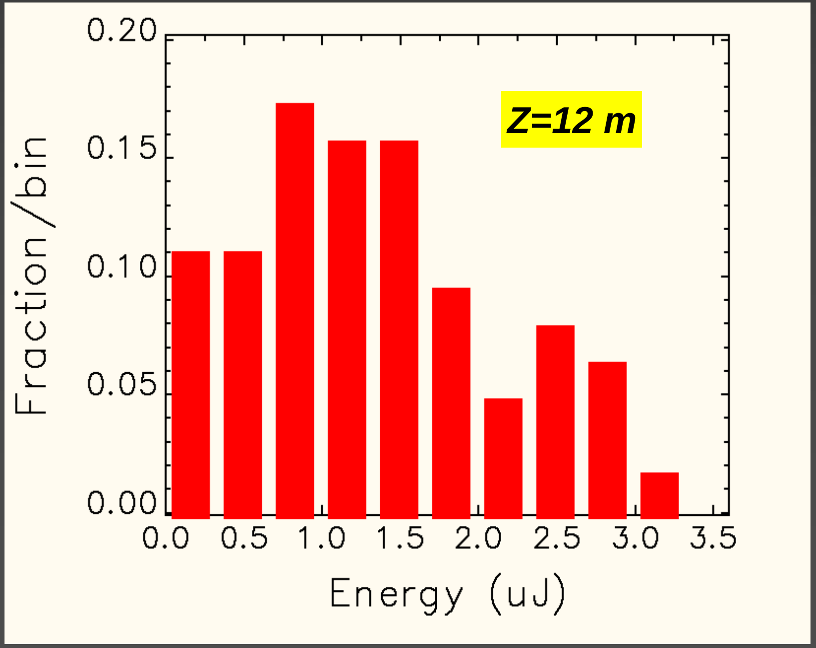
Near-field Spectra



Radiation Energy Statistics for 8-nm SASE radiation

- Same 64 SASE runs as previous slide
- Time-integrated total energy and RMS deviations show definite exponential increase with *z*
- Histogram distribution at 12-m output shows (perhaps) ~negative exponential *BUT* maximum does *not* occur at *E=0* (as would be true if output was due to one longitudinal mode) --- behavior more similar to short pulse case of Bonifacio *et al*. (PRL '96)



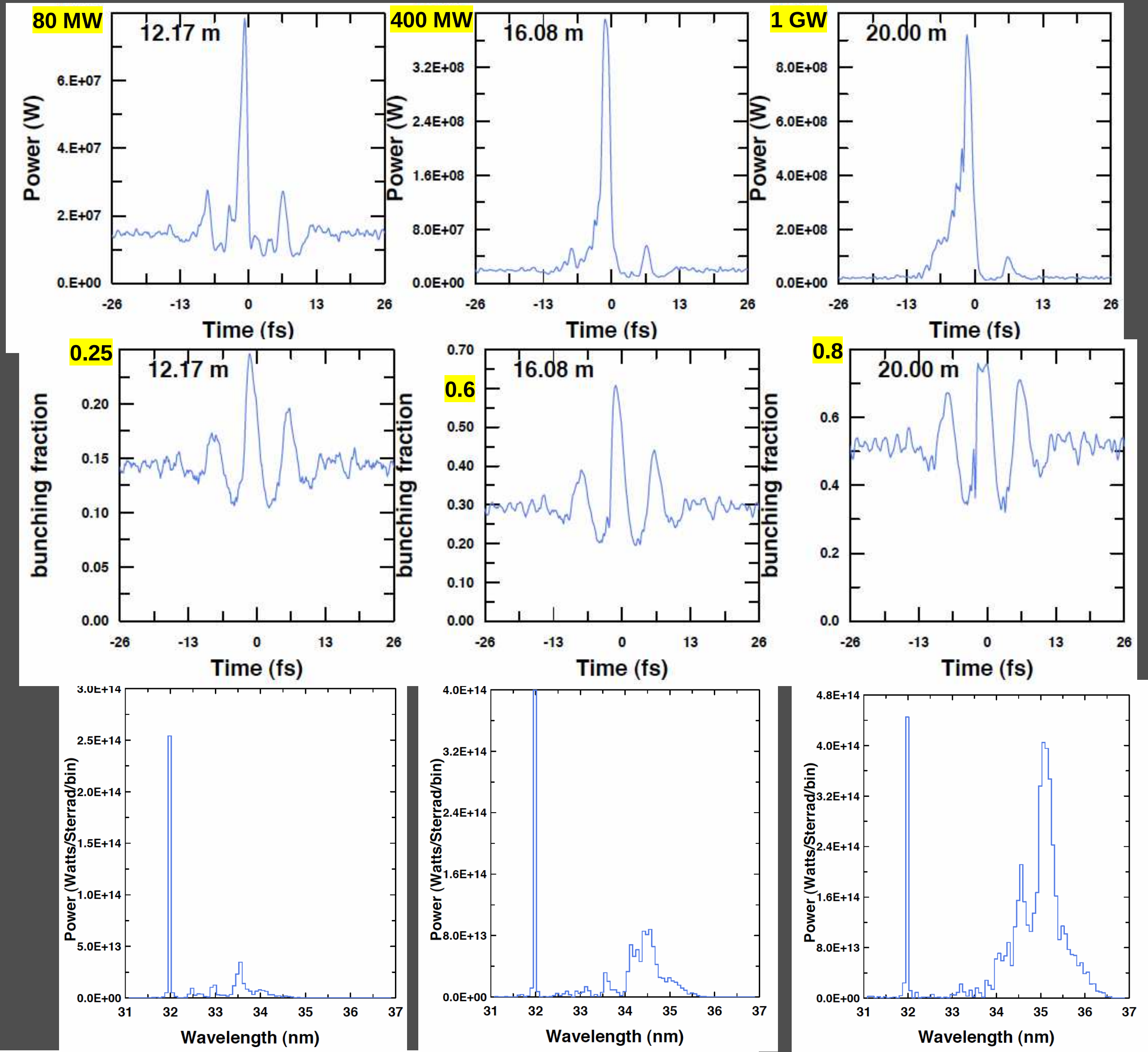


32-nm Seeded Output Diagnostics

P_{IN} = 10 MW
λ_W = 12 cm

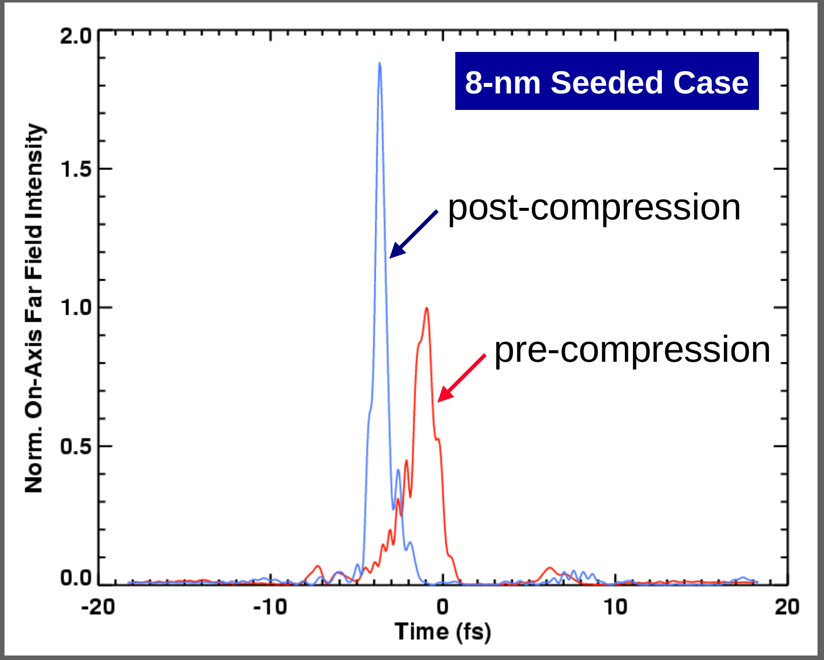
Same E_{MOD} and 3.5% positive taper in K as in 8-nm case

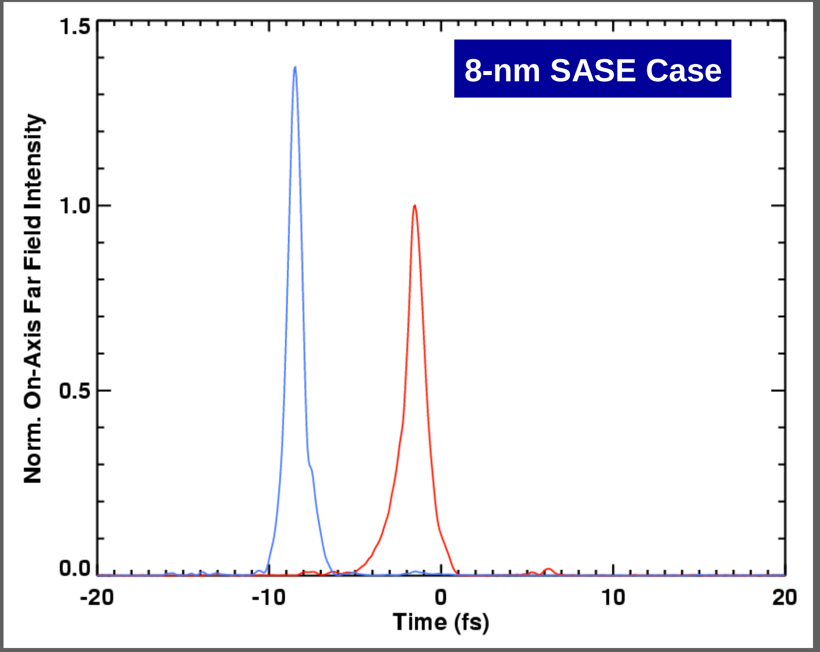
Peak power at 16 m ~400 MW in a FWHM spike of 2.5 fs or less



Chirp allows Temporal Pulse Compression

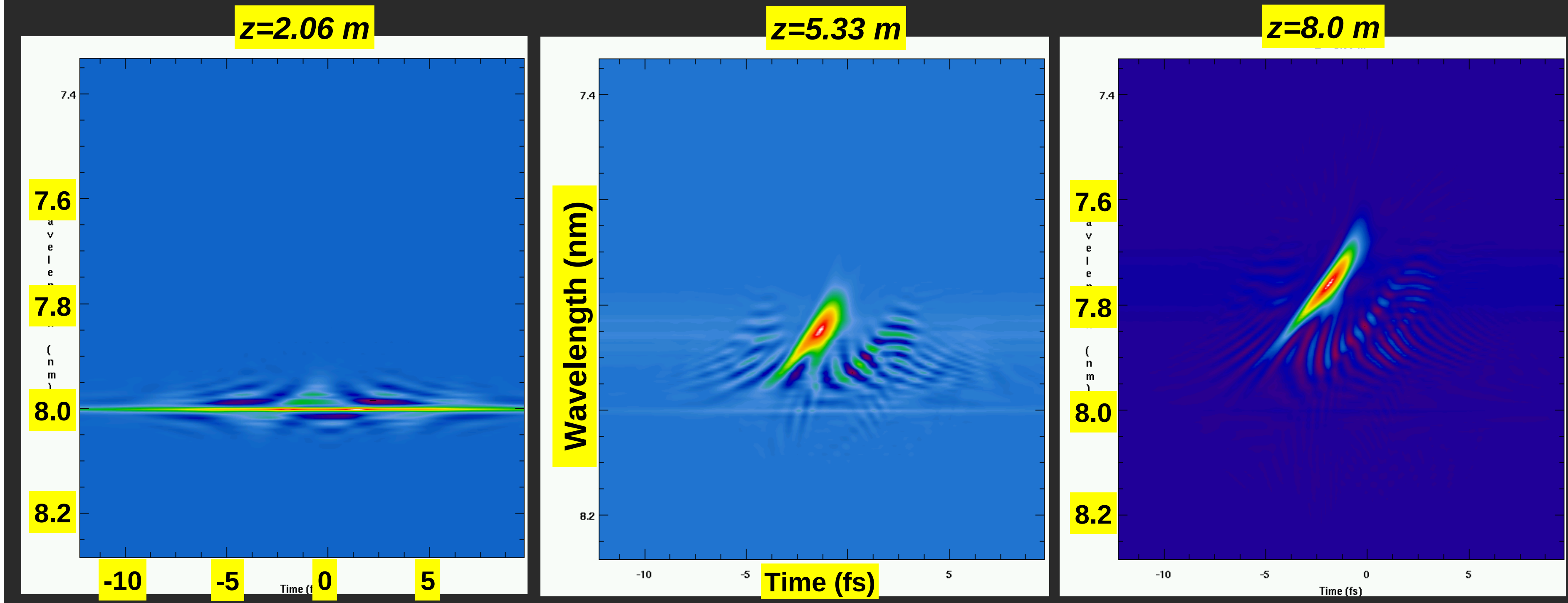
- Output chirp in ($d\lambda/dt$) implies that one can use standard pulse compression techniques to reduce σ_τ
- For seeded case, one can reduce FWHM to < 1.5 fs (nearly 2X); less compression possible in SASE case shown to right





Is it Possible to Control the Shift and Chirp --- Yes!

- The combination of "negative" taper and negative $d\gamma/dt$ produces a positive $d\lambda/dt$ (and a net redshift)
- Reversing dK/dz to ***negative*** and $d\gamma/dt$ to **positive** values gives a negative wavelength chirp (**and a net blueshift**)
- Example below is seeded with 8 nm, optical few-cycle laser phase shifted by π, and dK/dz = -3.2% / 10 m



SUMMARY

- Saldin *et al.* “reverse taper” scheme for production of ultrashort pulses scales well to soft x-ray and XUV wavelength regime
- Both SASE and seeded mode work well with GW-level peak powers possible for 1-kA, 1-2 GeV e-beams
- The inherent evolution of $\overline{\lambda}(z)$ suggests that extremely good contrast ratios should be obtainable by a “wide-jaw” spectrometer
- Underlying temporal wavelength chirp permits post-undulator pulse compression of fs-duration spike
- Users can exploit (likely) tunability of chirp and the (relative) ease of temporal synchronization
- By substituting a “many” cycle optical pulse for the “few-cycle” variant, one can produce a pulse train of spikes with uniform temporal separation
  - An underlying “slow” $\gamma(t)$ variation in SASE mode might allow the spikes to be separated in time AND central wavelength (related to energy-chirped SASE idea of Pellegrini, Schroeder, *etc.* of a few years ago)

Some additional observations…

- 20 years Dawson and co-workers published a paper on the use of a temporally-changing optical media to change the wavelengths of a propagating light beam --- the so-called "photon accelerator"
  (Wilks *et al*., PRL, 62, 2600 (1989))
- The e-beam in an FEL (together with the undulator) ***IS*** the effective optical medium
  - slippage allows the FEL radiation to sample time-dependent properties of a small portion of the e-beam
  - => monochromatic waves can have their $\lambda(t)$ properties modified
- To me at least, it seems that in the 2nd quarter-century of FEL theory and experiment we really can start massaging the temporal properties of FEL light in the complex plane via clever manipulations of e-beams, undulators, seed lasers, *etc*., to obtain output pulse properties matched to user desires