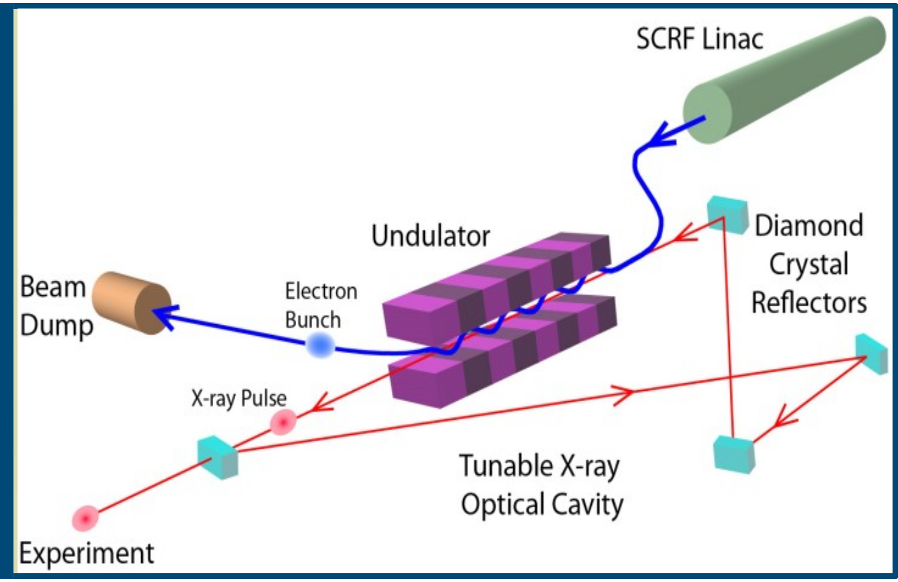
Beam dynamics for an x-ray free-electron oscillator (XFELO)



Ryan Lindberg
Accelerator Operations and Physics Group
Argonne National Laboratory

Coherence in particle and photon beams: past, present, and future
(Kwang-Je Kim Fest)
Friday March 15, 2019

Introduction

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- While SASE took off, the oscillator laid dormant for more than 20 years

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- This first modern XFELO paper contained many important contributions

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The XFELO revival paper[2] could be used to outline my outline

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Describes longitudinal evolution (my first work on this subject)

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One of my first calculations → harmonic XFELO

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Recent investigations using superconducting linacs and storage rings

7. Calculation of the basic stability requirements

Some progress + future work

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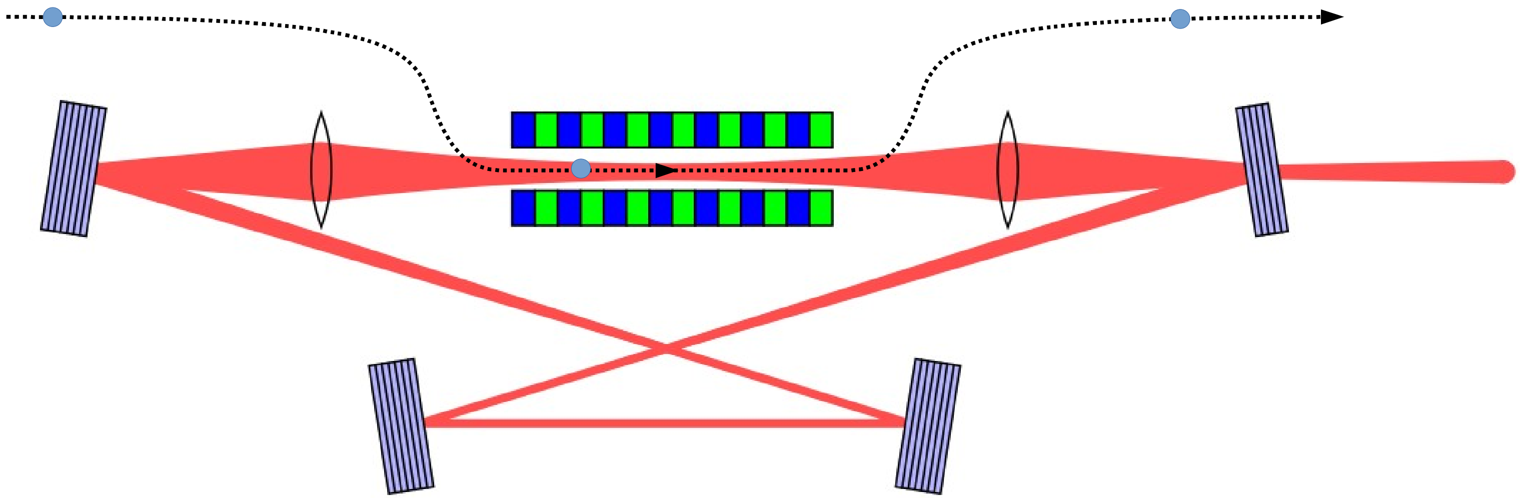
X-ray FEL oscillator schematic



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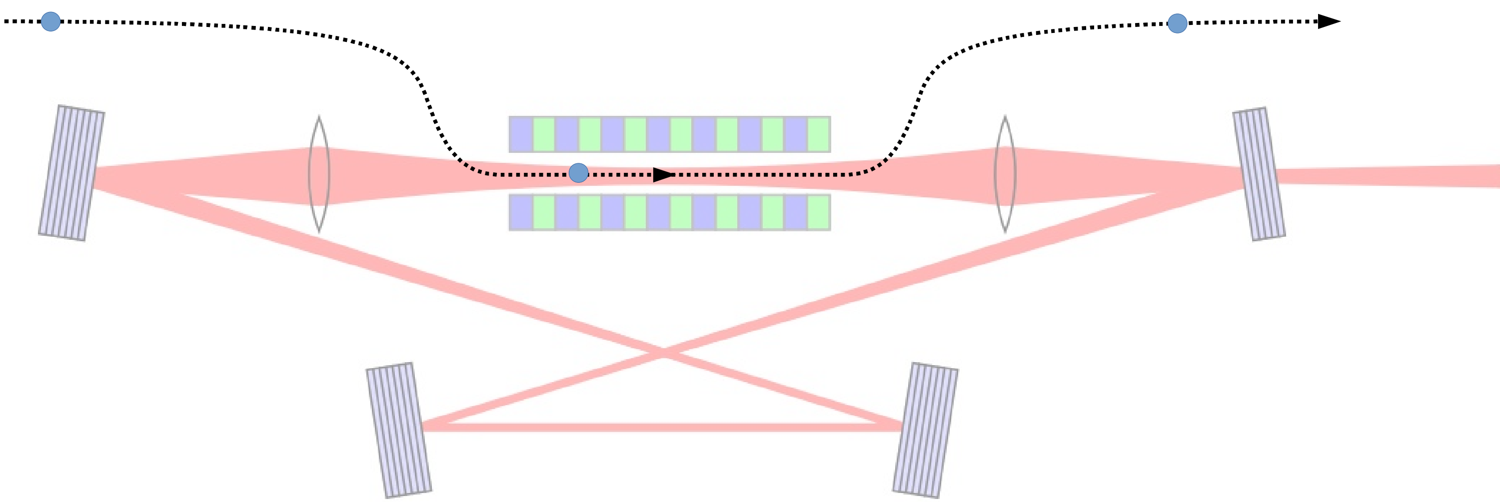

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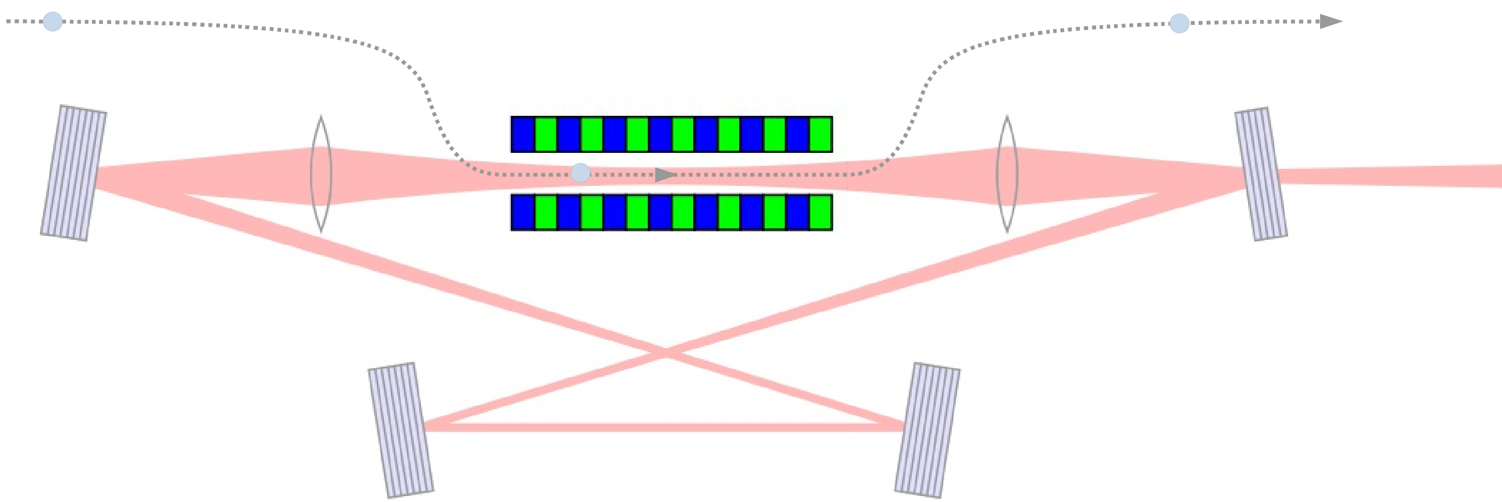

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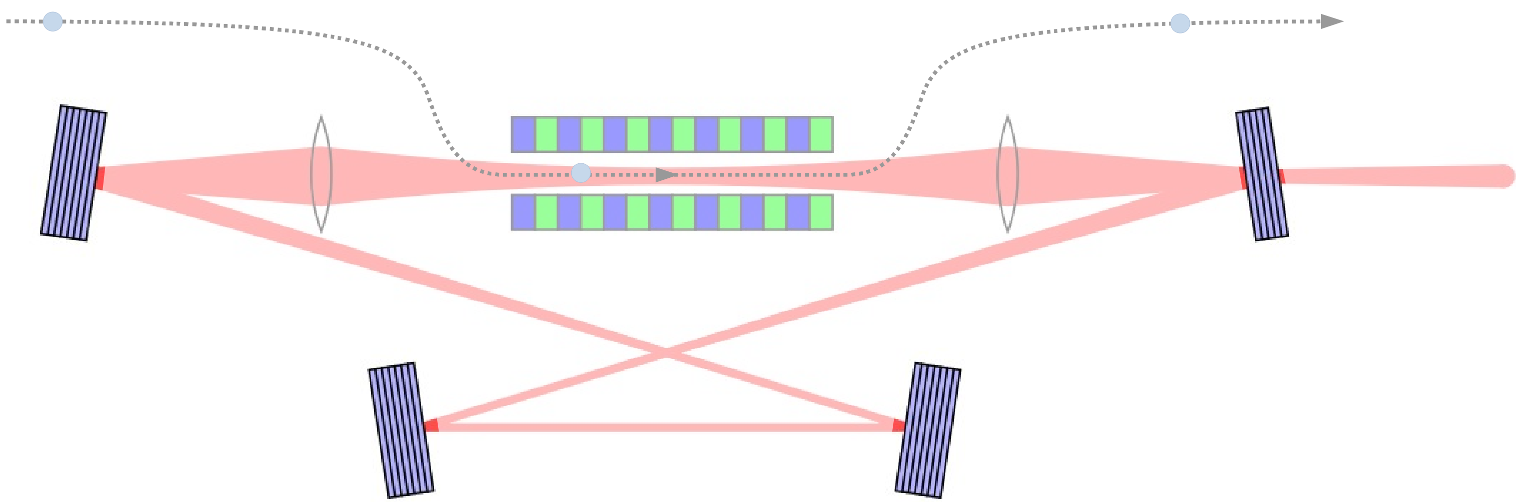

- High-brightness, low (10-300 A) peak current electron beam at high (~MHz) repetition rate
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  - Perfect diamond crystals that reflect x-rays via Bragg diffraction [3 thick crystals with low loss, $(1-R) < 5\%$; 1 thin crystal to allow for ~5% transmission]

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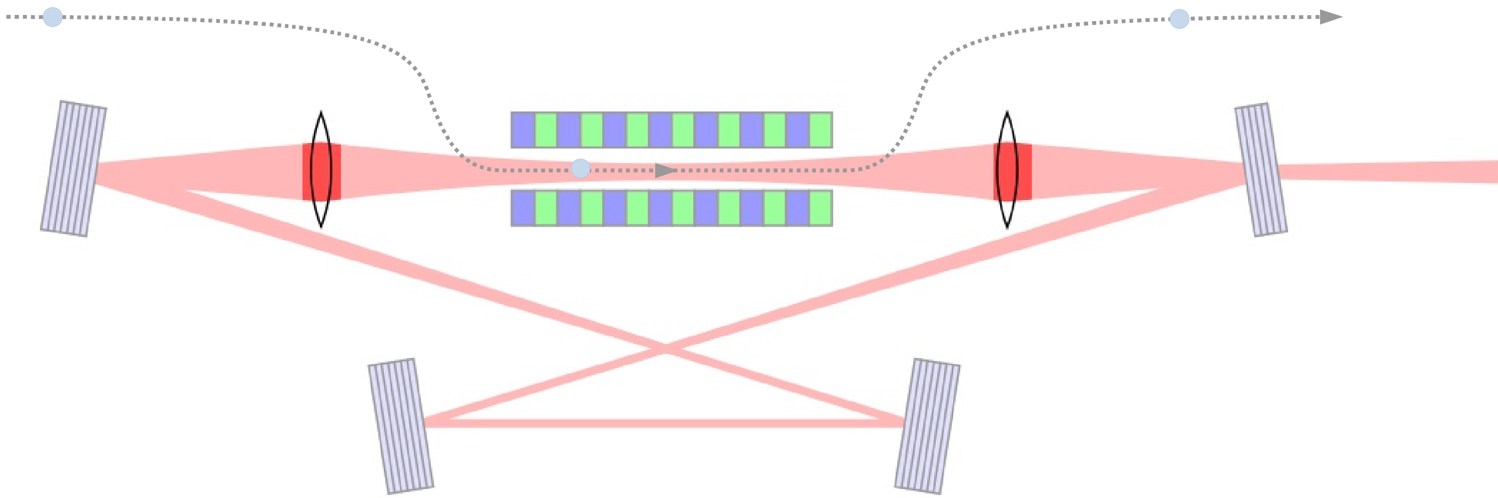

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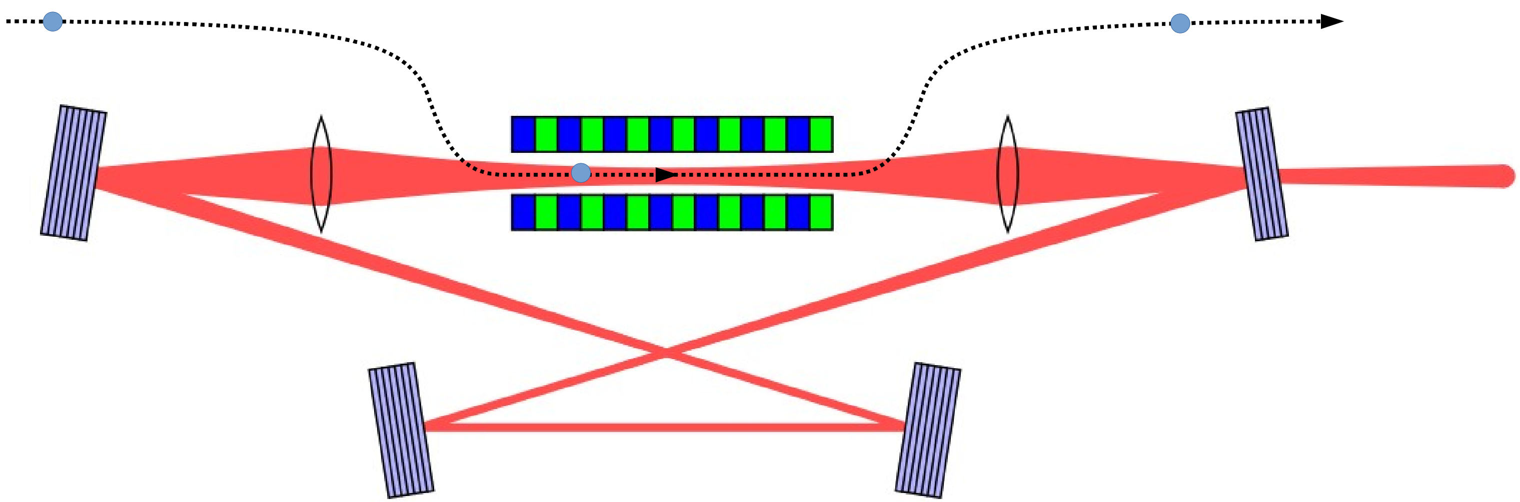

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  - Bow-tie shape is a wrapped-up monochromator that allows for wavelength tuning[3,4]

[3] R.M.J. Cotterill, "A universal planar x-ray resonator" Appl. Phys. Lett. **12**, 403 (1968).
[4] K.-J. Kim and Y. Shvyd'ko. "Tunable optical cavity for an x-ray free-electron-laser oscillator," PRST-AB **12**, 030703 (2009).

XFELO is a complementary source to SASE

Characteristic	SASE	XFELO
Pulse duration	1 to 200 fs	200 to 2000 fs
Photons/pulse	~10^{12}	~10^{9}
Energy BW	~ 10 eV	~10^{-2} eV
Coherence	Transverse	Fully
Repetition rate	Variable	~ MHz
Stability	1-100% depending on chosen BW	< 1%
Brightness	~10^{32}	~10^{32}

XFELO Science

1. Inelastic x-ray scattering
2. Nuclear resonant scattering
3. X-ray photo-emission spectroscopy
4. Hard x-ray imaging
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6. ???

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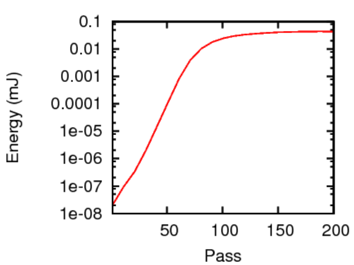
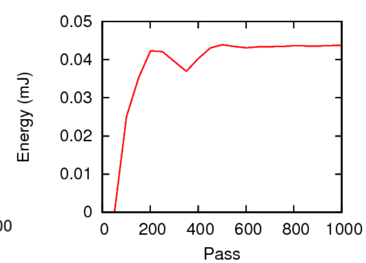
Beam energy γmc^2	7 GeV
Energy spread σ_γ/γ	$2\text{x}10^{-4}$
Norm. emittance ε_n	0.2 mm*mrad
Peak current I	10 A
Undulator periods N_u	3000
Undulator length L_u	53 m





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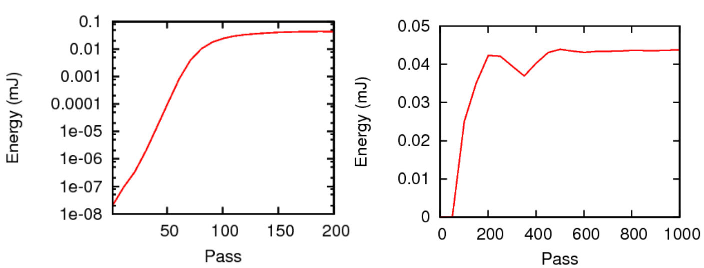

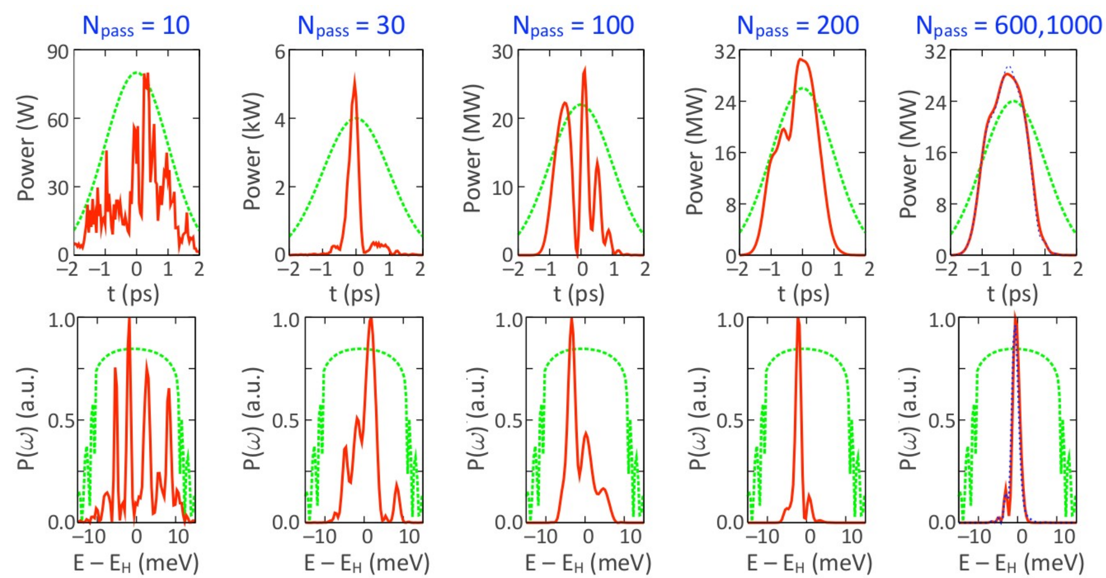

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From K.-J. Kim, Y. Shvyd'ko, and S. Reiche, PRL **100**, 244802 (2008):

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- Gain approximately follows electron beam current: $G(t) \approx G e^{-t^2/2\sigma_e^2} \approx G(1 - t^2/2\sigma_e^2)$
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➡ General solution is spanned by a sum of Gauss-Hermite modes

$$E_m(t,n) = e^{\Lambda_m n} e^{-t^2\sigma_\omega^2\ell/2} \exp\left(-\frac{\sqrt{G}\sigma_\omega}{2\sigma_e}t^2\right) H_m\left(G^{1/4}\sqrt{\frac{\sigma_\omega}{\sigma_e}}t\right)$$

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Gain due to finite electron beam

Loss and filtering due to Bragg crystal

Delay

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Effective single pass gain with $\Lambda_m = \frac{1}{2}\left[G - R - \frac{\sqrt{G}}{\sigma_e\sigma_\omega}(2m+1) - \frac{\sigma_\omega^2\ell^2}{2}\right]$

Gain is reduced when electron beam duration σ_e approaches the inverse bandwidth of crystal $1/\sigma_\omega$

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We decompose the growing field using the Hermite basis functions[8], whose growth we can compare to the supermode theory:

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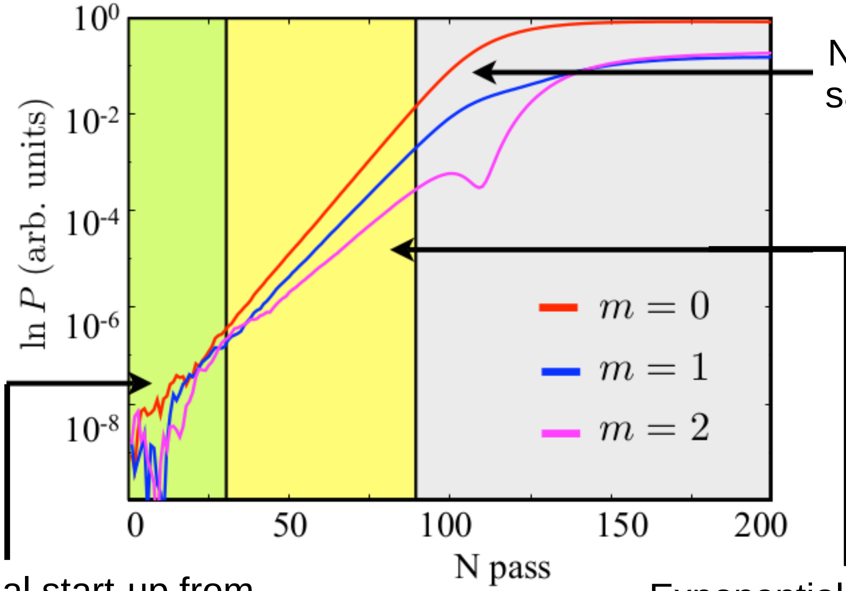

Nonlinear saturation

Initial start-up from noisy spontaneous radiation

Exponential growth of three lowest-order supermodes

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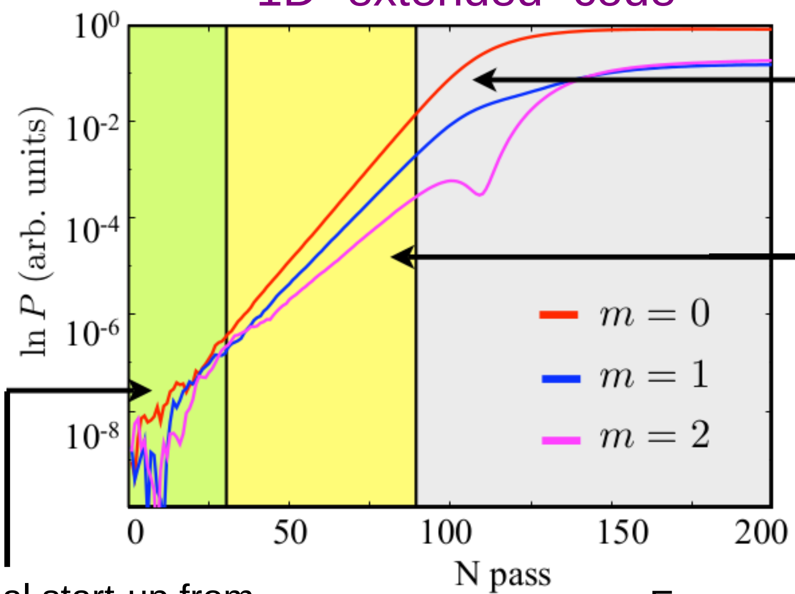

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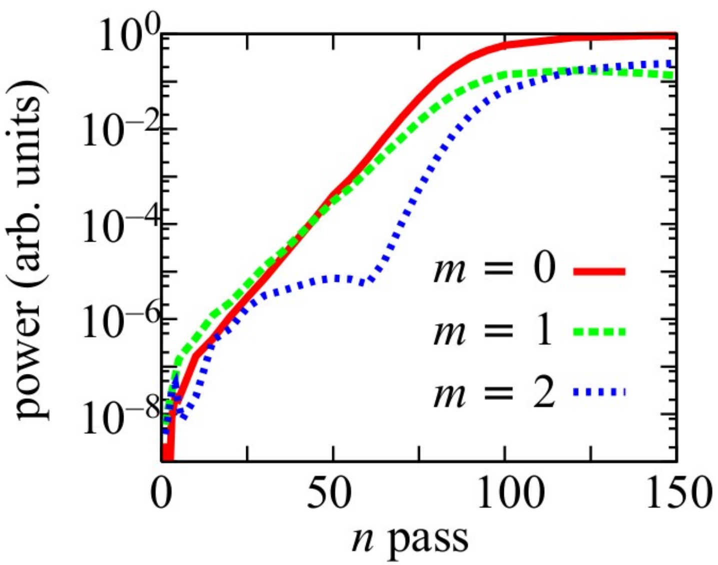
2D GINGER code



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3D formula for the linear FEL gain

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Gain can be written as a convolution over the initial brightness functions[9]

$$G = \frac{n_e \chi_h \kappa_h}{\lambda^2} \frac{\int d\eta d\boldsymbol{p} d\boldsymbol{\phi} d\boldsymbol{x} d\boldsymbol{y}\, \mathcal{B}_E(\boldsymbol{y}, \boldsymbol{\phi}) \mathcal{B}_U(\eta, \boldsymbol{x} - \boldsymbol{y}, \boldsymbol{\phi} - \boldsymbol{p}) \frac{\partial}{\partial \gamma} \bar{F}(\gamma, \boldsymbol{x}, \boldsymbol{p})}{\int d\boldsymbol{\phi} d\boldsymbol{y}\, \mathcal{B}_E(\boldsymbol{y}, \boldsymbol{\phi})}$$

Input radiation brightness

Undulator brightness (Wigner) function

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Assume Gaussian field in position and angle

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When the dust settles...

$$G = \frac{I}{I_A} \frac{\pi h K^2 [\mathrm{JJ}]_h^2 L_u^3}{\gamma^3 \lambda_u \Sigma_x^2} \int_{-1/2}^{1/2} dsdz\, e^{-2[2\pi N_u (z-s) h \sigma_\gamma/\gamma]^2} \frac{(z-s)\left\{\sin[2x(z-s)] - i\cos[2x(z-s)]\right\}}{1 + zs\frac{L_u^2 \Sigma_\phi^2}{\Sigma_x^2} - i(z-s)\left[kL_u\Sigma_\phi^2 + \frac{L_u}{4k\Sigma_x^2}\right]}$$

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Energy spread effect with harmonic

Detuning from resonance

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Emittance and diffraction effects

$$\Sigma_x^2 \equiv \sigma_x^2 + \sigma_r^2 \qquad \Sigma_\phi^2 \equiv \sigma_p^2 + \sigma_\phi^2$$

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Harmonic number

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Harmonic XFELO for "low" energy e-beams

- For fixed e-beam parameters, the gain at a harmonic can be larger than that at the fundamental if the energy spread is small enough, $h\sigma_\gamma/\gamma < 1/2\pi N_u$
- Hence, an XFELO is possible for with less linac and lower energy electron beams[11]

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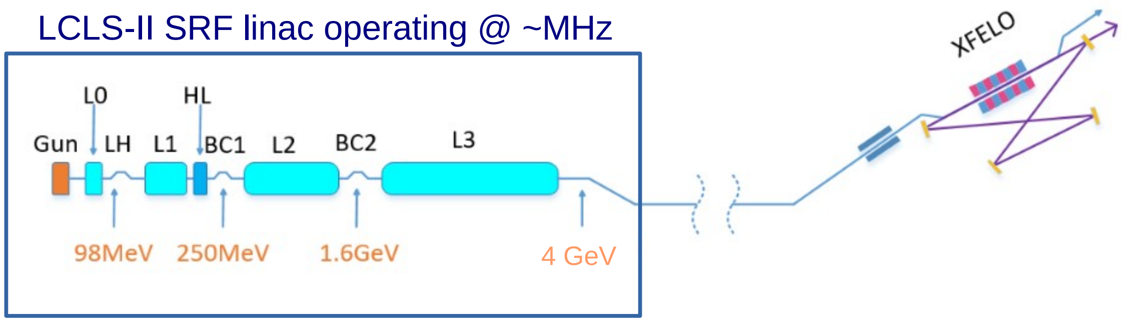

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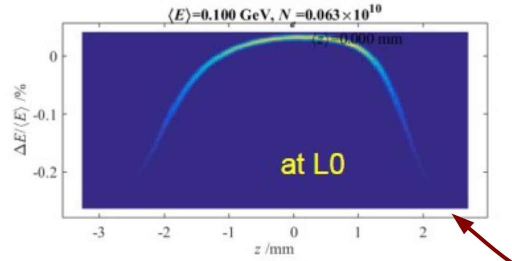

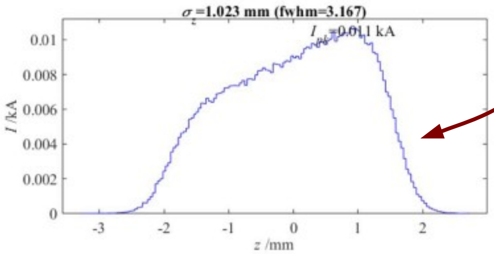

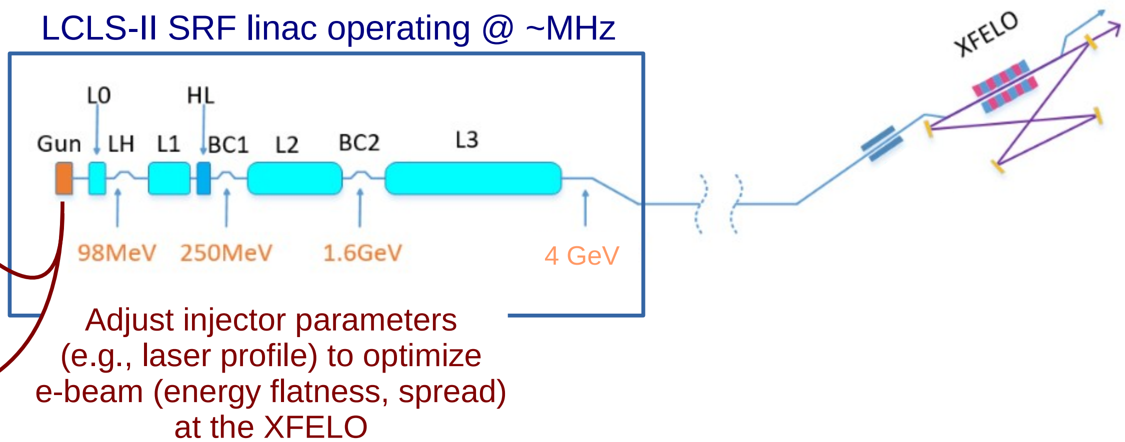

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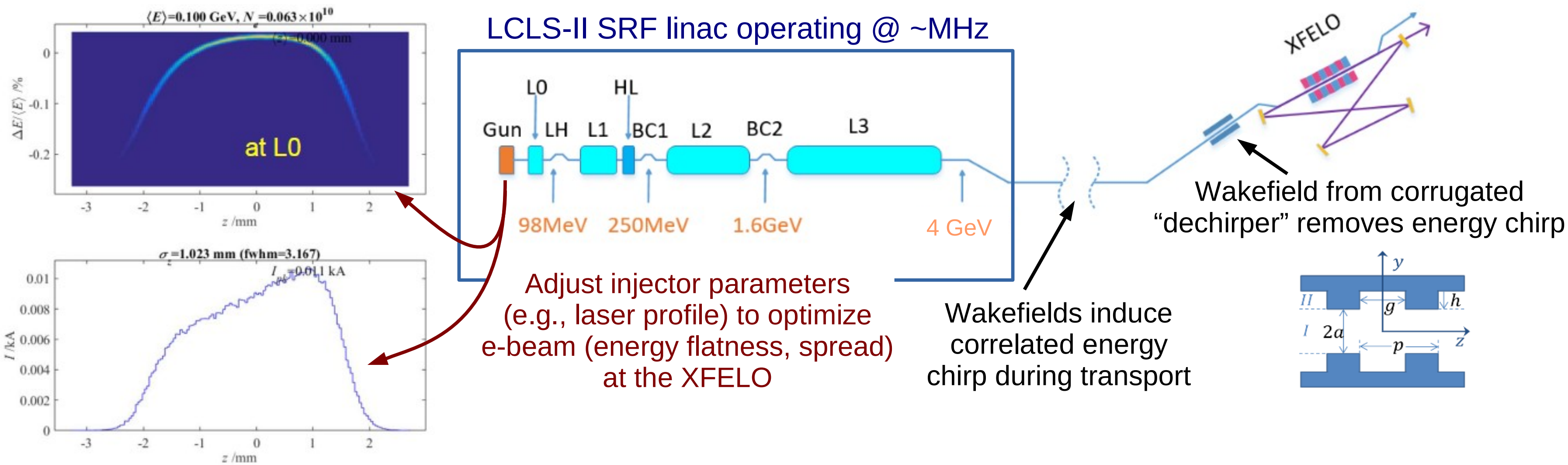

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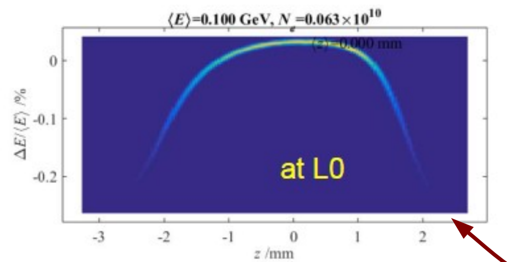
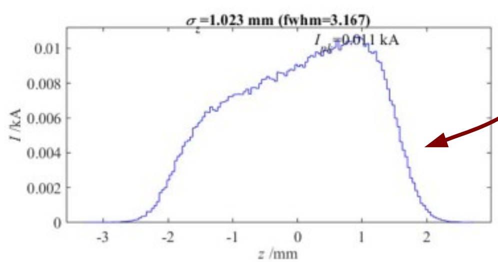
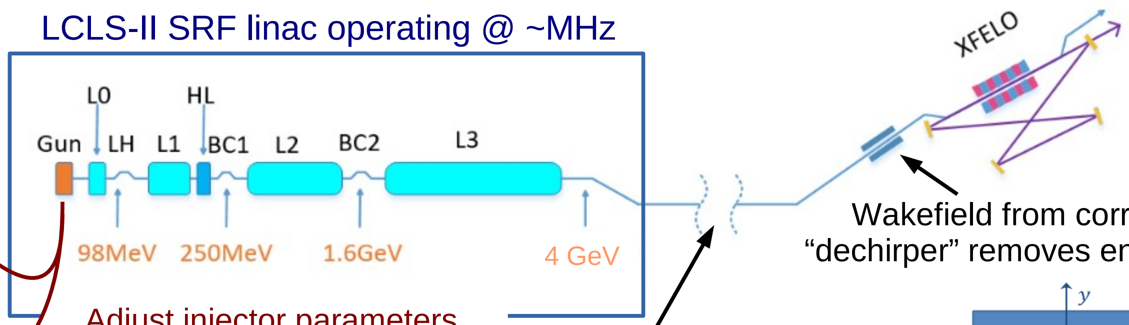


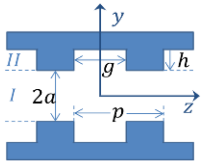


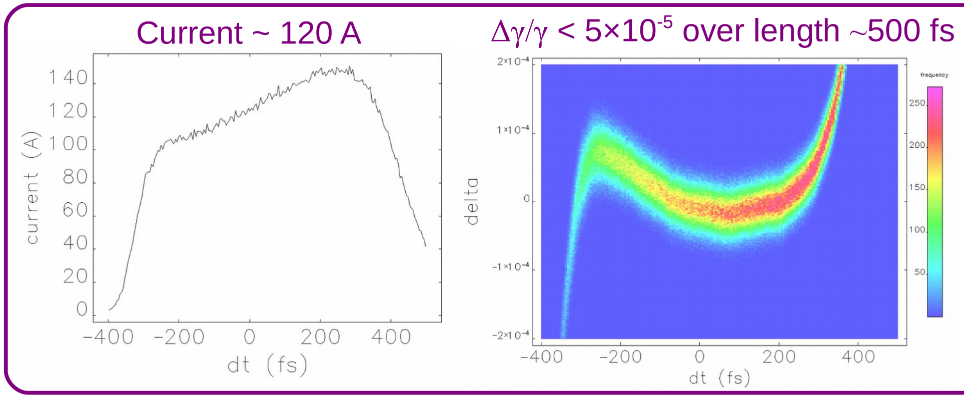
LCLS-II SRF linac operating @ ~MHz



Adjust injector parameters (e.g., laser profile) to optimize e-beam (energy flatness, spread) at the XFELO

Wakefields induce correlated energy chirp during transport





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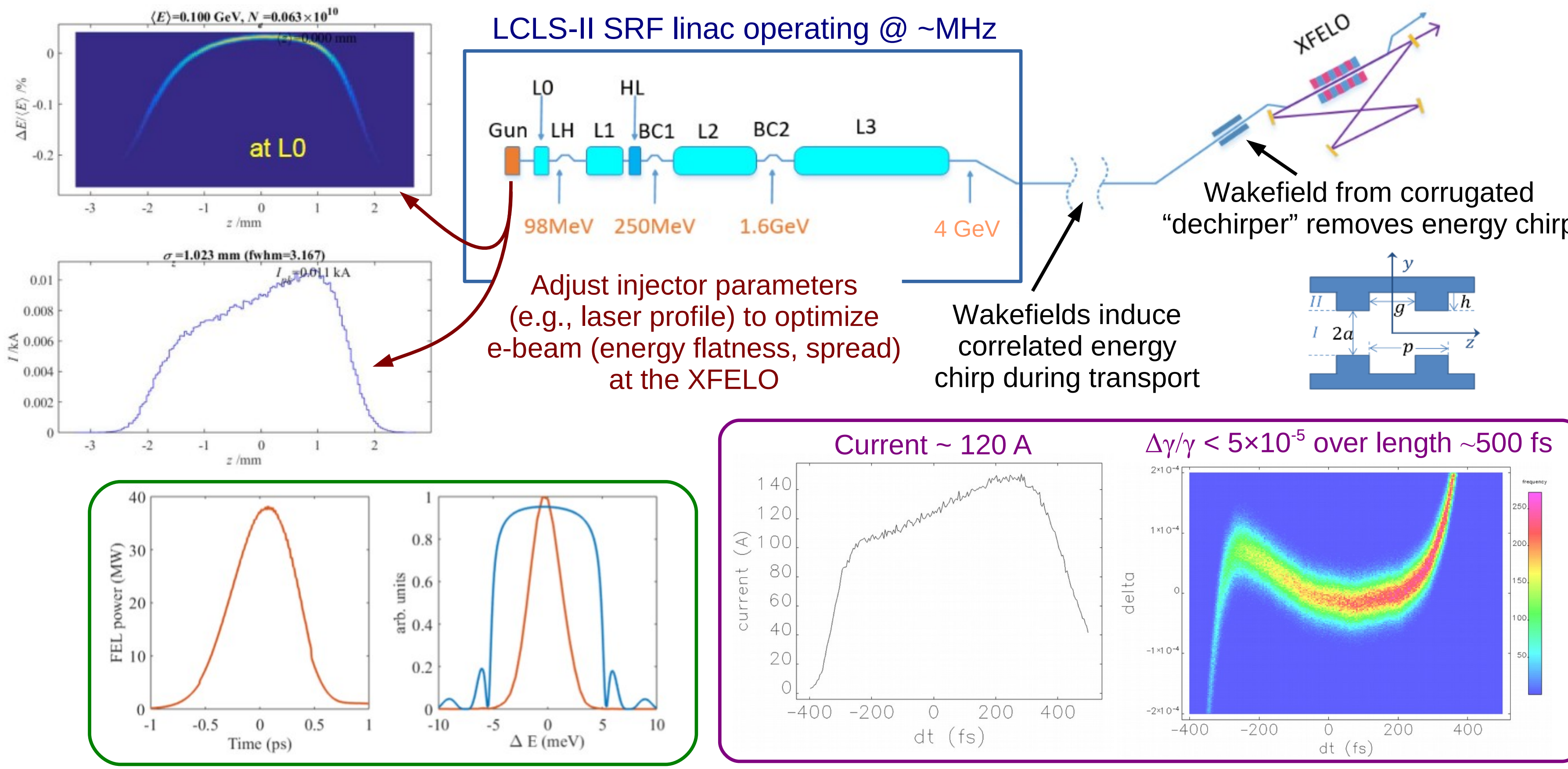

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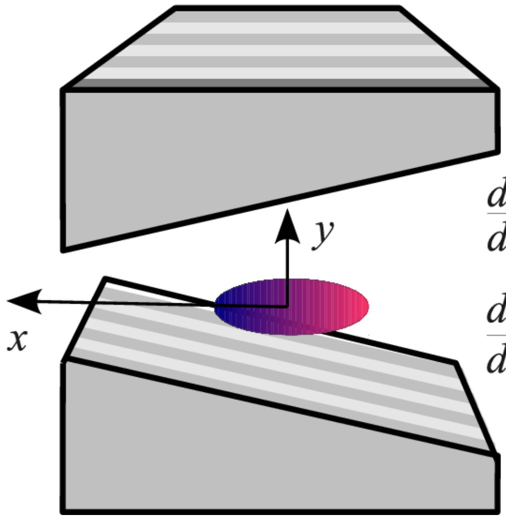
Reducing energy spread requirement with a transverse gradient undulator

- Gain suffers when the energy spread becomes larger than the FEL bandwidth, $\sigma_\gamma/\gamma > 1/3N_u$
- The energy spread effect can be compensated if we both
  1. Use a transverse gradient undulator (TGU) to vary the FEL resonance with position[13,14]
  2. Introduce carefully matched dispersion to correlate the energy with position

$$\lambda_1 = \lambda_u \frac{1 + \frac{1}{2}K(x_j)^2}{2\gamma_j^2}$$



$$\frac{dB}{dx} > 0$$

$$\frac{d\gamma}{dx} > 0$$

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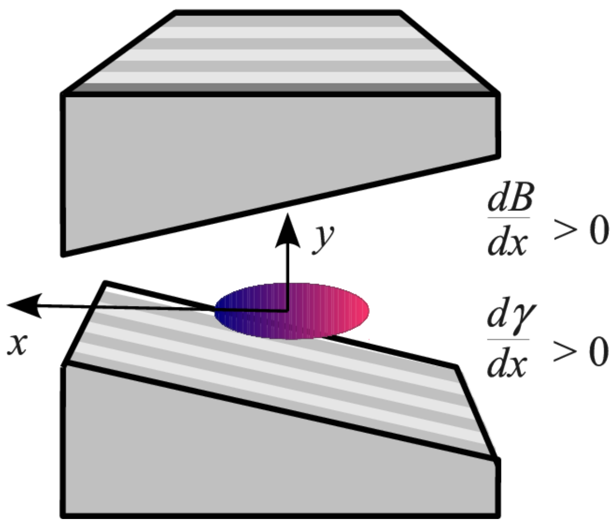

Introduce dispersion such that $x_j \to D\eta_j$

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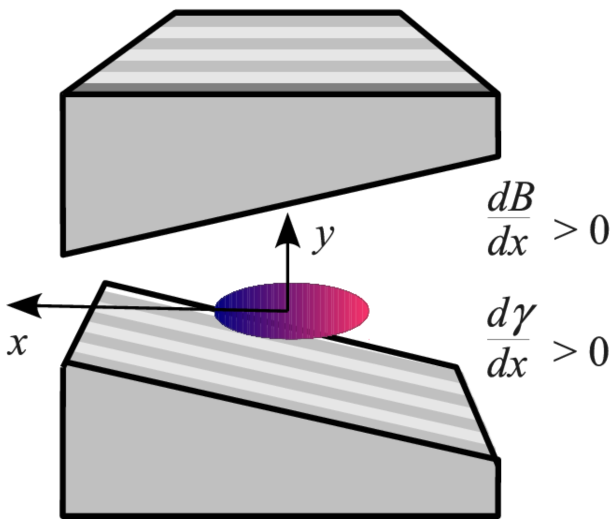

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Energy spread dependence vanishes if we choose

$$\frac{\partial K}{\partial x} D = \frac{2+K_0^2}{K_0}$$

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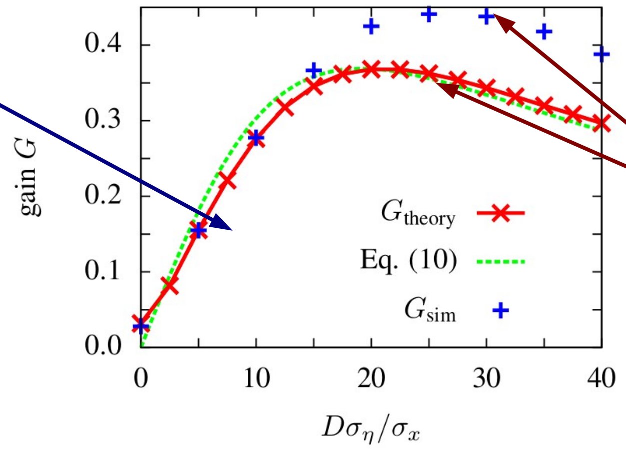
TGU-enabled XFELO in an "ultimate" storage ring[15]

Gain is maximized by choosing the dispersion/gradient to balance two competing effects:

Increasing γ-x correlation (dispersion D) reduces the variation in resonance condition due to energy spread, thereby increasing the gain



Increasing dispersion D further increases e-beam size, reducing e-beam density, and thus the coupling to the field

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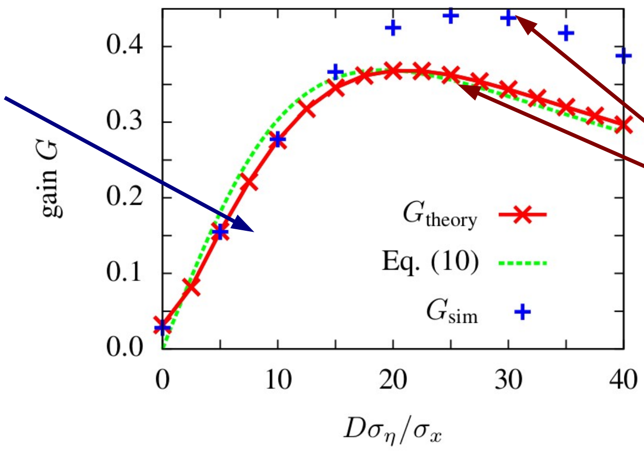

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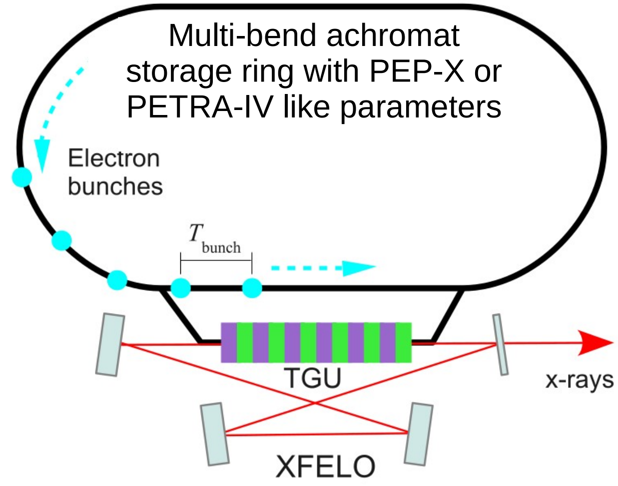
A TGU enables an XFELO in an ultra-low emittance hard x-ray storage ring with large circumference



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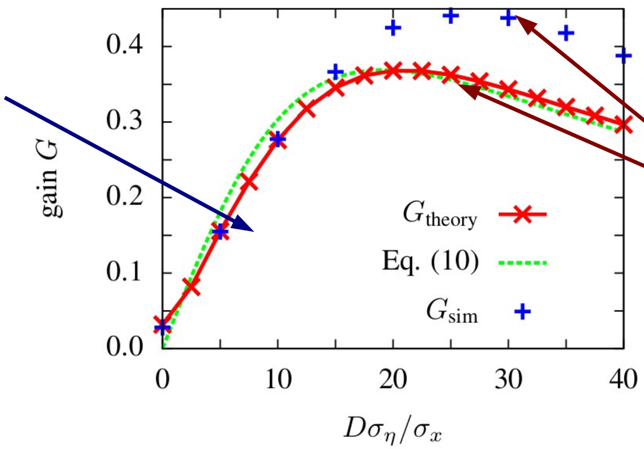

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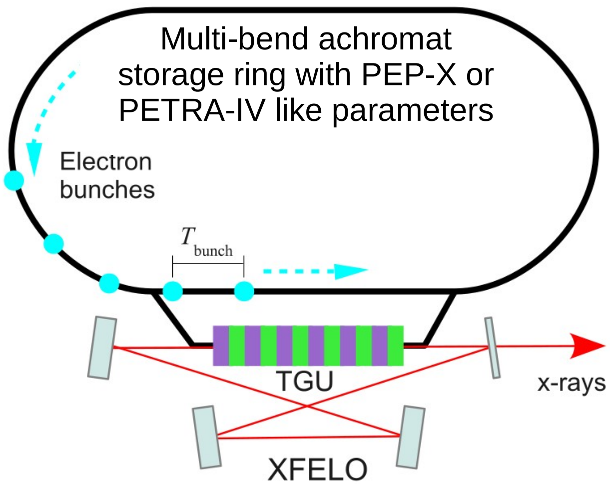
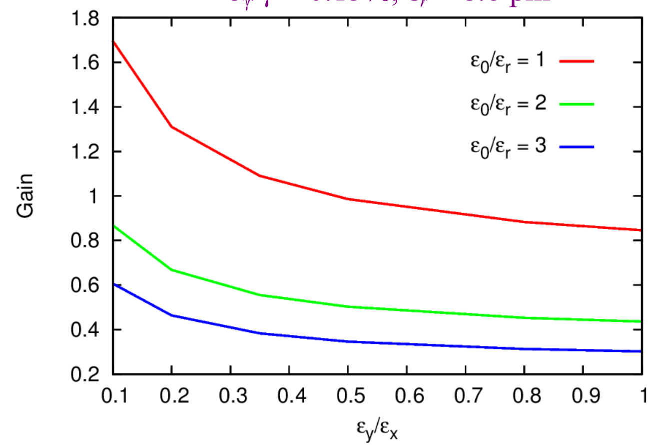


Decreasing the coupling and dispersing along y yields larger gain

$\sigma_\gamma/\gamma = 0.15\%$, $\varepsilon_r = 8.6$ pm



From Yuan Shen Li

[15] R.R. Lindberg, K.-J. Kim, Y. Cai, Y. Ding, and Z. Huang, "Transverse-gradient undulators for a storage ring XFELO" Proc. FEL 2013, pp 740 (2013).

Tolerances and stability

- Requirements on longitudinal tolerances given by supermode theory

Jitter in arrival time of electron & photon beams << 1/(crystal bandwidth)

Note that (bunch length) $\lesssim$ 1/(crystal bandwidth)

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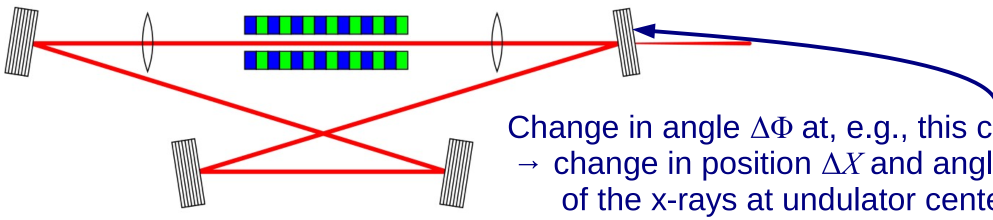

Change in angle $\Delta\Phi$ at, e.g., this crystal → change in position ΔX and angle $\Delta\Theta$ of the x-rays at undulator center

Requiring that ΔX < [0.1(FEL mode size) ~1 μm] implies that $\Delta\Phi$ < 20 nrad.

Requiring that $\Delta\Theta$ < [0.1(mode divergence) ~0.1 μrad] gives a less stringent requirement.

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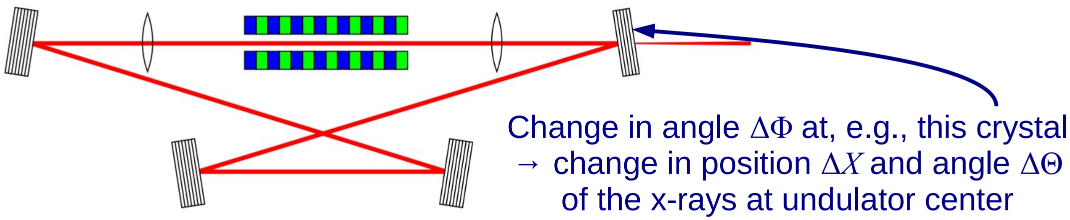

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- Fluctuations on time scales much less than the cavity ring-down time (microsecond) are averaged over, resulting in a reduction of the gain
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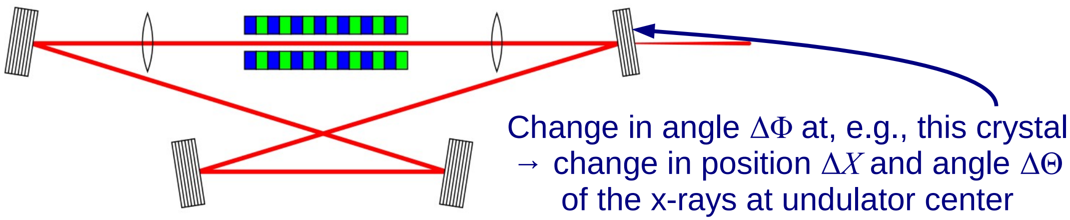

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- Ultimate stability should scale as the (spontaneous power in narrow BW)/(saturation power)

XFELO proof of principle at LCLS-II

- SLAC has proposed a regenerative amplifier FEL (RAFEL)[16] at LCLS-II[17]
  - RAFEL = high-gain oscillator with potentially large losses
  - Route to TW pulses if combined with Q-switching (sudden release of trapped cavity power via, e.g., pulse heating and lattice distortion of Bragg crystal)
- We are teaming up with the RAFEL team to propose an RA/XFEL(O) experiment at LCLS

[16] Z. Huang and R.D. Ruth. "Fully coherent x-ray pulses from a regenerative-amplifier free-electron laser, " PRL **96**, 144801 (2006).
[17] G. Marcus, Y. Ding, J. Duris, Y. Feng, Z. Huang, J. Krzywinski, T. Maxwell, D. Ratner, T. Raubenheimer, K.-J. Kim, R. Lindberg, Y. Shvyd'ko, D. Nguyen, "X-ray regenerative amplifier free-electron laser concepts for LCLS-II," Proc. FEL2017, pp. 192.

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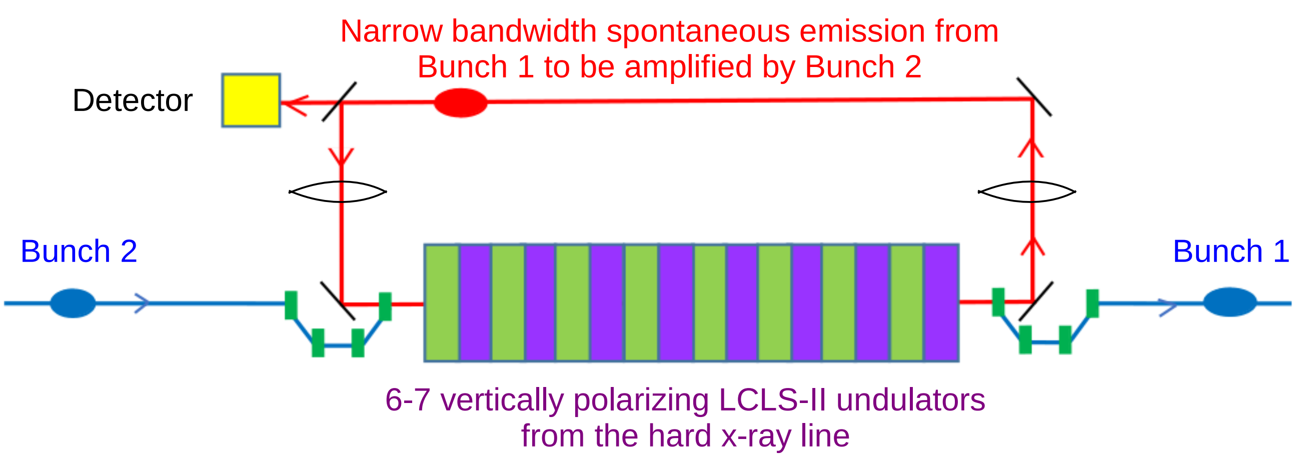
- XFELO goals are to show sufficient cavity stability to show gain in a two-bunch configuration



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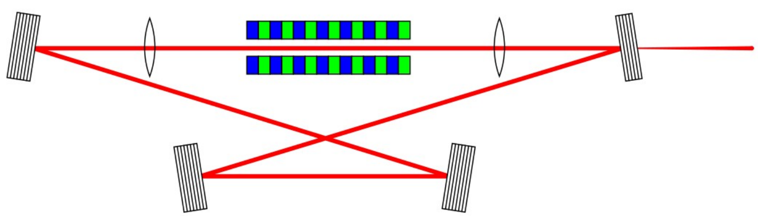
XFELO as the heart of an "ultimate" x-ray facility



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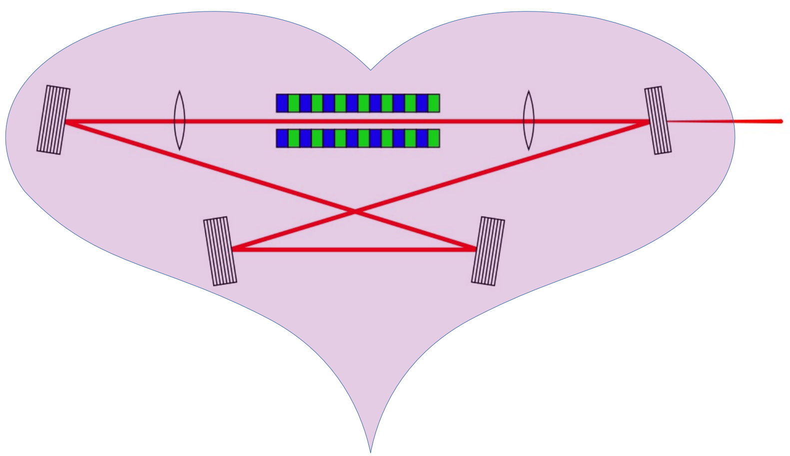

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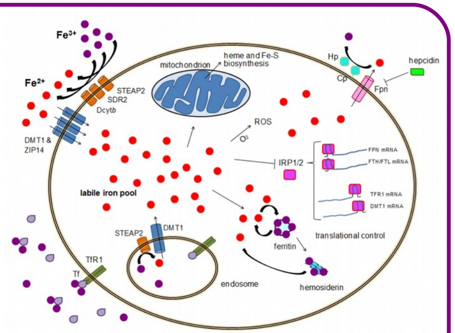
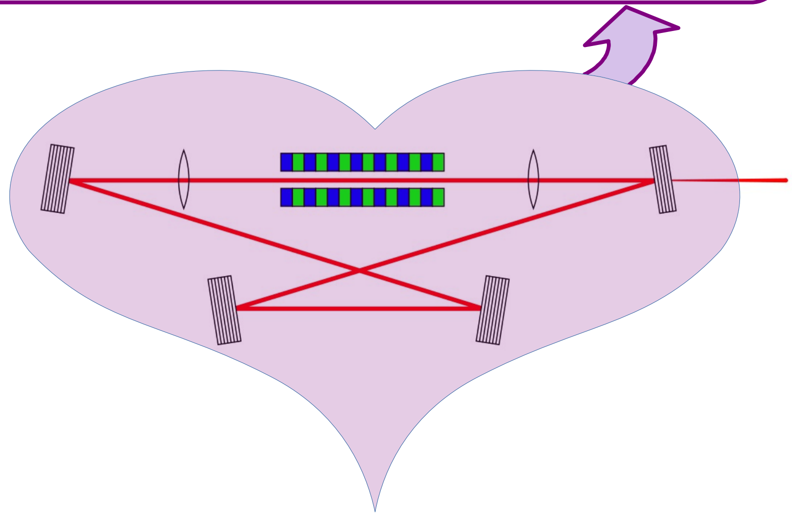
Science relying on fully coherent, 10^9 /pulse with ultrafine (meV) spectral resolution at a MHz rep rate[18]





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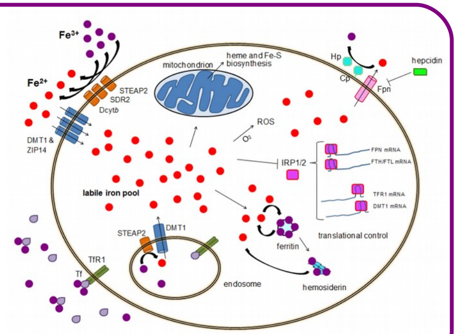
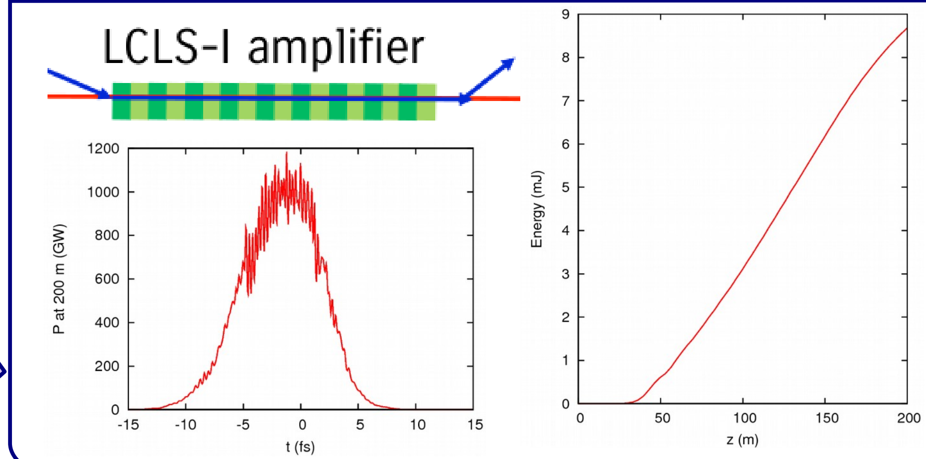
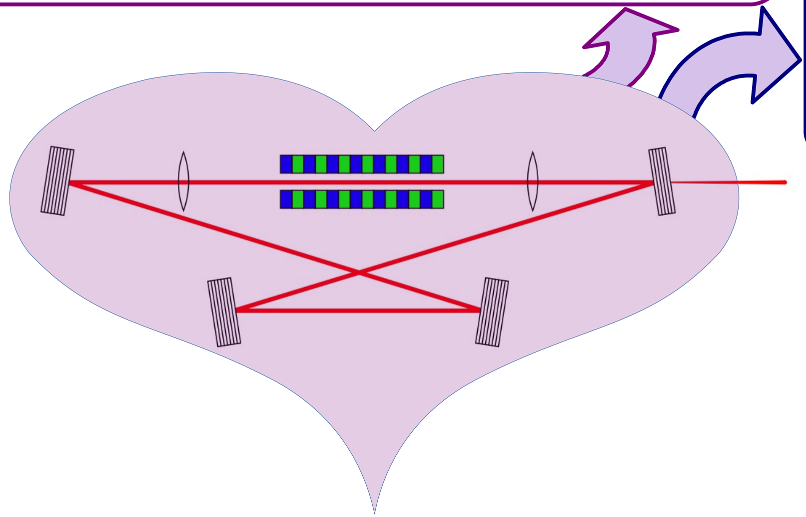


TW pulses by seeding a tapered high-gain FEL[19]





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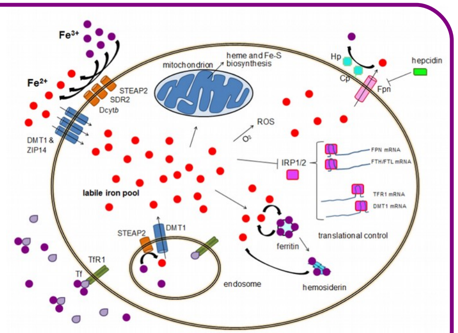

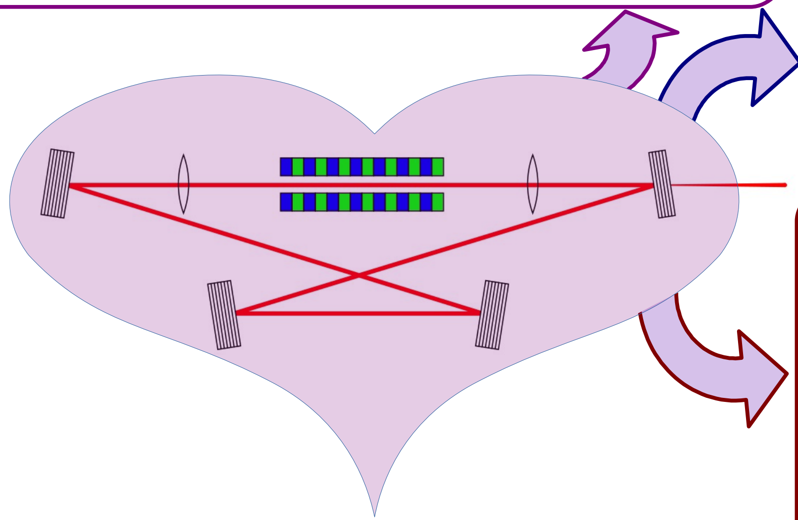

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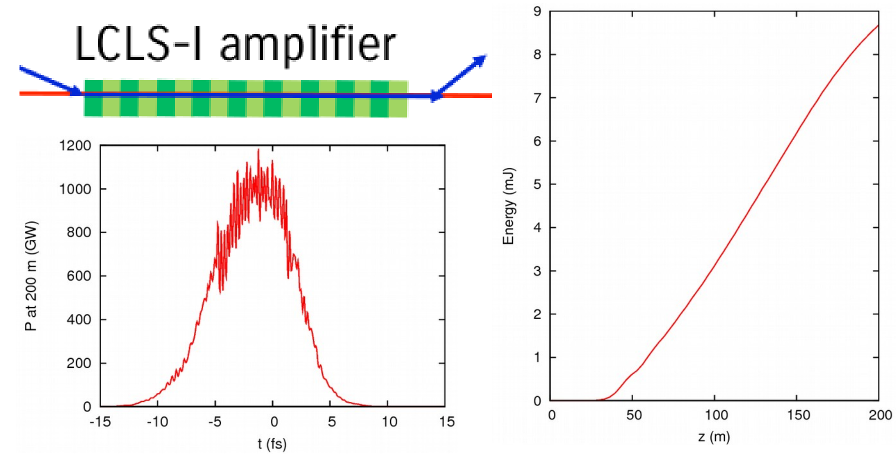

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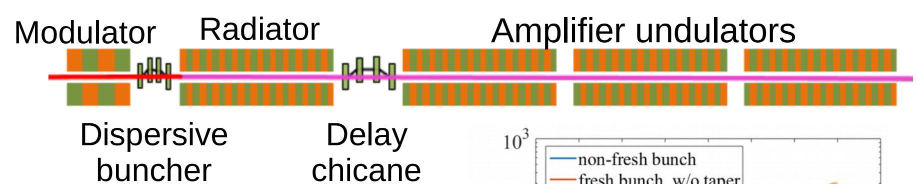
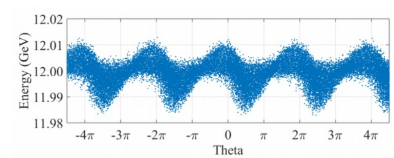
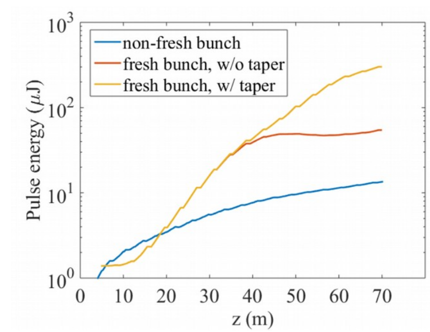




Bunching at 4th harmonic → 57.6 keV photons



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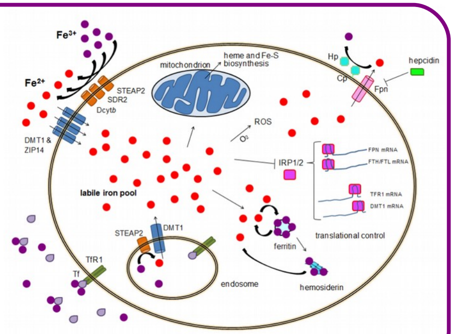

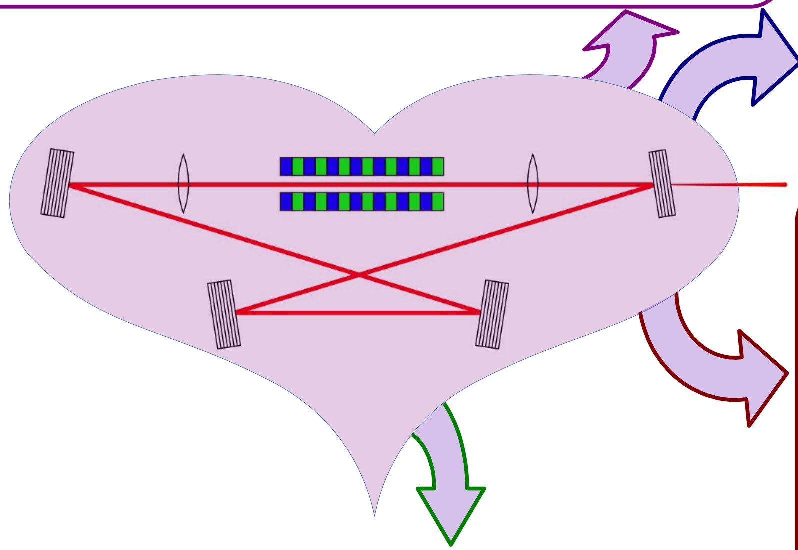

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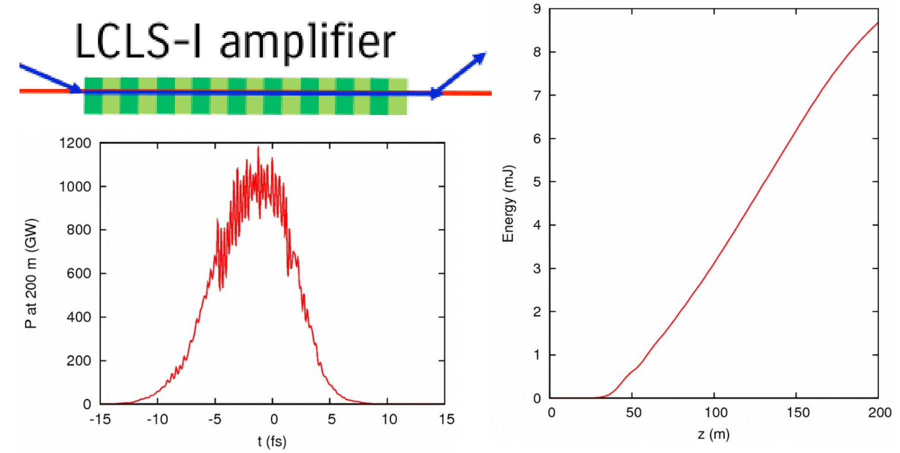

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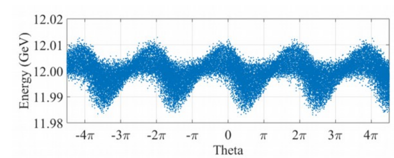

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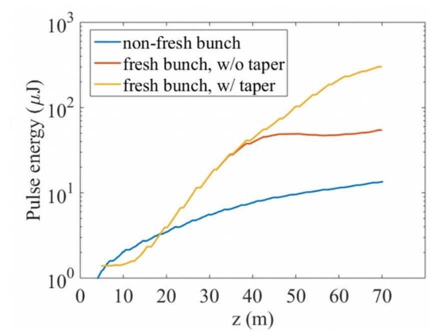

Q-switching for high-power, ultra-narrow bandwidth applications

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