Improvement Schemes to SASE FELs

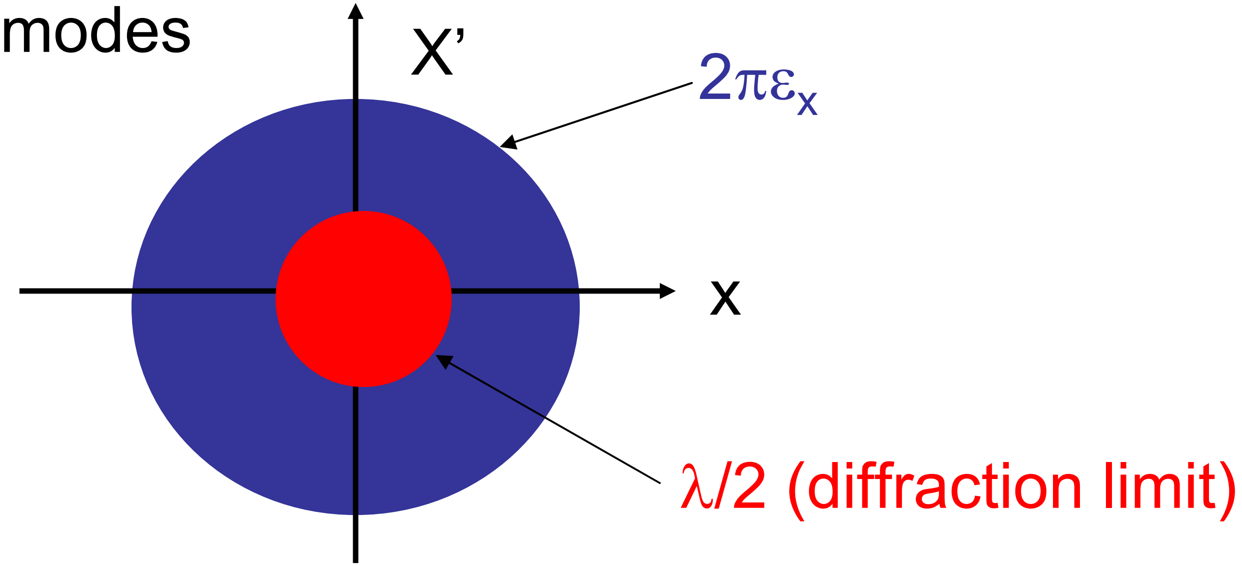
Zhirong Huang

BIG meeting

1/31/2003

SASE: Transverse Coherence

• Spontaneous undulator radiation phase space is the incoherent sum of the electron phase space, consists of many spatial modes



• SASE: higher-order modes have stronger diffraction + FEL gain is localized within the electrons

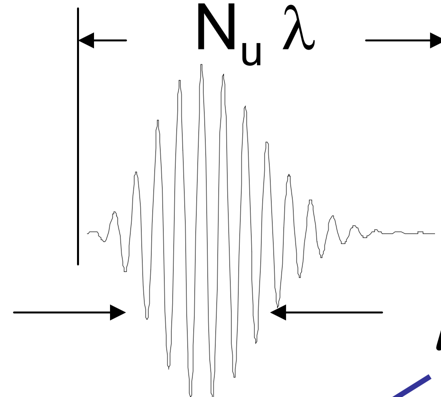
➔ selection of the fundamental mode (gain guiding)

➔ Fully transversely coherent even $\varepsilon_x > \lambda/(4\pi)$ (large L_G)

SASE: Temporal Coherence

- $E(t)=\sum_j E_0(t-t_j)$, t_j is the random arrival time of j^{th} e^-

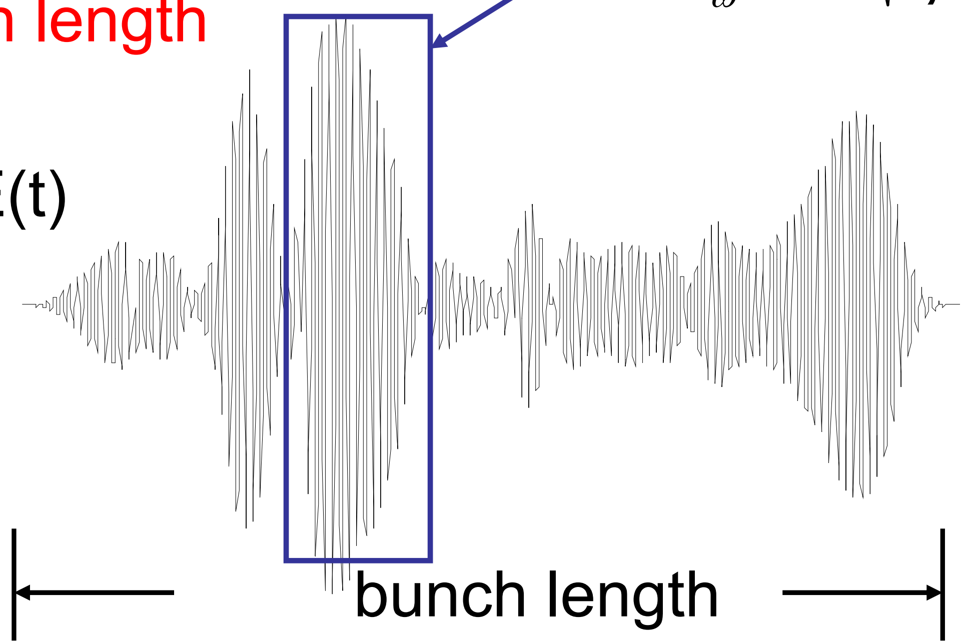
E_0: wave packet of a single e^-



$$l_c \approx \frac{2c}{\sigma_\omega} \approx \frac{\lambda}{\pi}\sqrt{\frac{N_u}{\rho}}$$

- l_c ~ 100-1000 λ < bunch length

- Sum of all packets ➔ $E(t)$



Statistical Fluctuation

Statistical Fluctuation

- Due to noise start-up, SASE is a chaotic light temporally with M modes (~ M spikes in intensity profile)

$$M \approx \frac{\text{bunch length}}{\text{coherence length}}$$

- Its longitudinal phase space is ~M larger than FT limit (rooms for improve!)

- Total energy fluctuation $\frac{\sigma_W}{W} = \frac{1}{\sqrt{M}}$

- SASE pulse length is comparable to electron bunch length ~100 fs (if flattop), can be shorter if bunch shape has spikes

- LCLS near saturation (80 m)

Coherence time 0.3 fs

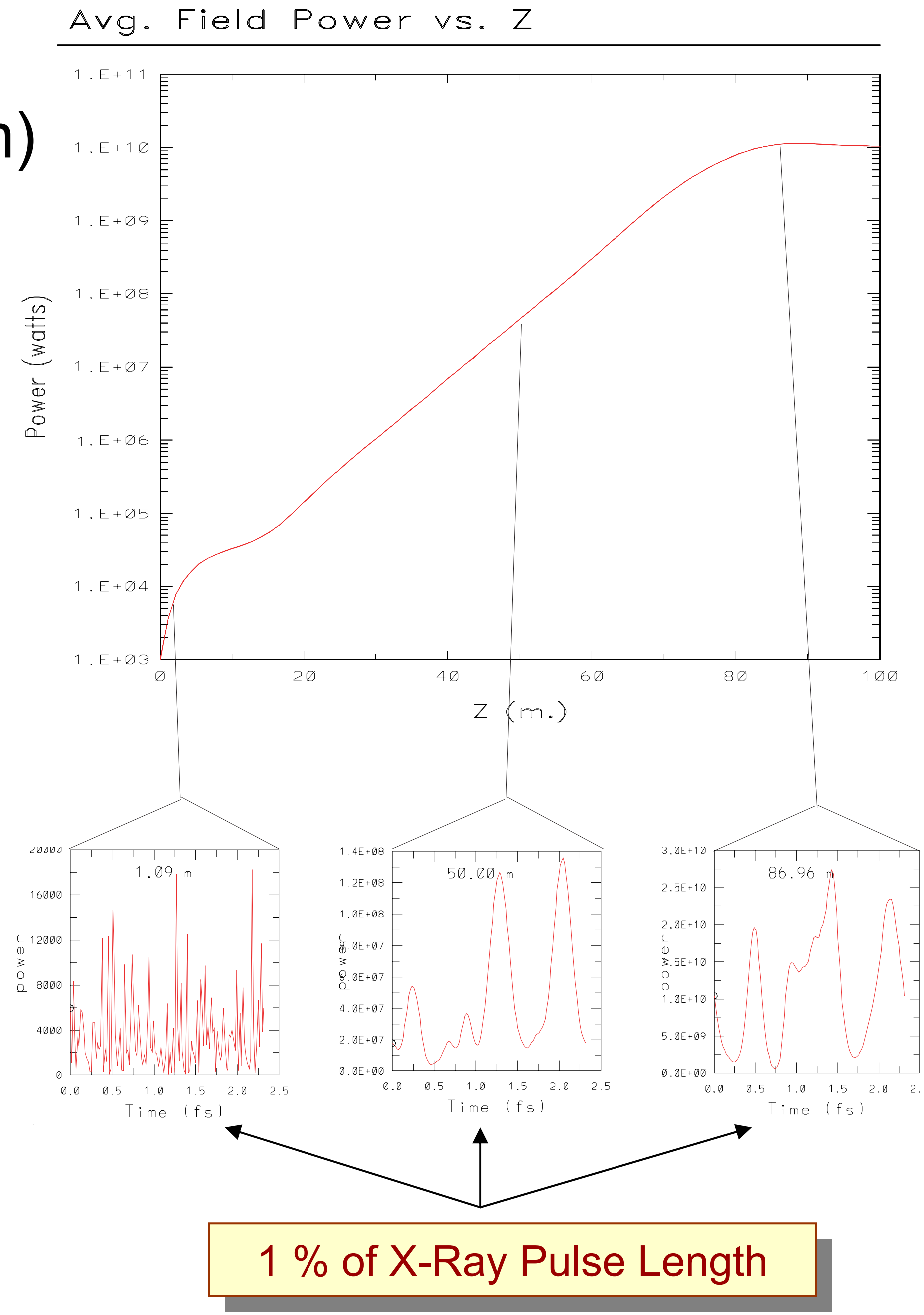
number of spikes ~ 400

number of modes ~ 600

➔ σ_w/W ~ 4 % (small!)

- If monochromatized, M=1

➔σ_w/W ~ 100 % (even after saturation)



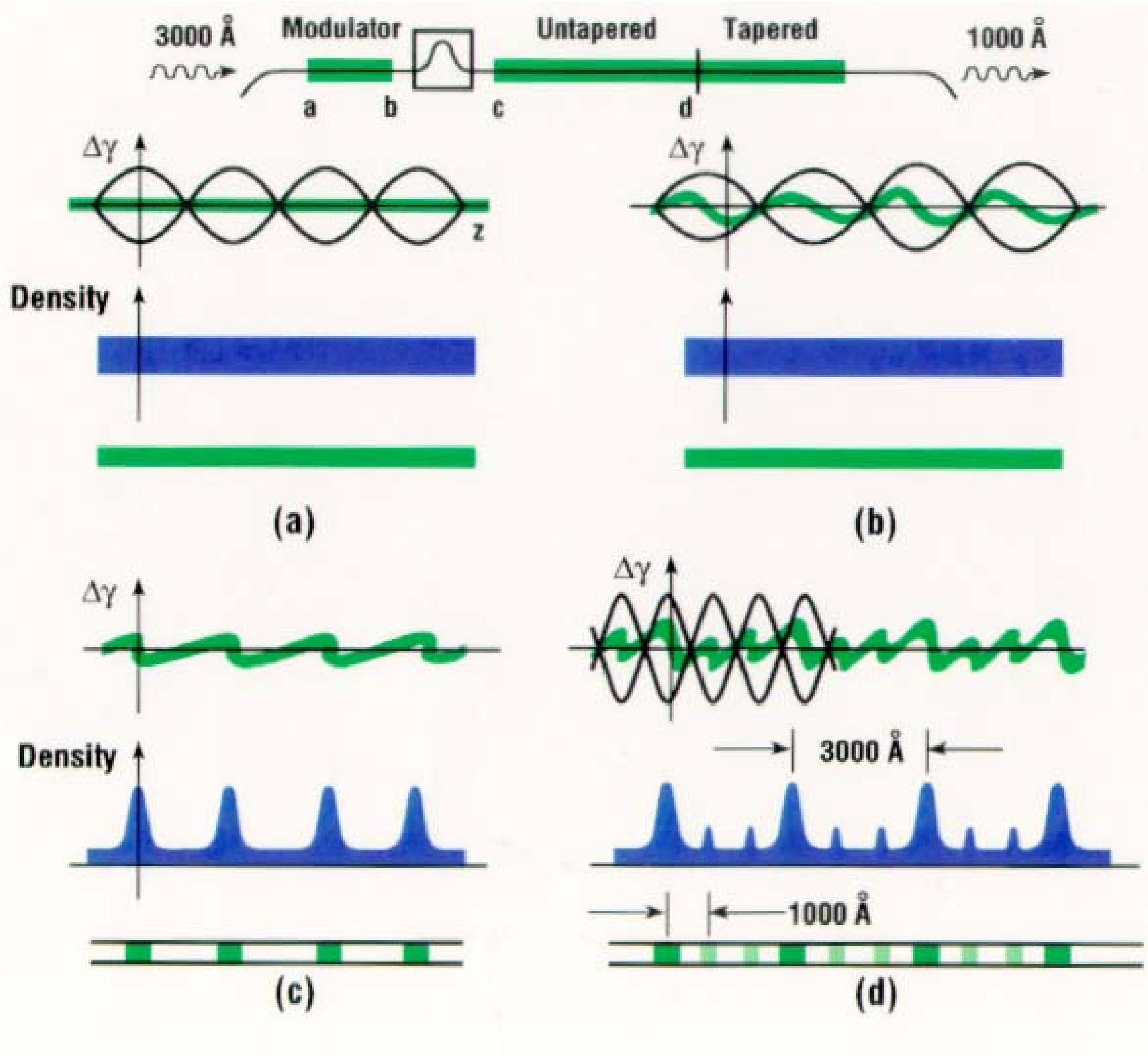
Survey of Improvement Schemes

- Longitudinal properties of SASE can be improved

- narrower bandwidth (through seeds or feedbacks)
  - External seed: HGHG
  - Self-seed: two-stage
  - Feedback: RAFEL

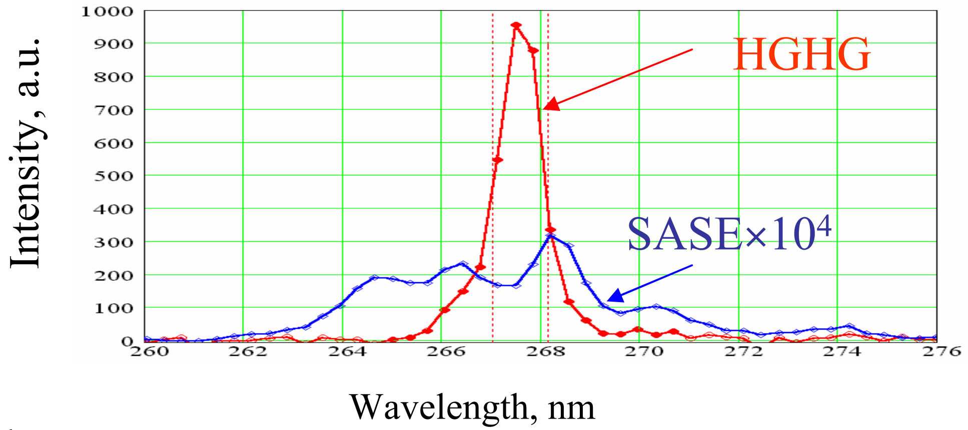
- Shorter x-ray pulses
  - X-ray manipulation of a frequency-chirped SASE
  - Electron bunch manipulation
  - Sub fs possibilities

HGHG Principle (L.-H. Yu)



Advantages of HGHG

•Narrow bandwidth



•Stable central wavelength

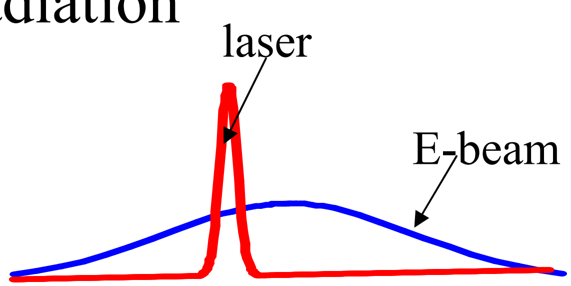
•Fourier transform limited

•Larger ratio of output/spontaneous radiation

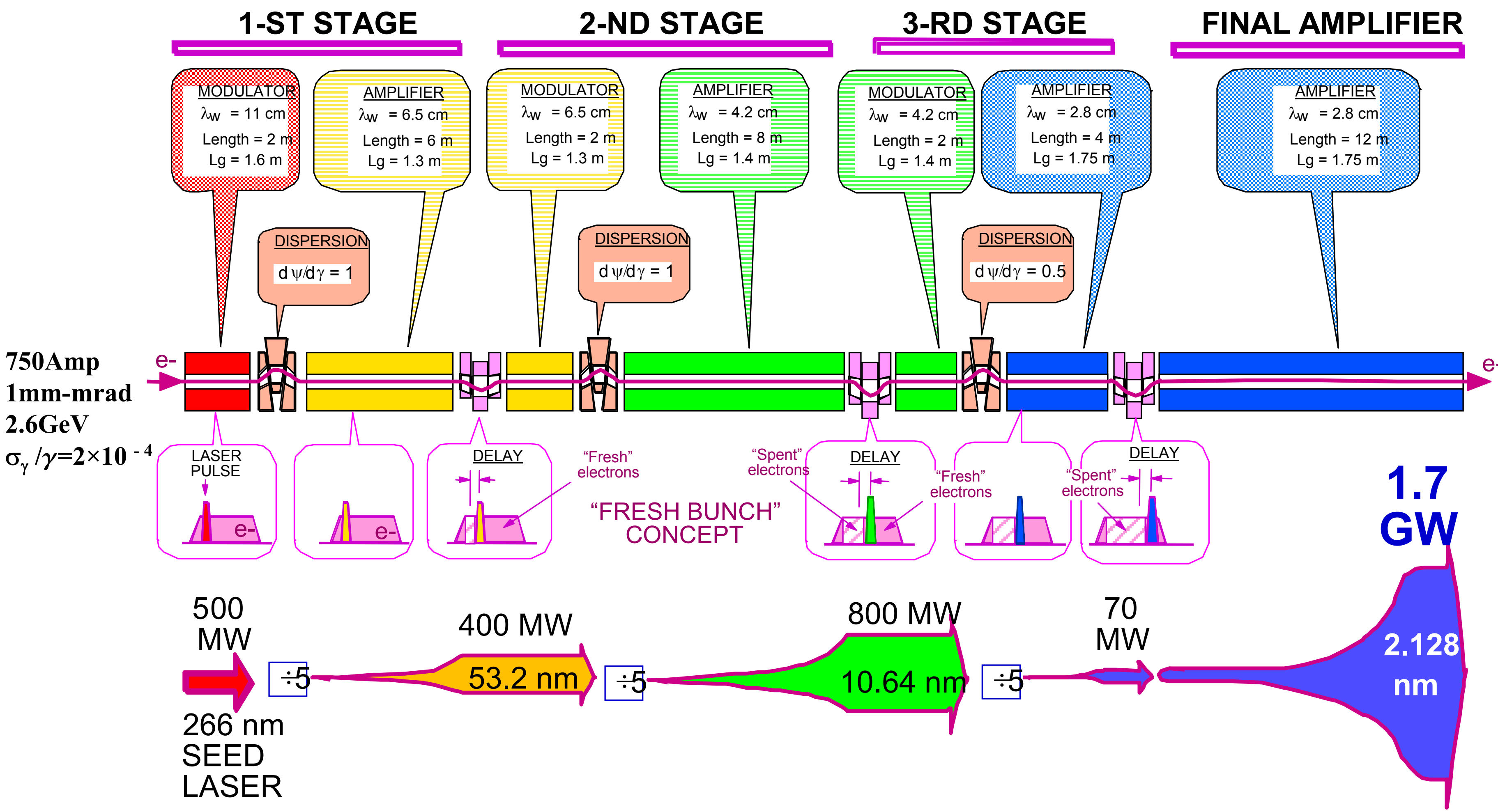
•Short pulse (20fs)

•Stable Intensity from shot to shot

•Can be cascaded to short wavelength

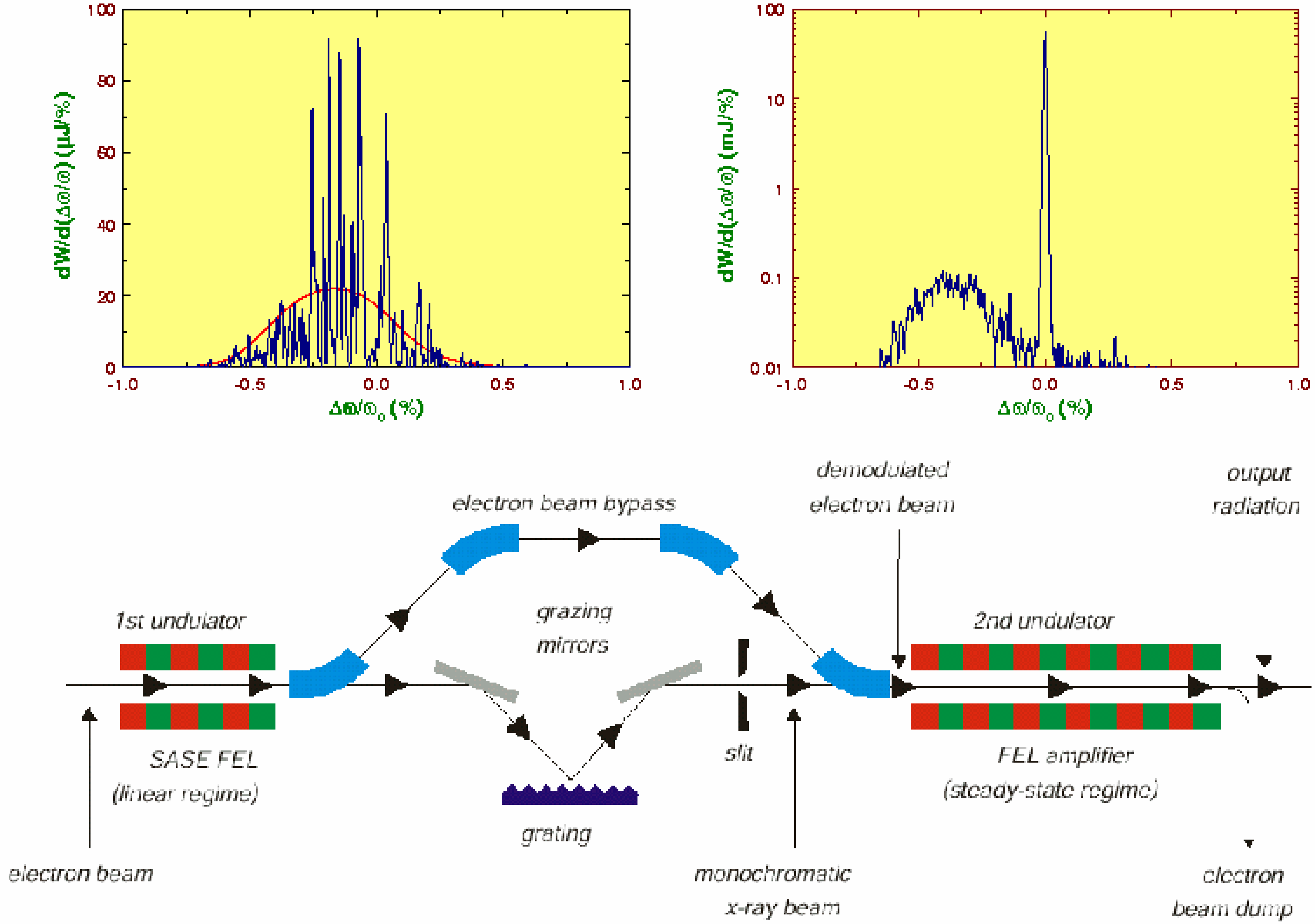


Soft X-Ray Free-Electron Laser



- Timing between e-bunch and laser < 100 fs (feedback)
- Noise degradation may be an issue to reach hard x-ray

Two-stage FEL (DESY)



2-stage vs. SASE+Monochromator

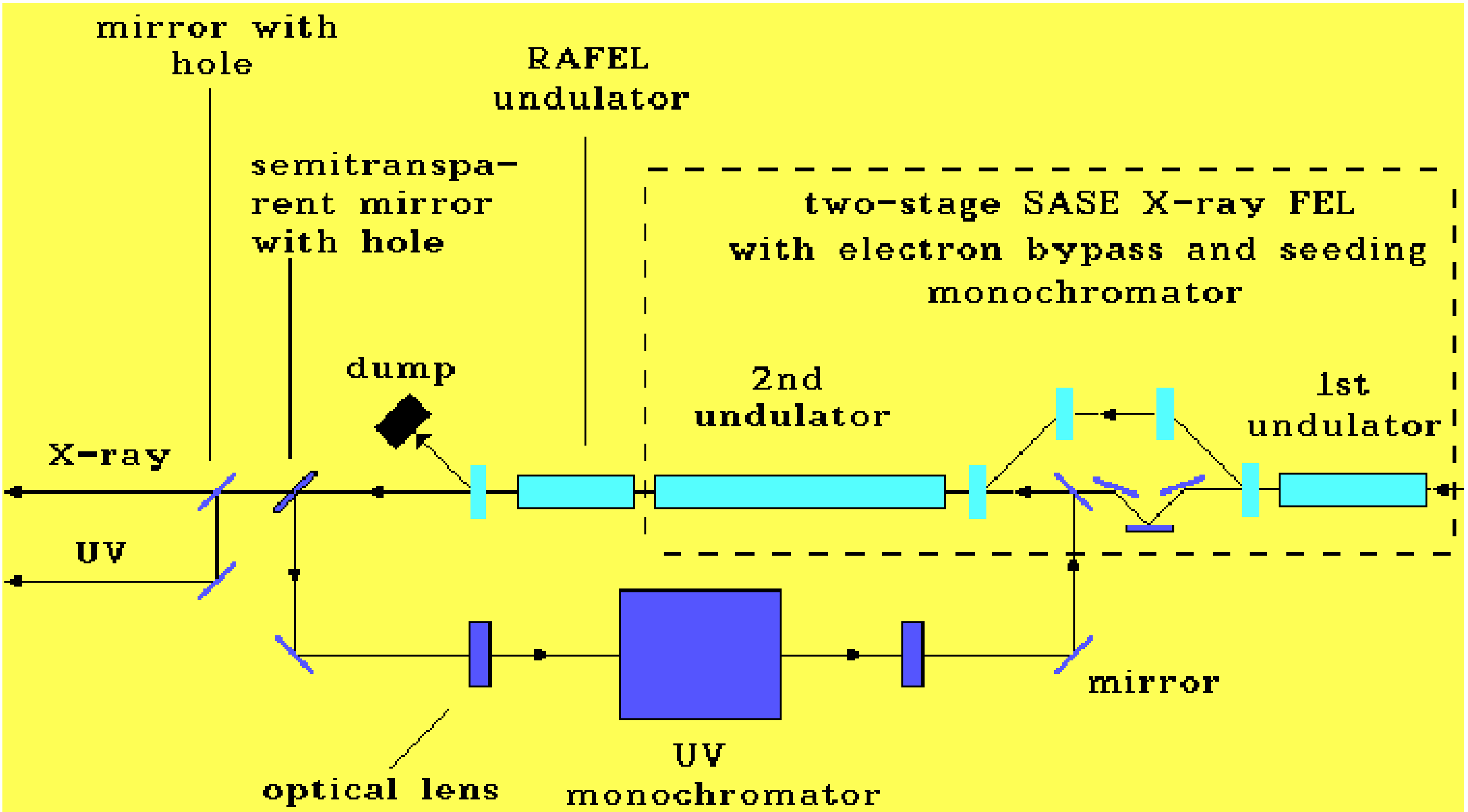
• Both gives the desired bandwidth σ_m (of the monochromator)

• Advantage of 2-stage
  - spectral brightness increase by σ_ω/σ_m
  - reduced intensity fluctuation
  (if single mode selected, SASE fluctuates 100%, but 2-stage ~10% after saturation)
  - reduced radiation damage to optics

• 2-stage funded for TTFII

• any limitation to go to hard x-ray wavelengths ?

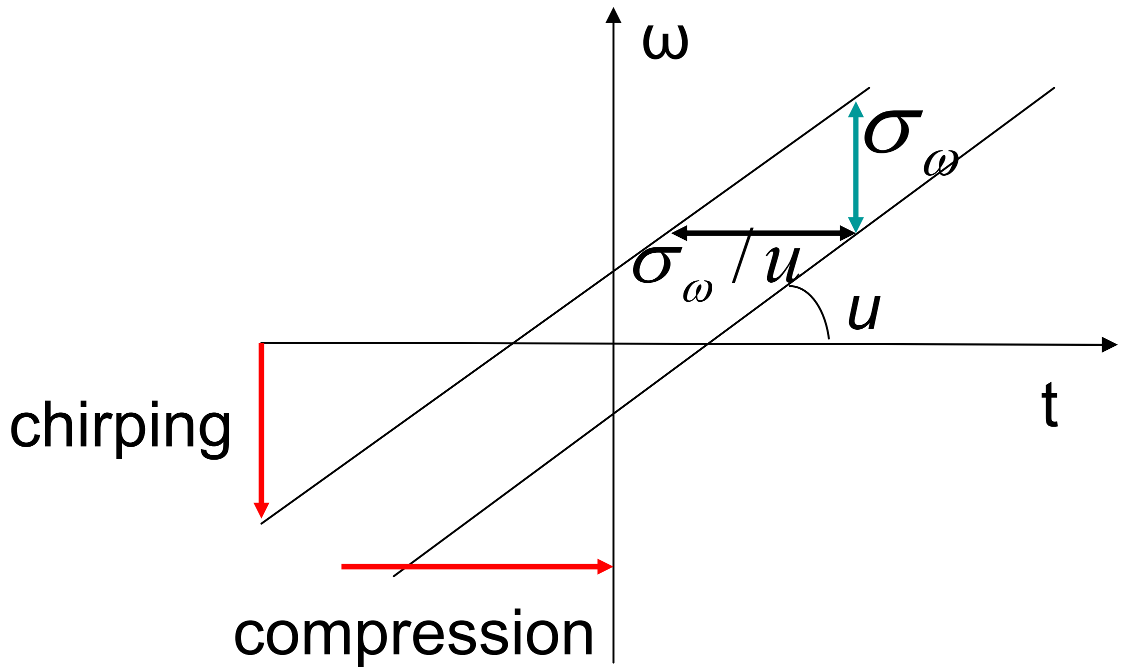
The Regenerative FEL



- RAFEL has been tested at TTF and did not work so far
- In x-ray wavelengths, some perfect crystals can have ~100% reflectivity in backscattering geometry

X-ray Pulse Compression

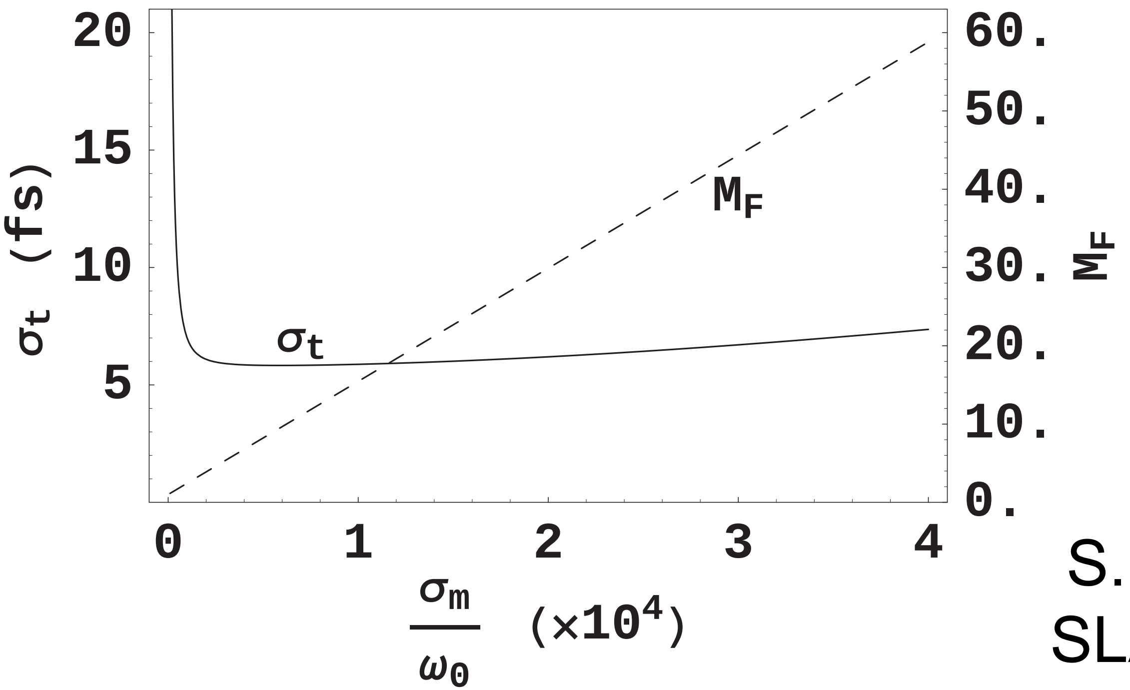
- works the same as the electron bunch compression



- No CSR, but demanding x-ray optics (a grating pair)
- Compressed pulse length limited by σ_ω / u ~ 10 fs

X-ray Pulse Slicing

- frequency-chirped SASE + monochromator
- Pulse length minimum σ_ω / u, but loses power
- Broad minimum ➔ control M_F (and fluctuation) through monochromator bandwidth

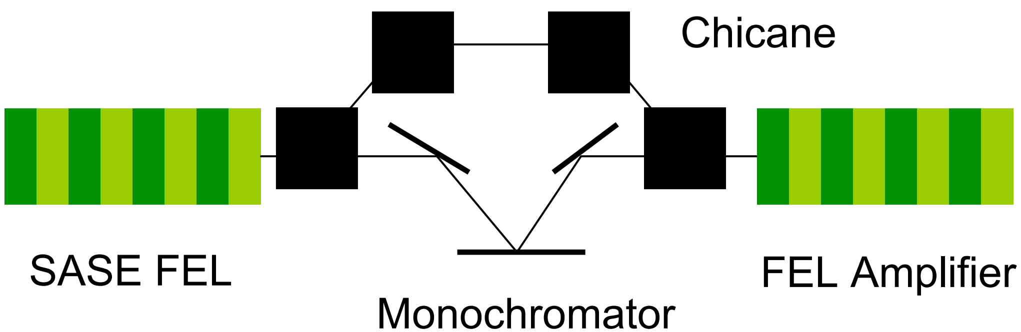


S. Krinsky & Z. Huang
SLAC-PUB-9633, 2003

C. Schroeder et al.

Two-stage Pulse Slicing

- Slicing before saturation reduces power load on monochromator
- Second stage seeded with sliced pulse (microbunching removed by bypass)
- Allows small bandwidth for unchirped bunches

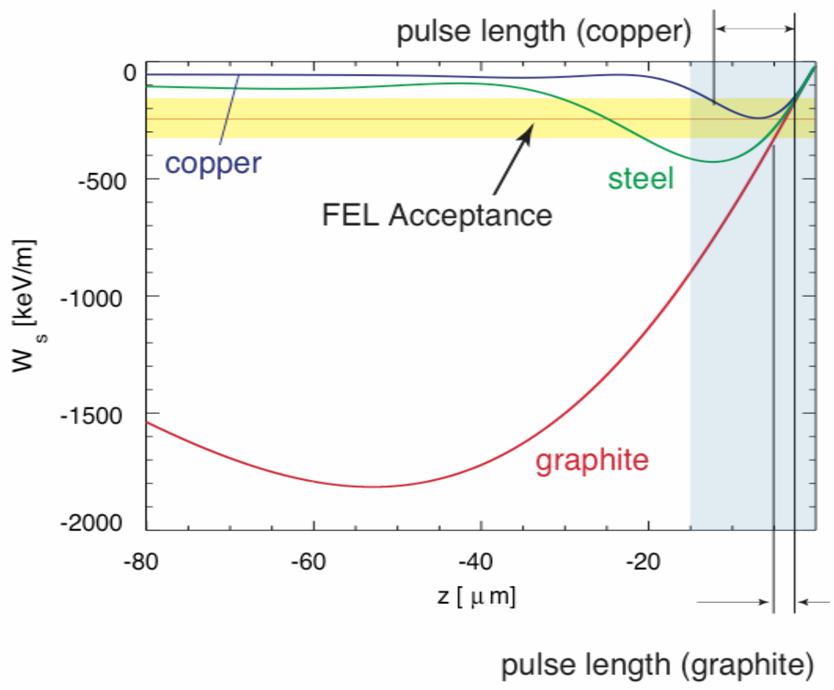


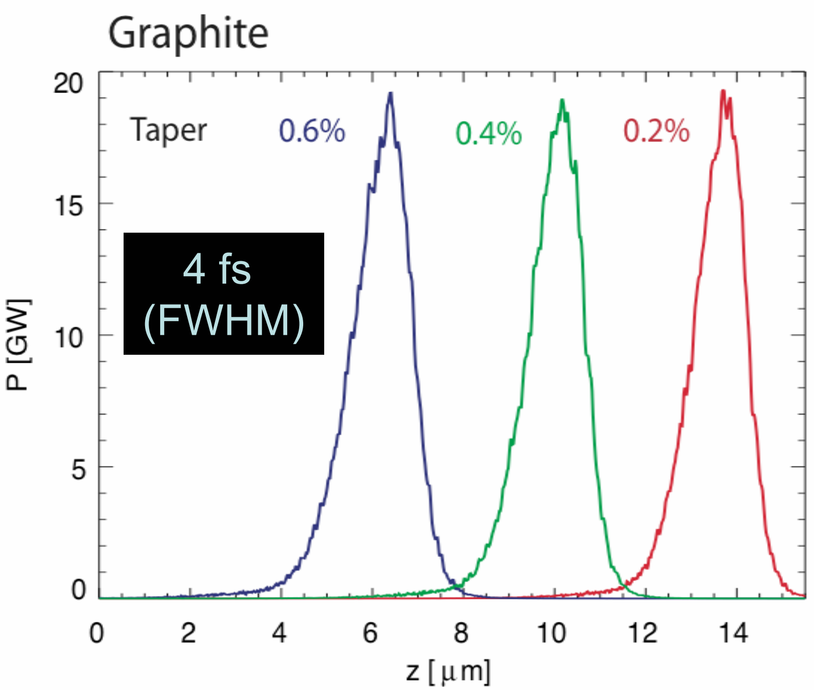
- Larger FEL bandwidth than at saturation when slicing, potentially longer x-ray pulse length than 1-stage
- Synchronization between sliced pulse and the part of electrons having the “right” energy

S. Reiche

Wakefield Effects

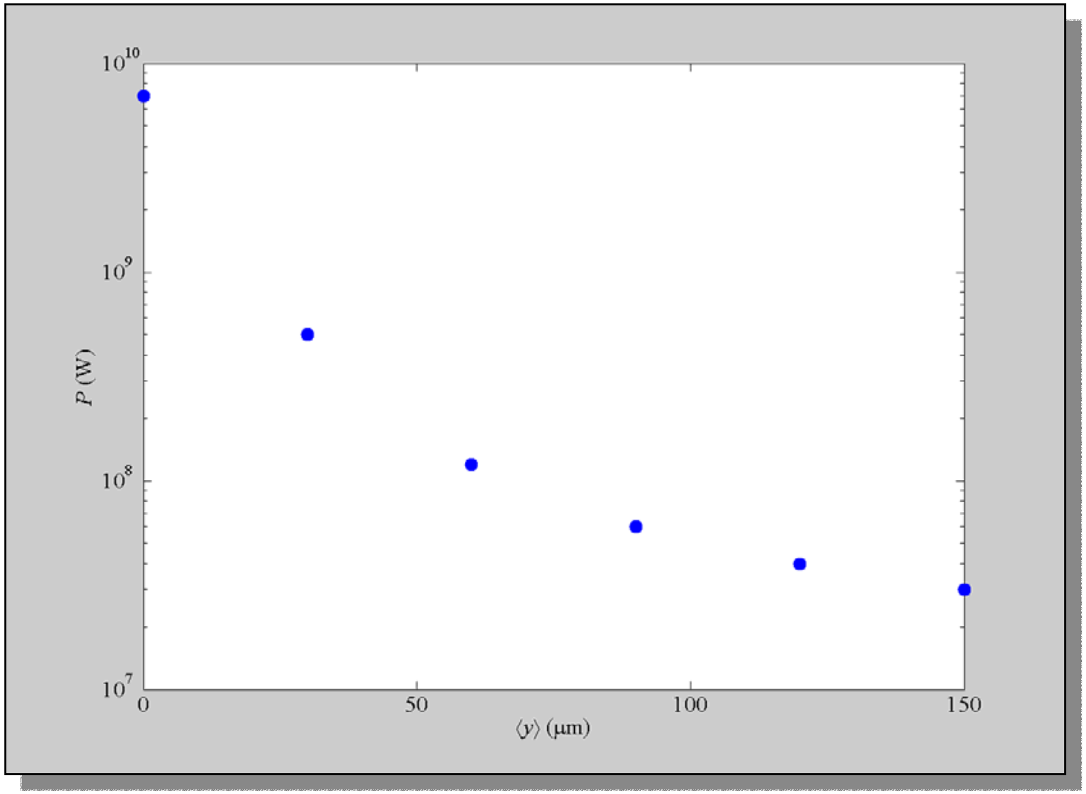
Ideal case (step profile) with various materials for the vacuum chamber to control wakefield amplitude





Spatially Chirped Bunch

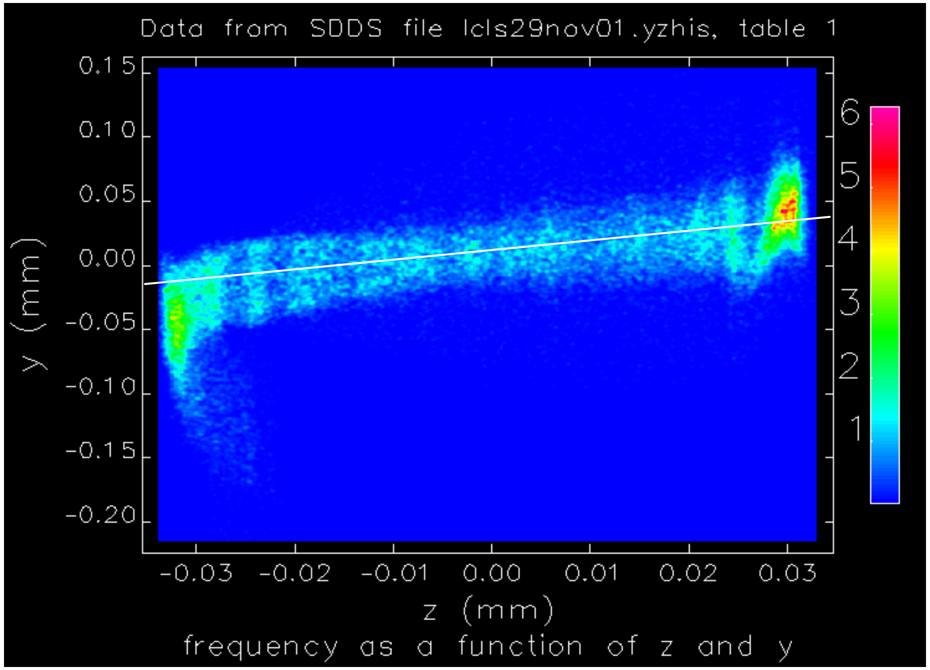
- FEL gain is very sensitivity to the offset of the slice centroid
- Mean Power vs. Initial *y*-centroid e^- Offset



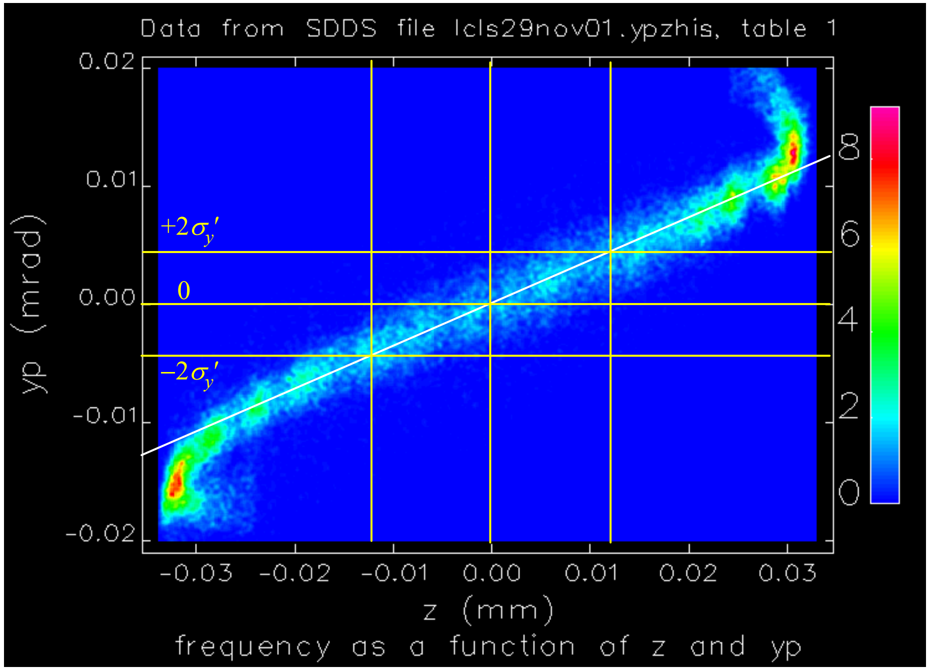
- A spatially-chirped bunch will lase mainly in the part that's initially on the undulator axis

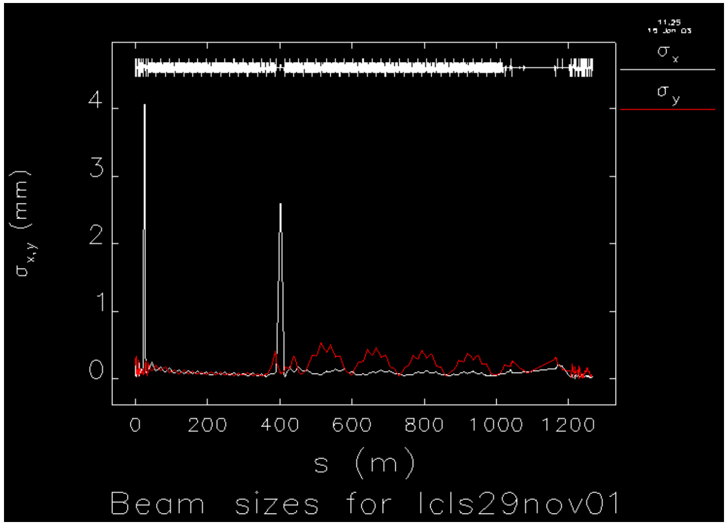
TCAV **prior** to BC2 @ V_{cav} = 5 MV, L_{cav} = 1.0 m, E_{cav} = 4 GeV

y vs. *z* at start of undulator



y′ vs. *z* at start of undulator





P. Emma

slope = 0.36 mrad/mm

$\sigma_y'(V=0)$ = 0.002 mrad

<2% FEL power at ±10 μm

FWHM x-ray pulse ~20 fs

$\Delta\phi_{rms}$ < 0.5 deg S-band

Sideband Seeded Soft XFEL

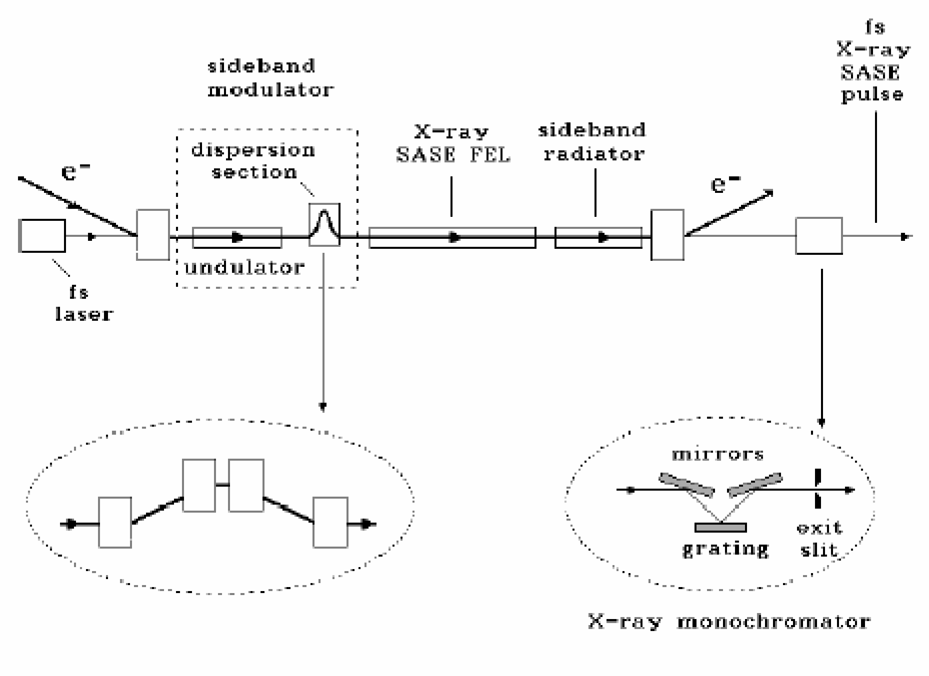
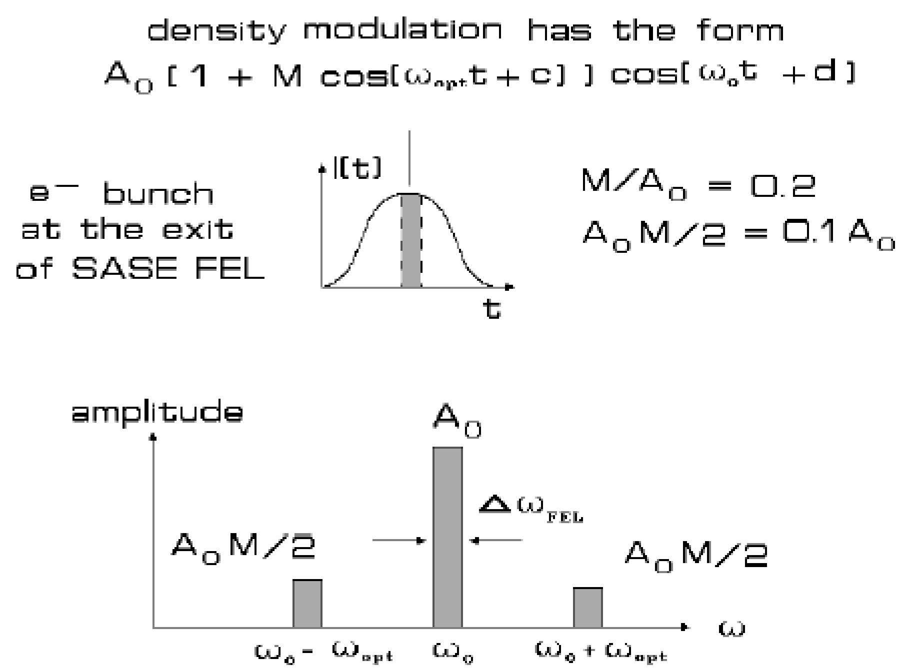
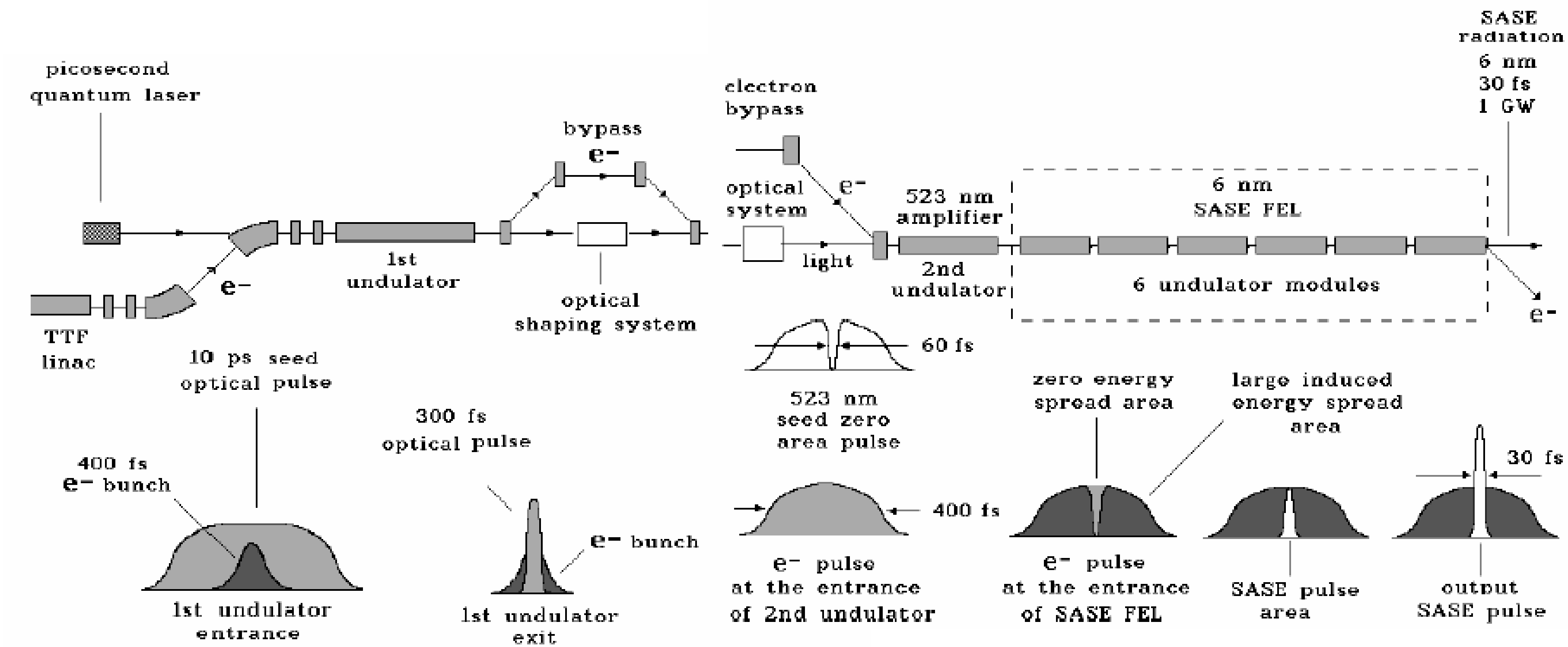


Fig. 1. Basic scheme of a sideband seeded SASE FEL



Need clear sideband separation $\lambda_o/\lambda_L >> \rho$,
this limits shortest $\lambda_0 \sim 10$ nm

Laser Manipulation of energy spread



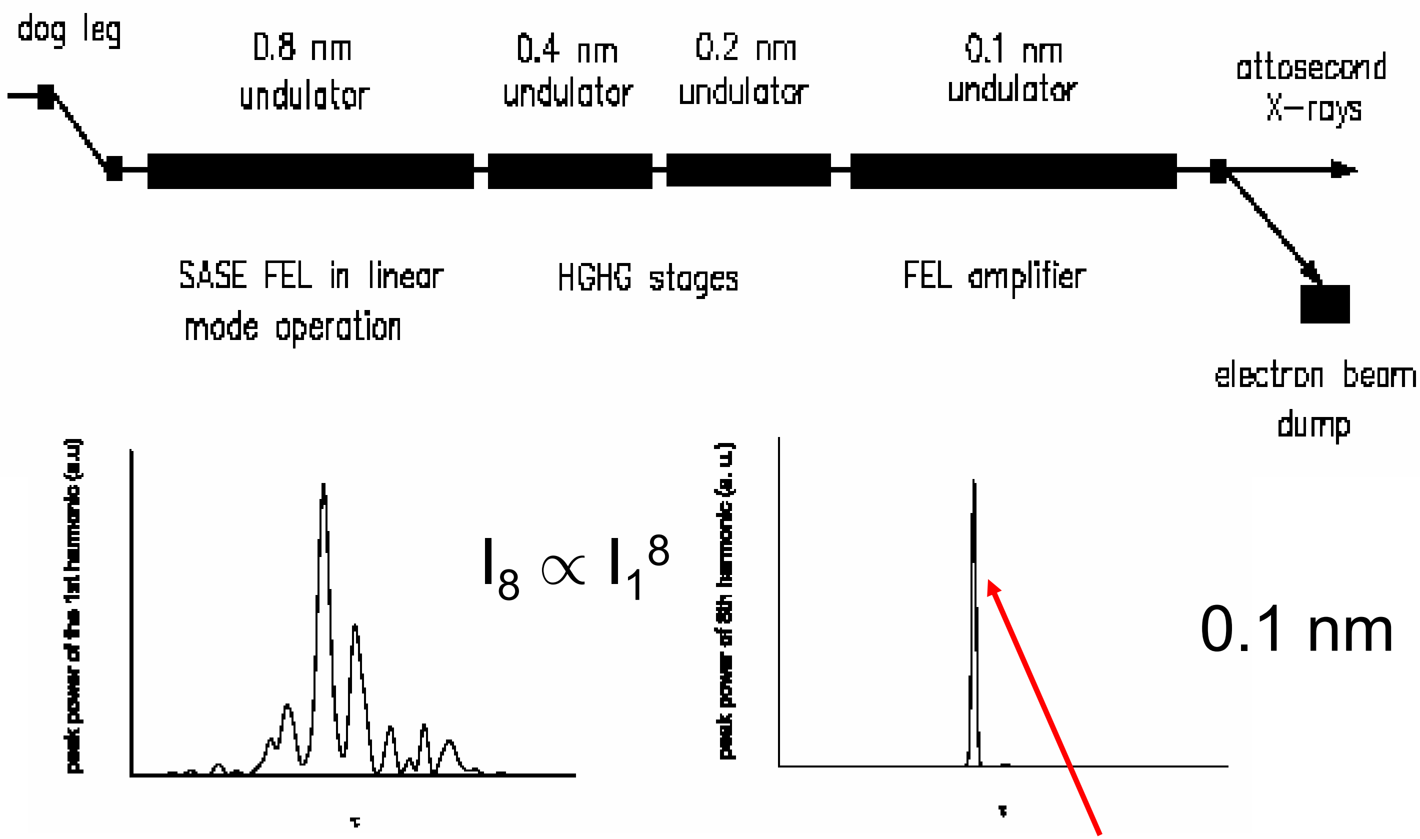
resolves the timing issue

shape laser and electron

short-pulse x-ray generation

Statistical Single-Spike Selection

Unseeded HGHG (E. Saldin)



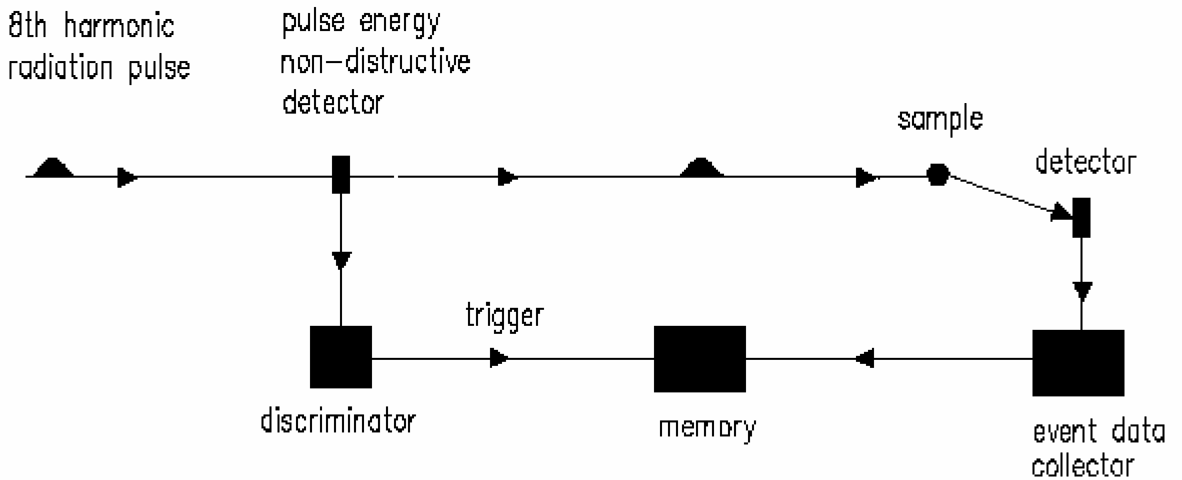
0.8 nm

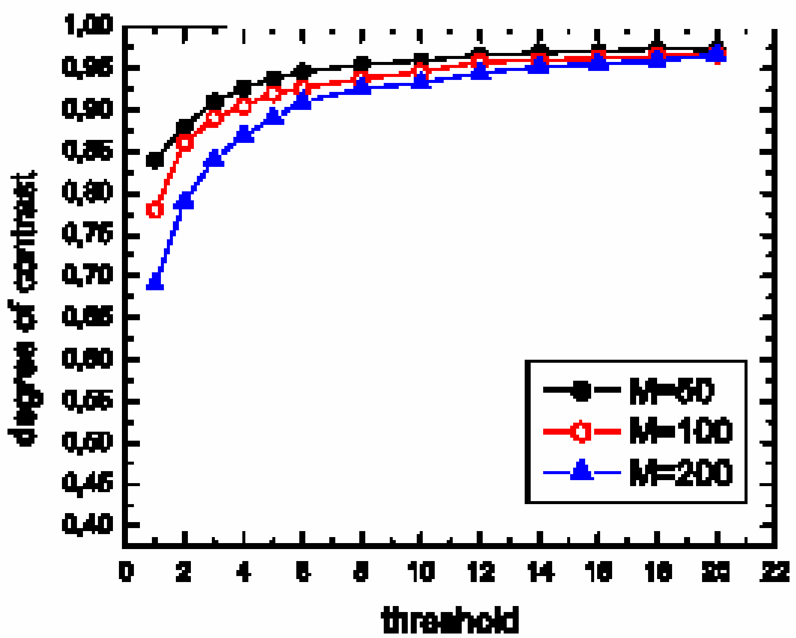
$I_8 \propto I_1^8$

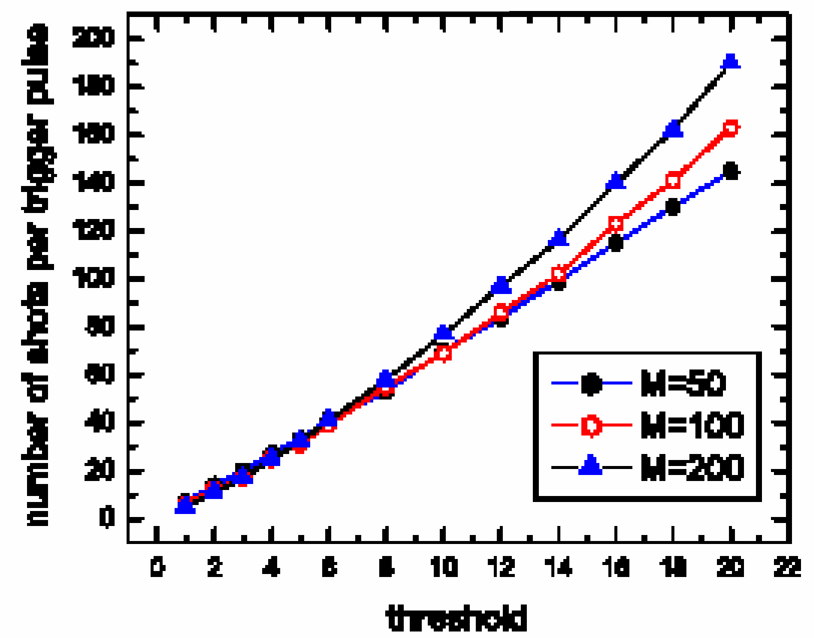
0.1 nm

sub-fs spike

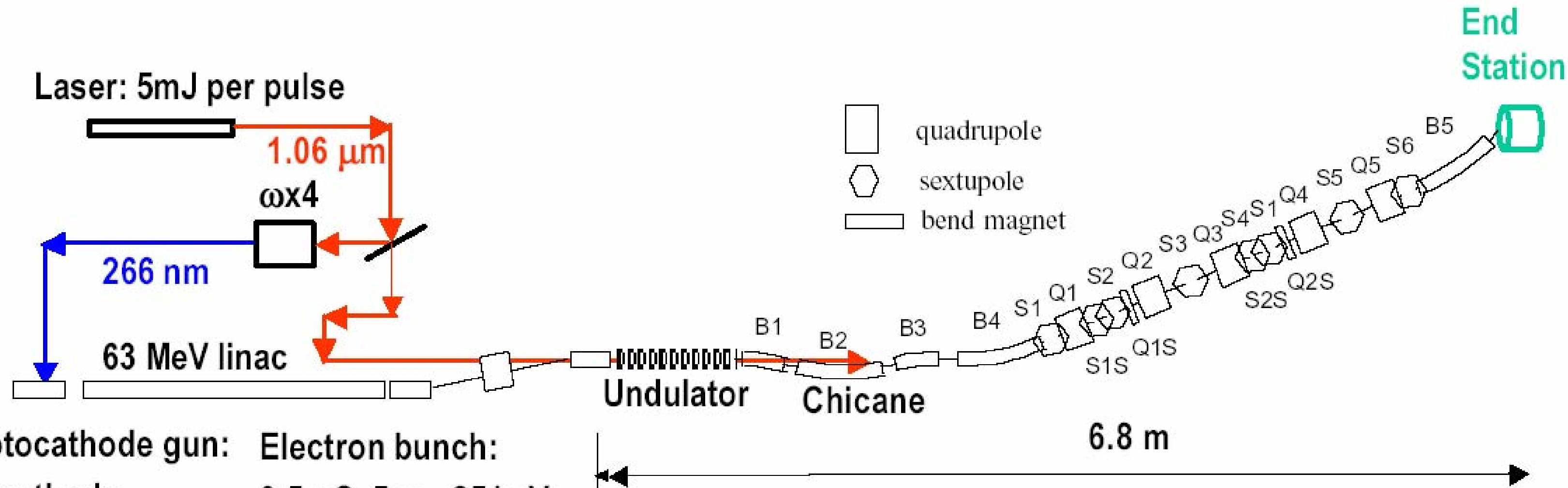
Selection Process





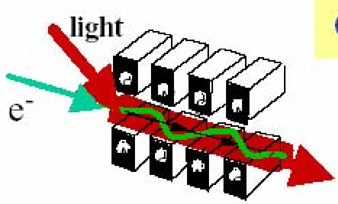


Method   Attosecond slicing (M. Zoloterov)



Photocathode gun:
Mg cathode

Electron bunch:
0.5 nC, 5ps , 25 keV,
2 mm-mrad



e-beam-light interaction in the undulator

laser peak power   Bessel functions   undulator parameter

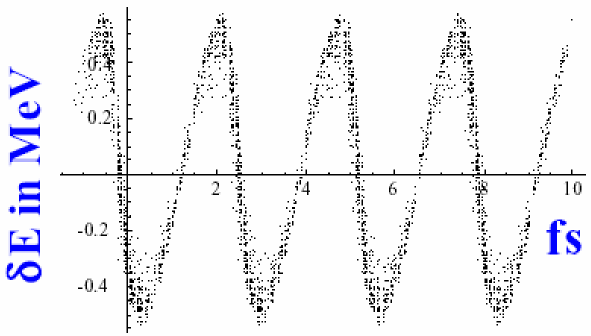
$$(\Delta\gamma)^2 = 32\pi\, M \frac{P}{P_0} \xi \left[J_0(\zeta/2) - J_1(\zeta/2)\right]^2 \qquad \xi = \frac{K^2/2}{1+K^2/2}$$

number of undulator periods $8.7\text{x}10^9$ W

Method cont'd

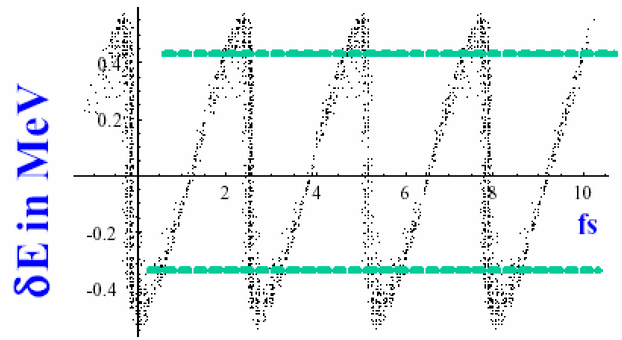
Estimate: $\delta E = 0.6$ MeV for P=10 MW, K=1.28, M=55

Simulations (GINGER was used)



Longitudinal phase space at the exit of the undulator.

Modulation amplitude = 40 σ_e



cut out with masks

Longitudinal phase space at the End Station

Histogram of electron longitudinal density →