PAUL SCHERRER INSTITUT


Sven Reiche :: Paul Scherrer Institut

# Schemes for Large Bandwidth Pulses

NOCE 2017 - Arcidosso

# Outline

- Manipulating the energy chirp of electron bunch
  - Over-Compression
  - Wakes
  - Laser Shaping
  - LSC

- Using a Transverse Gradient Undulator (TGU)

- Spectral Broadening due to short pulses

# The Basic Knobs to Generate Frequency Spread

- **FEL Resonance Condition:**

*Global* ☹

*Can vary if beam is tilted*

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

*Can be spread by short coherence time*

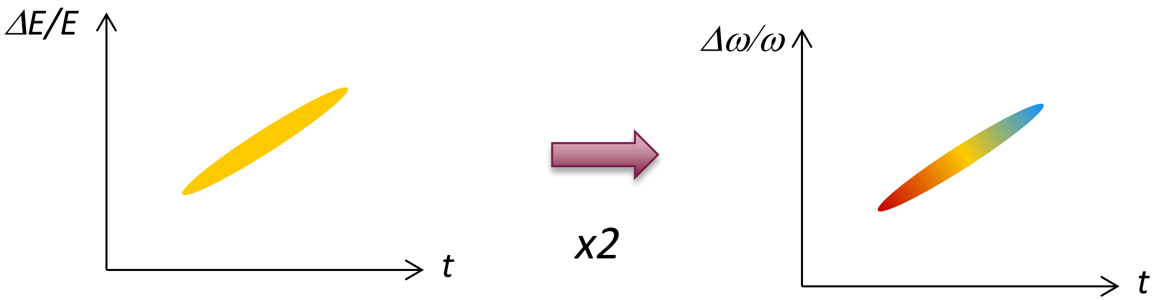
*Can vary within bunch*

**… while providing FEL like power levels**

*(excluding incoherent undulator radiation, large variation in undulator field etc.)*

# Methode 1: Energy Chirp

- If bunch length is longer than cooperation length, a correlated energy chirp in electron beam is transferred into a chirp in FEL pulse




- From resonance condition the effective chirped is doubled: $\frac{\Delta\omega}{\omega} = 2\frac{\Delta E}{E}$

- To amplify till saturation, the local SASE spike is not allowed to slip onto electrons outside of the resonance condition:

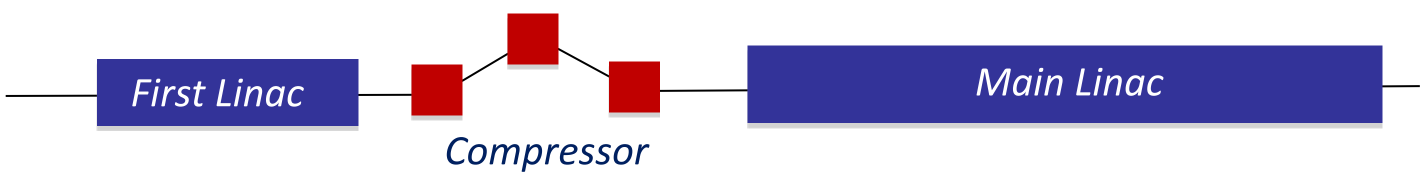
$$\frac{\Delta E}{E} \ll \rho \cdot M_{spikes}$$ *(For SwissFEL @ 1 Angstrom and 100 spikes: 4%)*

- This can be overcome if undulator is tapered to preserve resonance condition

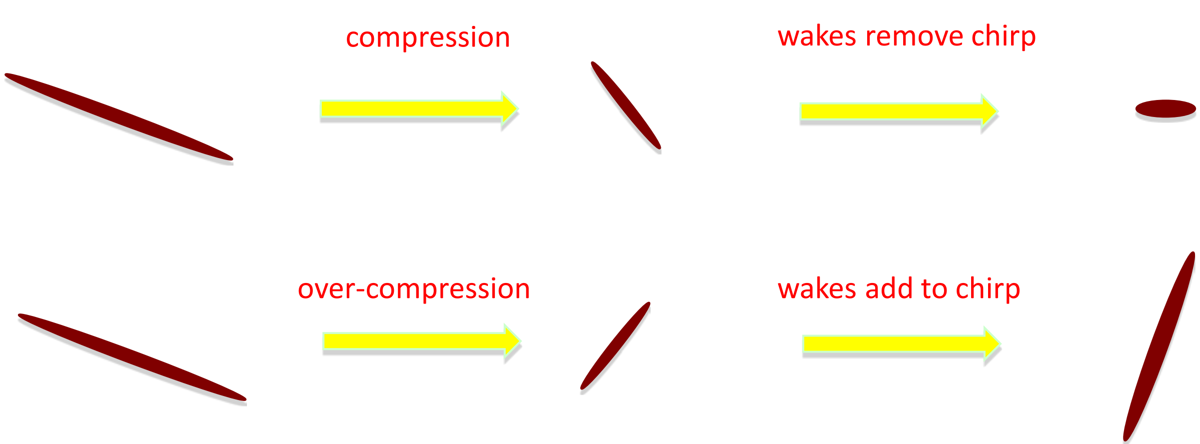
# Generating the Chirp

- In general any kind of time-dependent change in electron acceleration can be used:
  - Off-crest acceleration
  - Wakefields
  - Longitudinal Space Charge

- Very effective is the method to overcompress the beam to add the chrip for compression with the wakes, normally removing it.



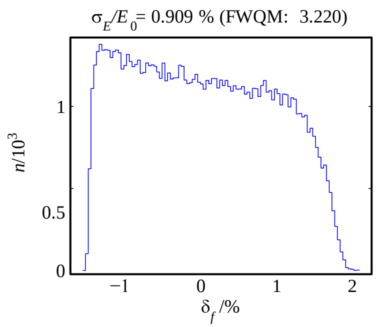

- *Normal*:
- Large Bandwidth:



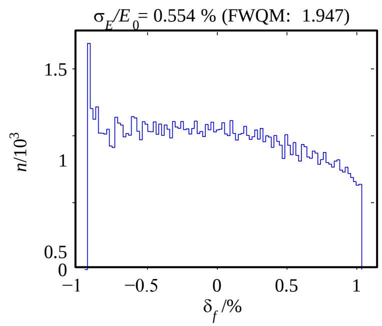
# LCLS Large Bandwidth Mode

- Simulations @ 1nC: *[P. Emma, LCLS-TN-00-6, 2000]*

*After Compressor*




*Before Undulator*



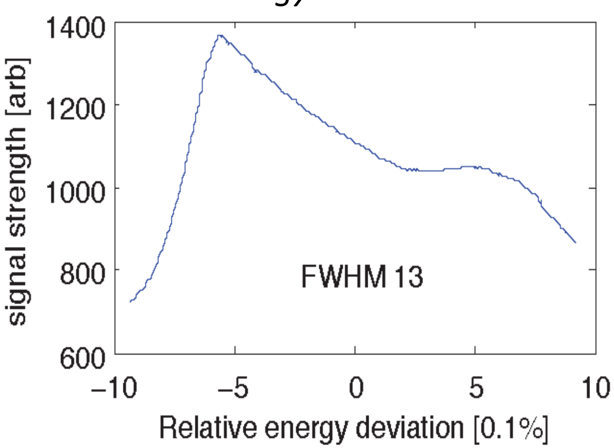

RMS value of 0.55% correspond to Peak-peak value of 1.9%.

No FEL simulation done

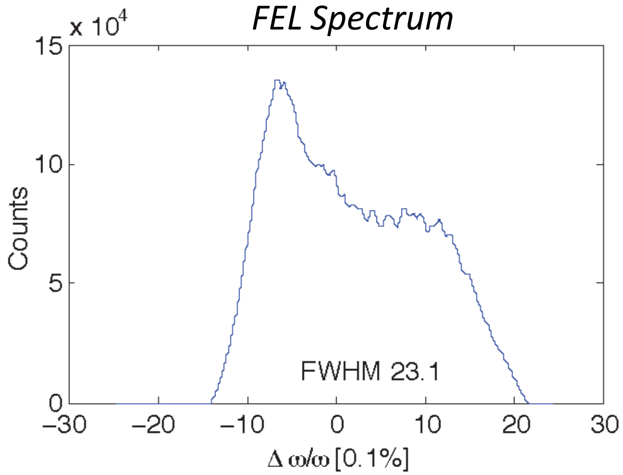
- Experiment @ 250 pC:

  *[J. Welch et al, "FEL Spectral Measurements at LCLS. FEL2011]*

*Energy Distribution*



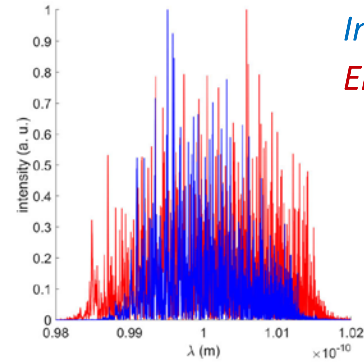

*FEL Spectrum*

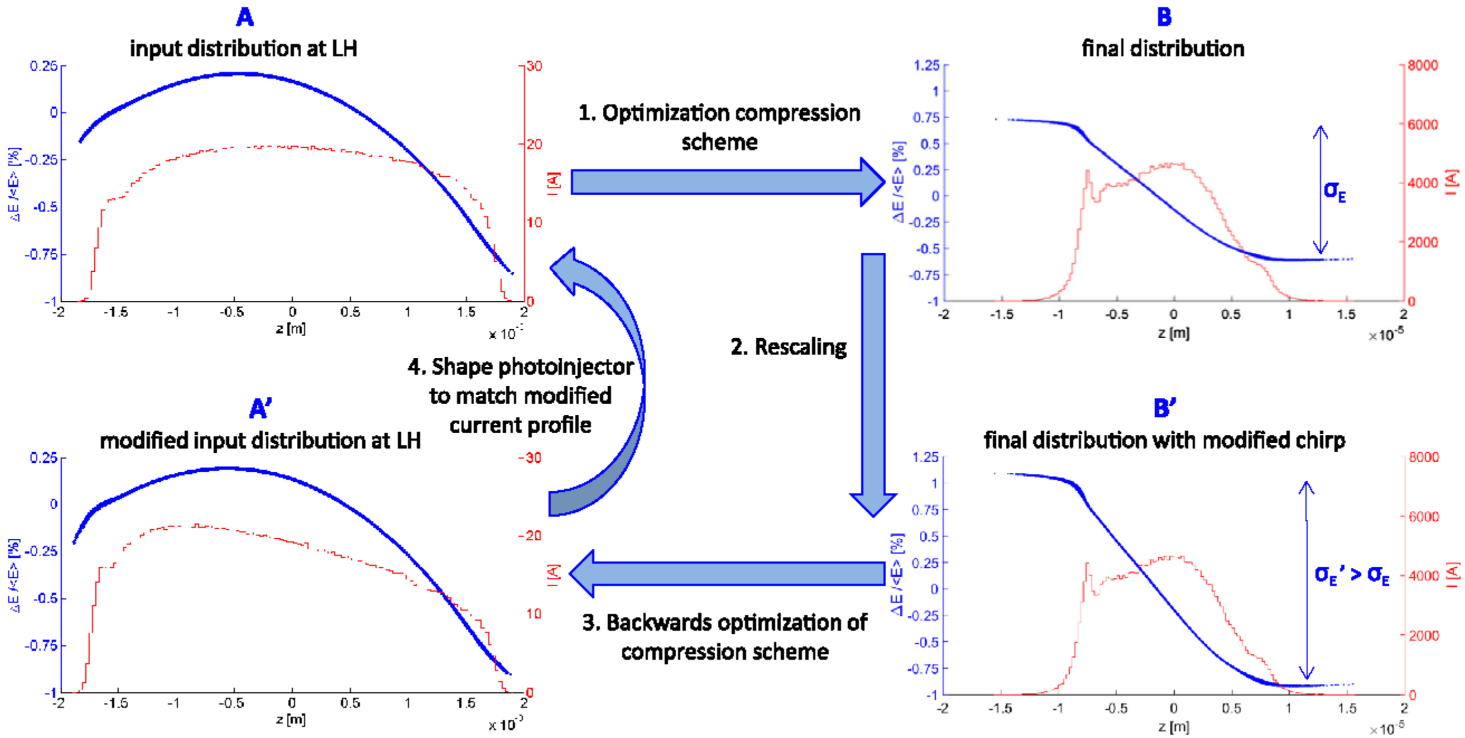


# Enhancing Energy Spread in Overcompresion

- Apply an iterative forward/backtracking to optimize beam profile
  *[A. Saa Hernandez et al, PHAB 19, 090702 (2016)]*

Example for SwissFEL at 1 Angstrom.
Enhancement of bandwidth by 50% achieved.

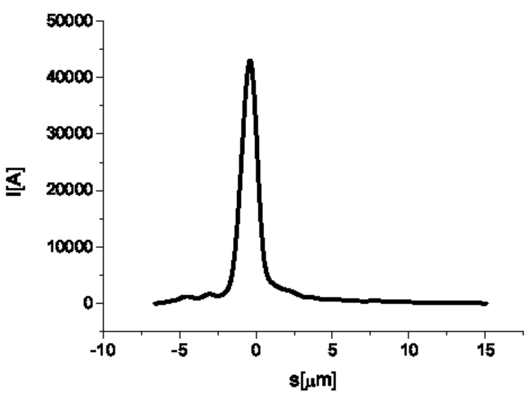


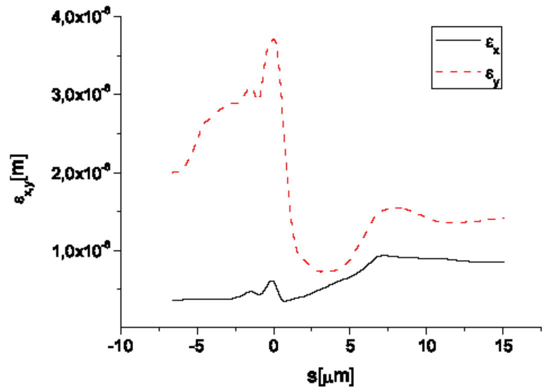



# Chirp Induced by Space Charge

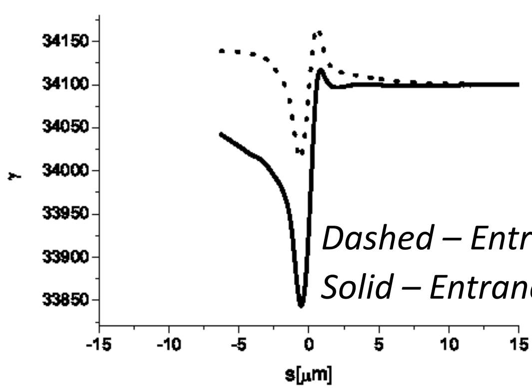
*[S. Serkez et al, DESY 13-109]*

- Alternative method is nearly full compression at last bunch compressor and let the space charge naturally induced a chirp.
- Promising for FELs with low wakefields (e.g. European FEL)



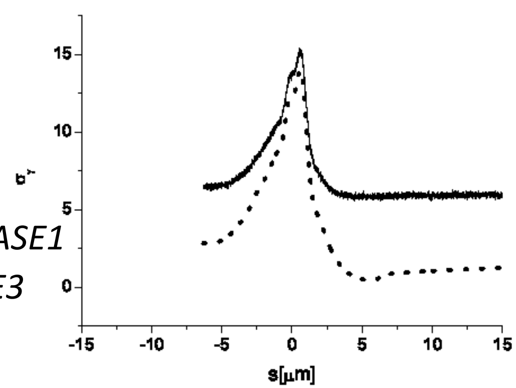



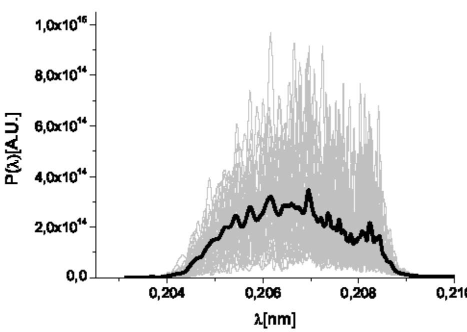

Note that still half of the chirp comes from wakefields in SASE1 undulator which proceeds the used FEL beamline SASE 3




*Dashed – Entrance SASE1*

*Solid – Entrance SASE3*



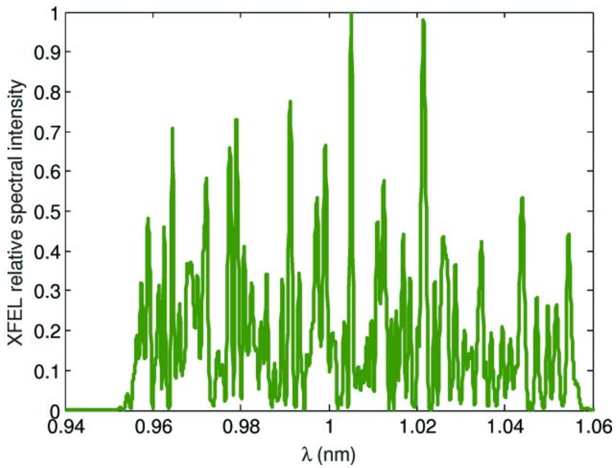
# Transverse Gradient Undulators

*[E. Prat et al, JSR, 23 (2016) 874]*

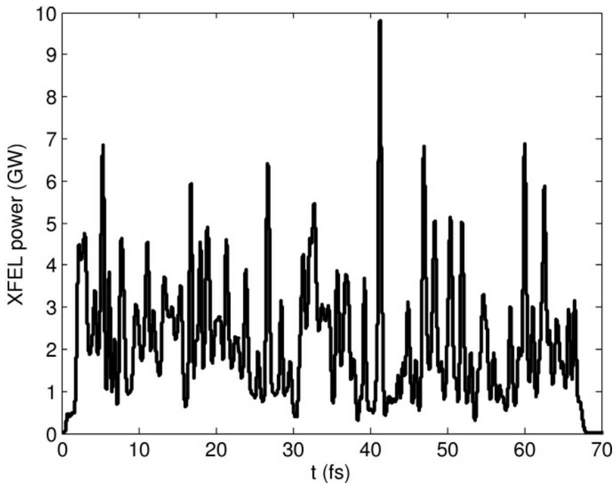
- Inject a tilted beam into a TGU with no external focusing.


- Spatial Temporal Chirp, which direction can be inverted
- Reduced efficiency due to lack of focusing is acceptable.
- Soft X-ray FEL beamline Athos @ SwissFEL using new type of undulator

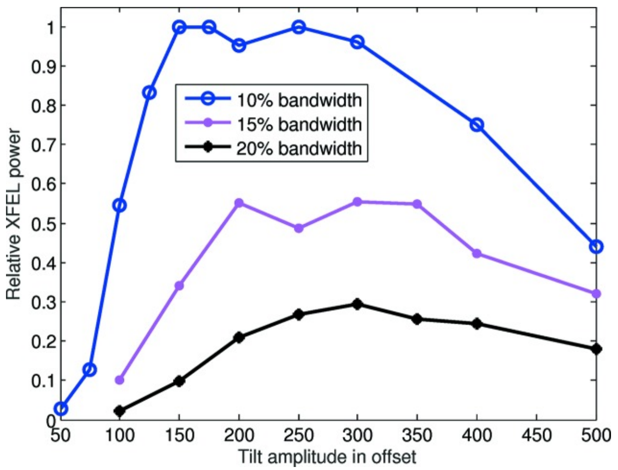
*Spectrum*




*Time Profile*

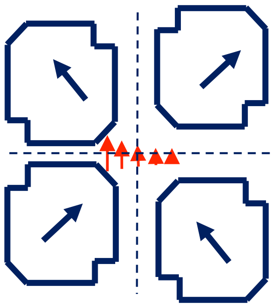


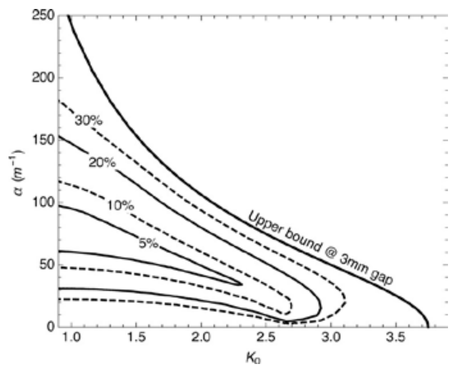

*Optimization*

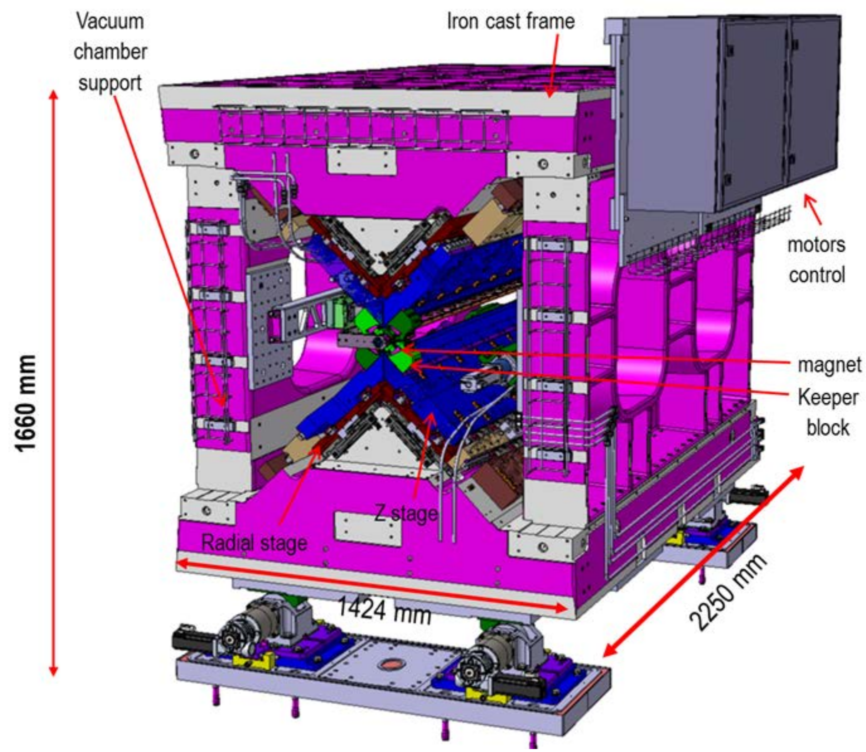


# Transverse Gradient Undulator

- SwissFEL soft X-ray FEL undulator uses novel design to control gradient of TGU






- Alternatively a strongly misaligned normal undulator can be used

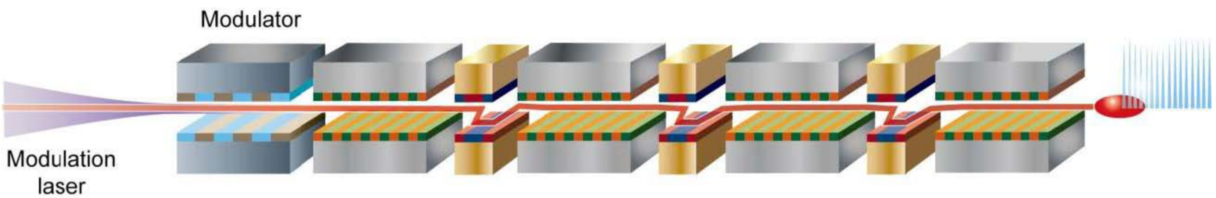
$$K(x) = K \cdot \left[ 1 + \frac{1}{2} k_u^2 \left( x - \Delta x \right)^2 \right]$$

[*Q. Jia and H. Li, RAB 20 (2017) 020707*]

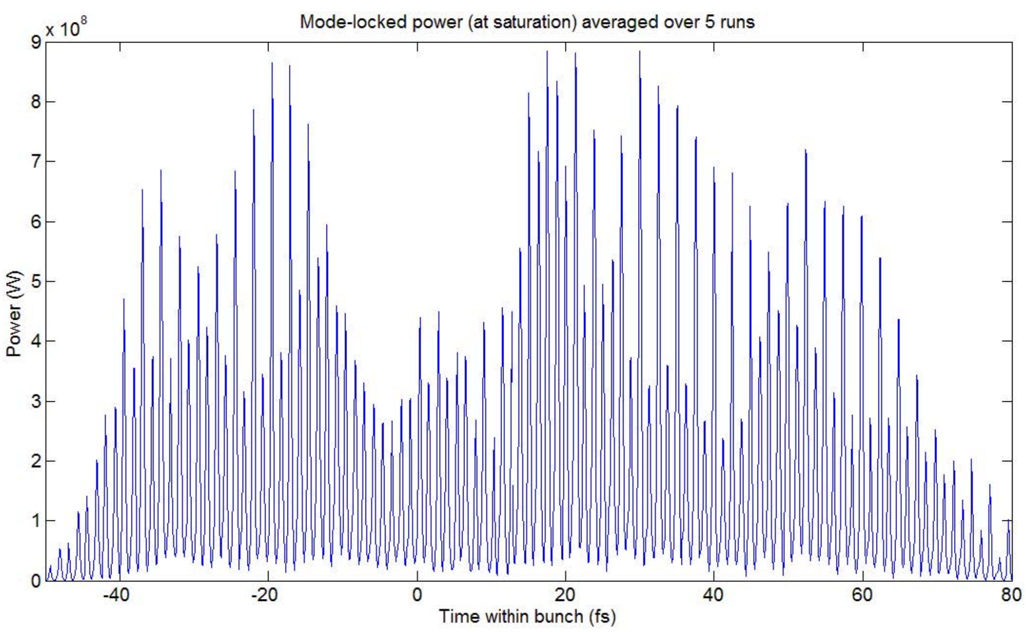
# Mode-locked FELs

*[E. Kur et al, New Journal of Physics 13 (2011) 063012]*

- Use the short undulator in mode-lock configuration to generate pulse train of short pulses




- Requirements are short modules, with a length much shorter than gain length

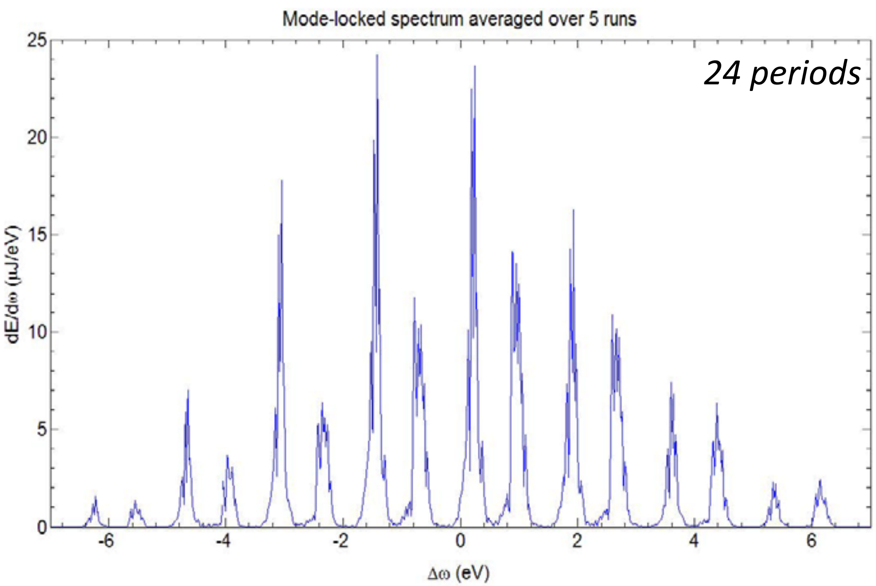


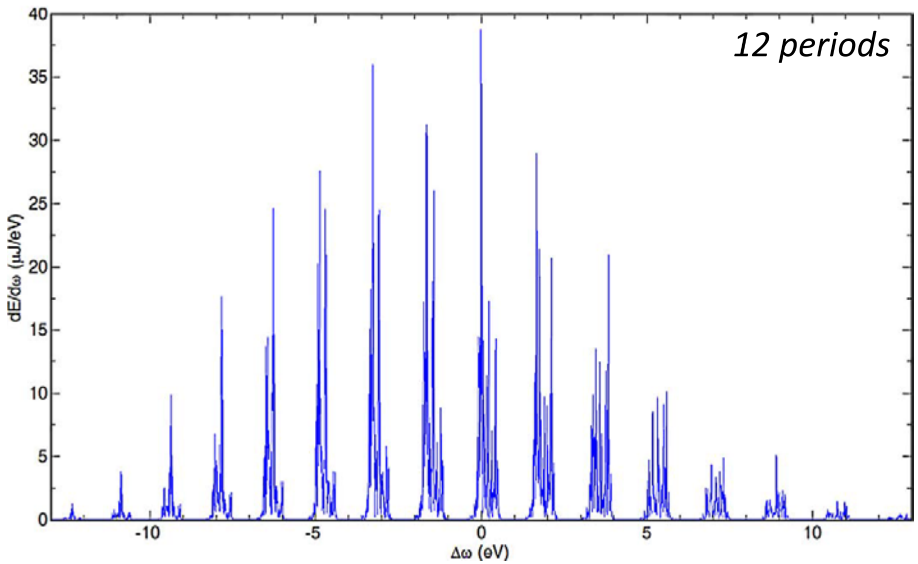
# Mode-Locked FELs

- Example for 6 nm laser
- Relative spectral width:
  - SASE FEL : ρ – Parameter
  - Mode-locked: $1/N_u$

Simulations show an rms width of 2.6% for a module length of Nu=24 periods, twice as much for half the length.

Results show with ideal delaying chicane with no dispersion



# Comparison

| | Expected Bandwidth | Hardware | Chirp | Challenge | Flexibility |
|---|---|---|---|---|---|
| Electron Chirp | 2-4 % at max energy | Eventually Wakefield source (e.g. dechirper) | positive | Overcompression | Little |
| TGU | Up to 20% | Apple-type undulator | Positive and negative | Tilt Generation | Full |
| Mode-locking | Up to 5% | Specific configuration of FEL, modulation laser | No chirp | Realization of mode-locking | None |