Possibility of a High-Power, High-Gain Amplifier FEL

Dinh C. Nguyen
Los Alamos National Laboratory

Henry Freund
Science Application International Corporation

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Outline

- Basic features of an Amplifier FEL
- Why Amplifier FEL?
- Amplifier FEL with Energy Recovery
- MEDUSA Simulations
- Generation and Transport of Bright Electron Beams
- Energy Spread Compression
- Summary

Basic Features of an Amplifier FEL

- Exponential growth

$$P(z)=\frac{1}{9}\frac{P_0 e^{z/L_G}}{\left[1+\frac{1}{9}\frac{P_0}{P_{sat}}\left(e^{z/L_G}-1\right)\right]}$$

- Large single-pass gain

$$L_G=\frac{\lambda_w}{4\pi\sqrt{3}\rho}\left(1+\eta_{3D}\right)$$

Diffraction

Emittance

Energy spread

- Optical guiding

$$w_{FEL}=\sqrt{\frac{4\varepsilon_n\beta}{\gamma}}$$

- Saturated power
  - Uniform wiggler

$$P_{sat}=1.68P_e\rho\left(\frac{1}{1+\eta_{3D}}\right)^2$$

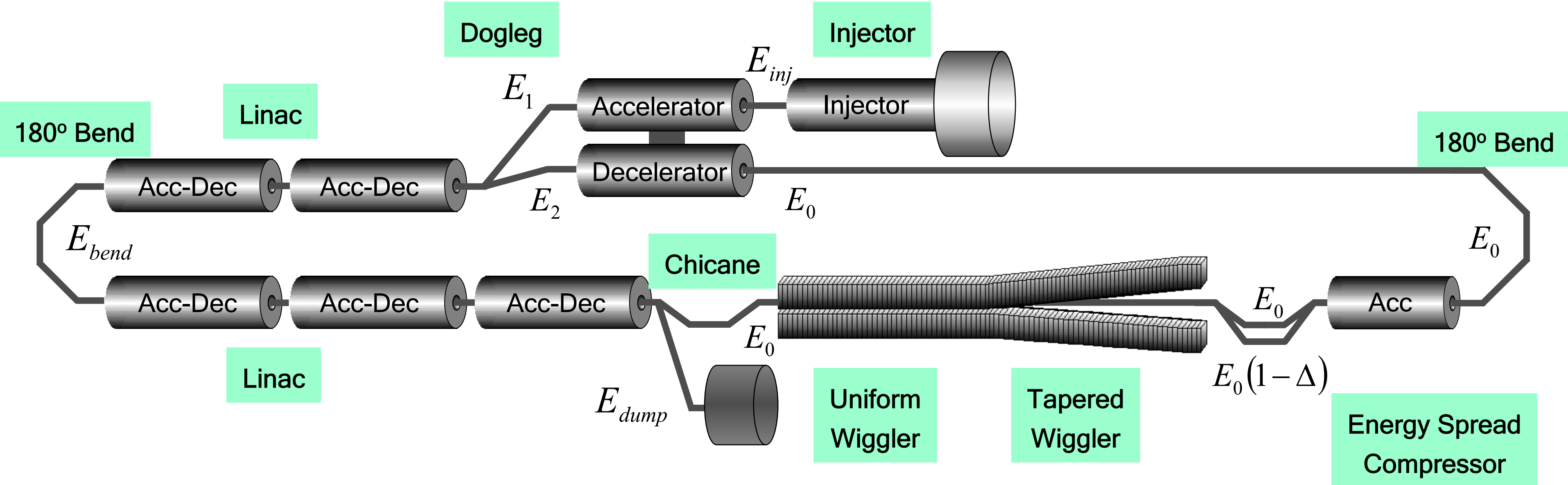
  - Tapered wiggler

$$P_{FEL}=P_e\frac{\Delta\gamma}{\gamma_0}\cdot\eta_C\left(I,\frac{\Delta\gamma}{\gamma_0},L_{taper}\right)$$

Why Amplifier FEL?

- Fixed wavelength $$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + K^2\right)$$
- No optical resonator $$I_{peak} > 10\frac{GW}{cm^2}, I_{ave} > 100\frac{kW}{cm^2}$$
- High efficiency $$\eta_{taper} = \frac{\Delta\gamma}{\gamma}\cdot\eta_C\left(I, \frac{\Delta\gamma}{\gamma}, L_{taper}\right)$$
- Small slippage parameter $$\frac{N_w\lambda}{c\tau} < 1$$
- Beam expansion inside wiggler $$\theta_{FEL} = \frac{\lambda}{4\pi}\sqrt{\frac{\gamma}{\varepsilon_n\beta}}$$

Amplifier FEL Can Achieve High Efficiency with a Tapered Wiggler and Energy Recovery



Energy Balance

$$E_1 - E_{inj} = E_0 - E_2$$

$$E_{bend} - E_1 = E_2 - E_{bend}$$

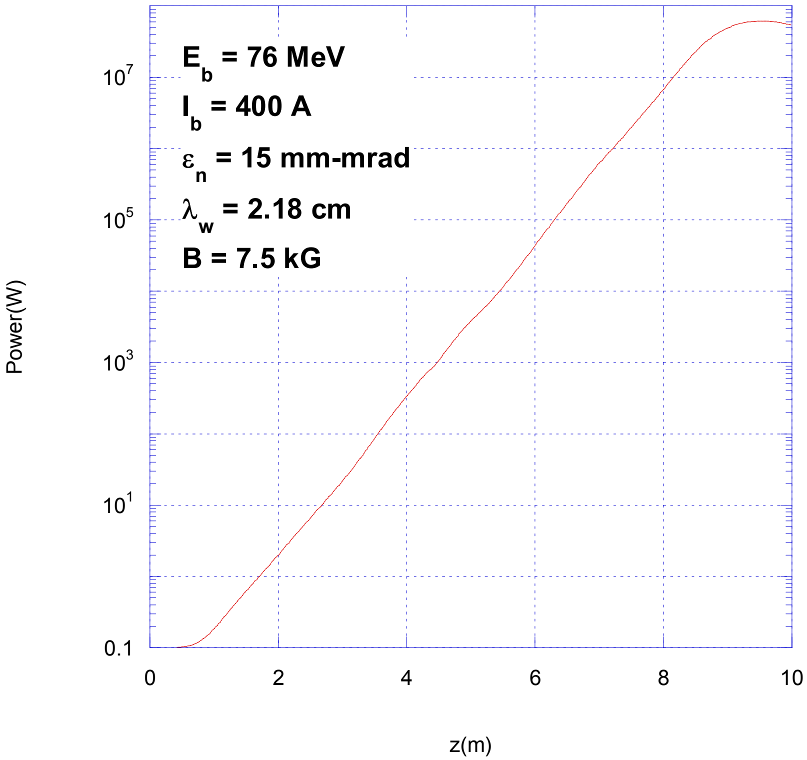
$$E_0 - E_{bend} = E_{bend} - E_{dump}$$

Example:

E_{inj} = 10 MeV	E_0 = 76 MeV
E_1 = 21 MeV	E_2 = 65 MeV
E_{bend} = 43 MeV	E_{dump} = 10 MeV

MEDUSA Simulation for a Uniform Wiggler Predicts 0.2% FEL Efficiency at Saturation

λ	1.06 μm
λ_w	2.18 cm
K	1.085
ρ	0.005
L_G^{1D}	20 cm
L_G^{3D}	37 cm
L_{sat}	9 m
P_{sat}	54 MW



$$P(z) = \frac{1}{9}\frac{P_0 e^{z/L_G}}{\left[1+\frac{1}{9}\frac{P_0}{P_{sat}}\left(e^{z/L_G}-1\right)\right]}$$

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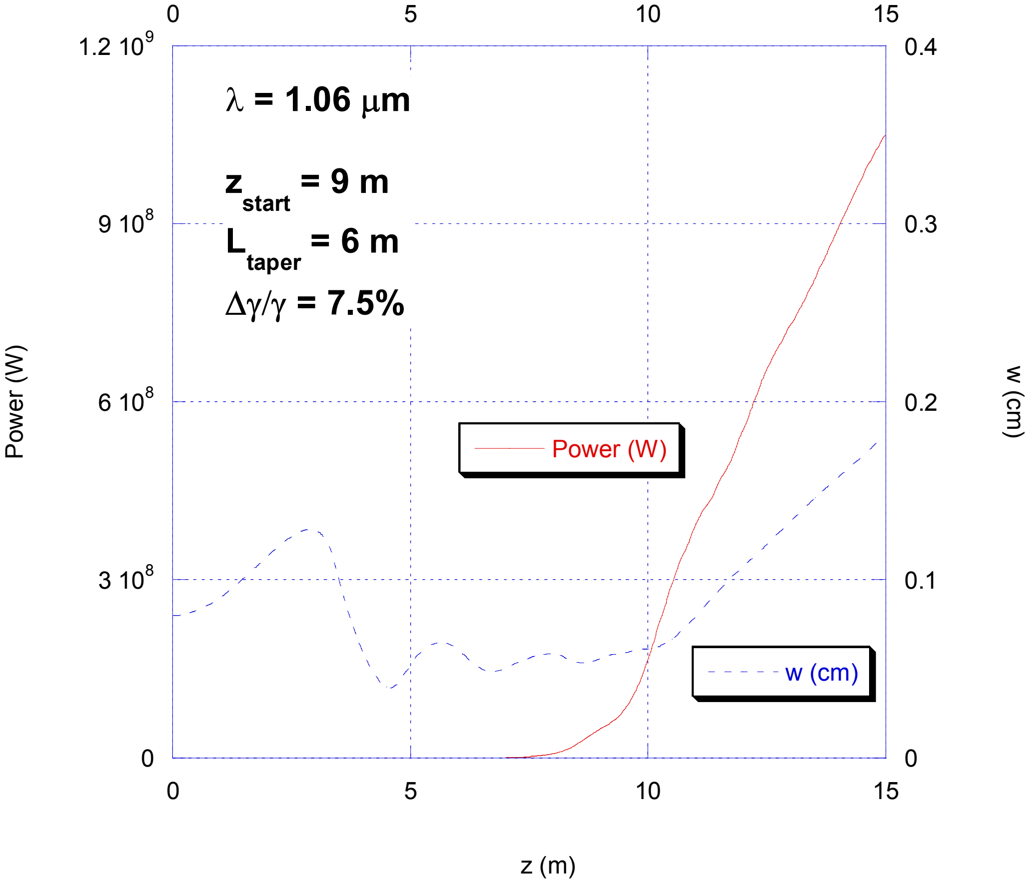
MEDUSA Simulation for a 7.5%, 6-meter Tapered Wiggler Shows 3.5% Efficiency

λ_w	2.18 cm
L_{taper}	6 m
$B_{initial}$	7.5 kG
$K_{initial}$	1.085
K_{final}	0.929
dB/dz	-173 G/m
P_{FEL}	1.05 GW
η_{FEL}	3.5%



$$\eta_{taper} = \frac{\Delta\gamma}{\gamma} \cdot \eta_C\left(I, \frac{\Delta\gamma}{\gamma}, L_{taper}\right)$$

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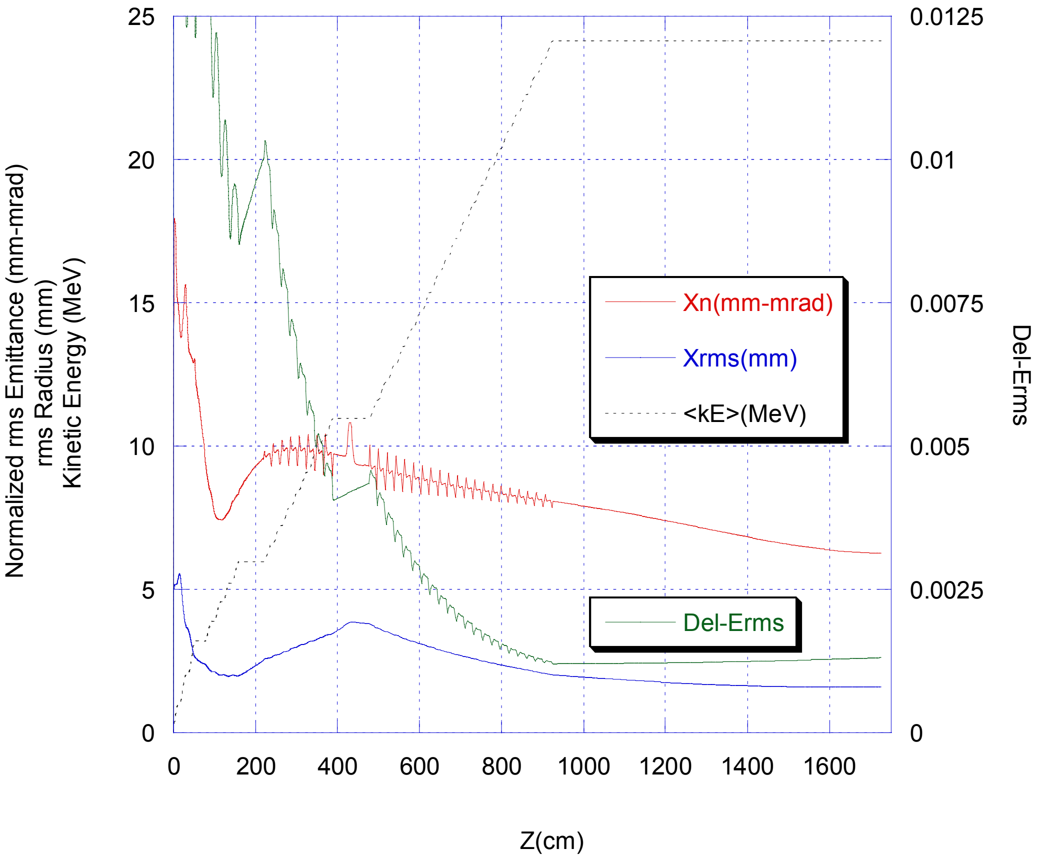
LANL/AES Are Designing a cw 700 MHz Injector to Generate High-Brightness Electron Beams

E	24 MeV
Q	3 nC
$\varepsilon_{x,\,n,\,rms}$	6.3 µm
$\Delta\gamma/\gamma$	0.13 %
$\varepsilon_{z,\,u,\,rms}$	293 keV-ps
τ (fwhm)	24 ps
I_{peak}	125 A



Steve Russell, PARMELA Simulations
See Kurennoy *et al.*, WE-P-30.

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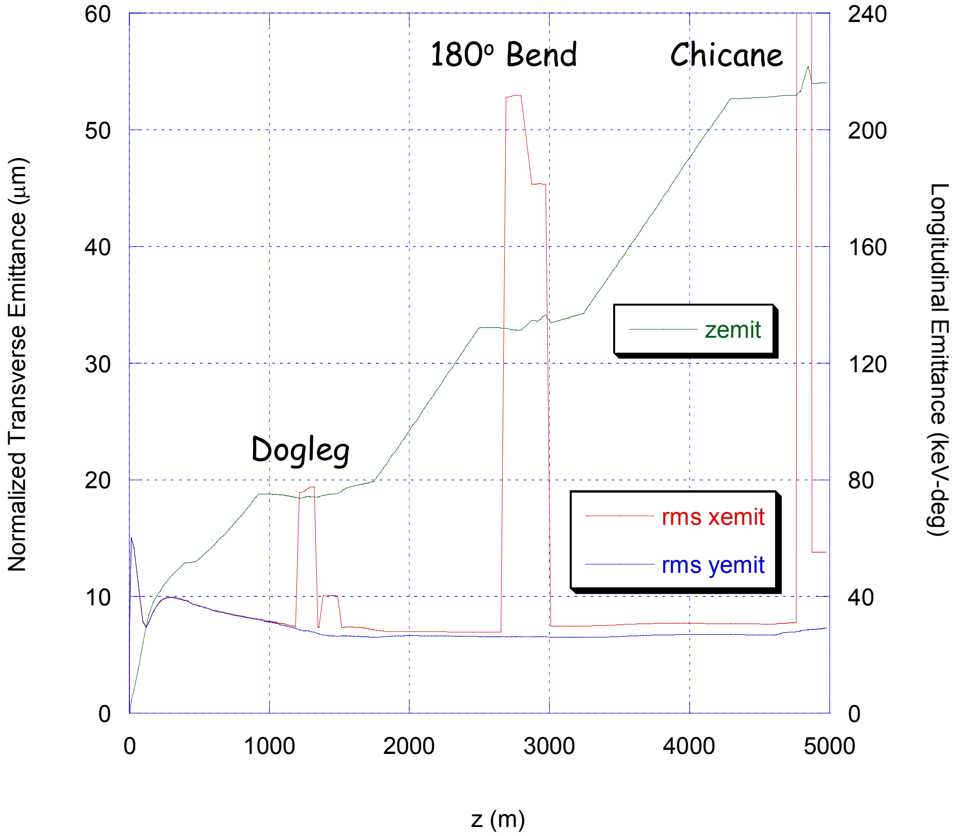
Beam Brightness Can Be Preserved by Mitigating Space Charge Emittance Growth

Q	3 nC
$\varepsilon_{x, in, rms}$	7.1 μm
$\varepsilon_{y, in, rms}$	6.6 μm
$\Delta\gamma/\gamma_{in, rms}$	0.13%
$\varepsilon_{x, out, rms}$	13.8 μm
$\varepsilon_{y, out, rms}$	7.3 μm
$\Delta\gamma/\gamma_{out, rms}$	0.5%



Steve Russell's PARMELA Simulations

CSR-Induced Emittance Growth in Bends and Chicane Is Harder to Calculate and Correct

- Space-charge emittance growth

For 3 nC, emittance growth = 7 → 14 mm-mrad

- Coherent Synchrotron Radiation

$$\boxed{P_{CSR} = 3^{1/3} \frac{N^2 e^2 c}{4\pi\varepsilon_0 R^{2/3} \delta^{4/3}}}$$

  - Emittance Growth

$$\boxed{\Delta\varepsilon_{CSR} = 3^{1/3} \alpha \cdot r \cdot \left(\frac{I}{I_A}\right) \frac{1}{R^{2/3} \delta^{1/3}}}$$

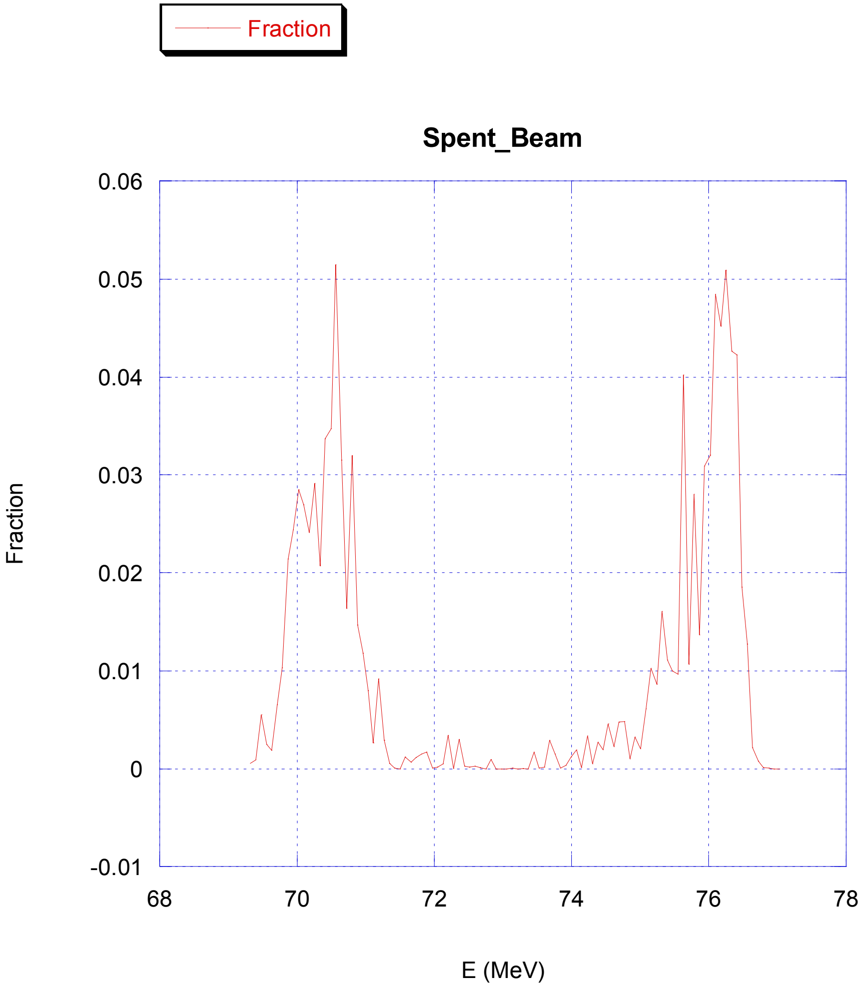
  - Microbunching

Chicane (Simple Analytic Prediction)
$\Delta\varepsilon_{CSR}$ ~ 100 mm-mrad

180° Bend (STI-Optronics)
$\Delta\varepsilon_{CSR}$ ~ 8 mm-mrad

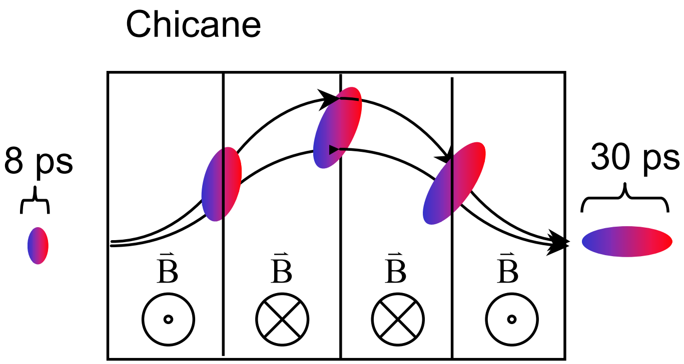
Electron Beam Energy Spread exiting a Tapered Wiggler Is Twice the FEL Efficiency

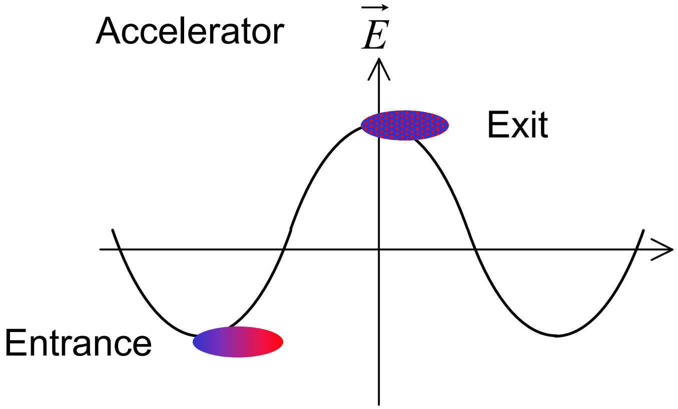
- Capture efficiency ~ 50%
- $\Delta\gamma/\gamma$ ~ 2 x FEL efficiency
- Difficult to transport beams with large energy spread
- <u>Solution</u>: Compress energy spread before 2nd 180° bend.

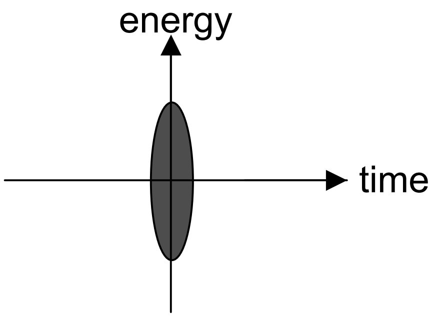


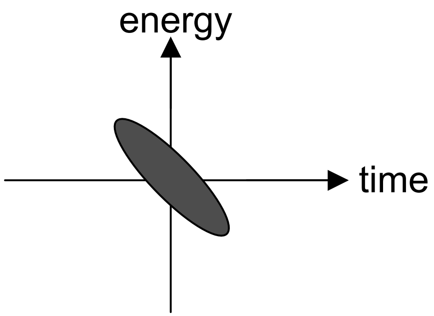
MEDUSA Simulations

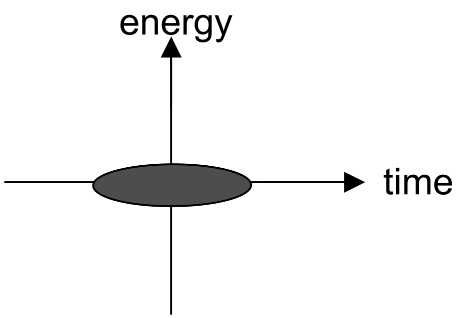
Energy Spread Compressor Facilitates Transport of Large Energy Spread Beams











Use chicane to stretch electron bunch and near-zero-crossing linac to accelerate only low-energy electrons to original energy.

Summary

- Amplifier FELs have the potential of:
    - Large single-pass gain (10^5 - 10^8)
    - Low risk of optical damage (No high-R optics)
    - High efficiency (3.5% scalable to 10-15%)
- Key technological challenges include:
    - Brightness preservation in bends (CSR)
    - Energy spread compression