Regenerative Laser Undulator X-ray (ReLUX) Free-Electron Laser

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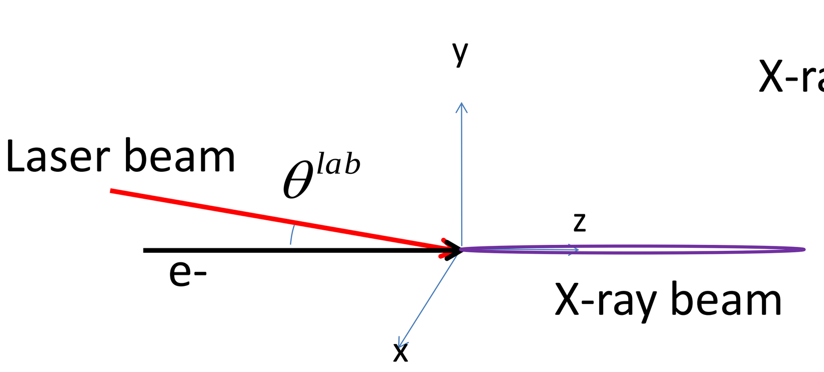
ABSTRACT

We present a new high-gain x-ray FEL concept based on a nearly co-propagating sheared laser undulator [1] and regenerative amplification [2] of a single x-ray pulse via successive interactions between a single electron bunch and a TW laser undulator pulse. This new x-ray FEL configuration is called the Regenerative Laser Undulator X-ray FEL which uses a relativistic electron beam crossing a sheared TW laser beam at small angles. The generated x-ray pulse follows a zigzag path between Bragg reflectors and repetitively interacts with the laser pulse and the electron bunch. Between interactions, the electron bunch is advanced longitudinally to maintain its overlap with the x-ray pulse. The laser pulse follows a different path that includes an optical delay to synchronize it with the electron and x-ray pulses. The laser wave-front tilt and width are designed to increase the interaction time to provide many oscillation cycles. We present a ReLUX FEL design that can produce coherent 12-keV photons with 2 GeV electron beams. Time-dependent Genesis simulations with 3 kA peak current and a 1D rho of 0.00054 yield ~0.6 GW saturated power after 10 sections.

[1] J.E. Lawler et al., J. Phys. D: Appl. Phys. 46 (2013) 325501.
[2] D.C. Nguyen et al., NIMA 429 (1999) 125; Z. Huang et al., PRL 96 (2006) 144801

SMALL-ANGLE SCATTERING GEOMETRY

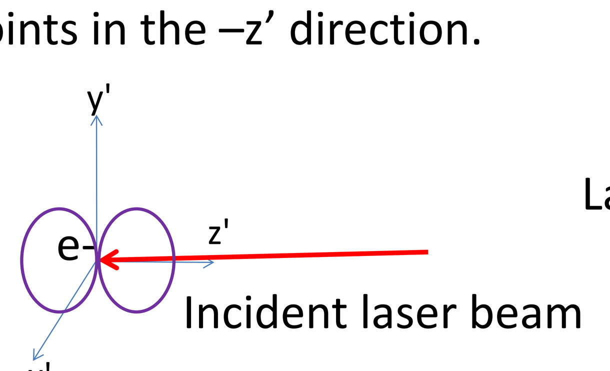
Consider the collision between a relativistic electron (black) traveling in the +z direction with a laser beam (red) at small angle θ in the lab frame



X-ray wavelength

$$\lambda_X = \lambda_L \frac{1+K^2}{\left(\gamma\theta^{lab}\right)^2}$$

In electron rest frame, the Doppler shifted laser beam points in the –z′ direction.



Dimensionless undulator strength

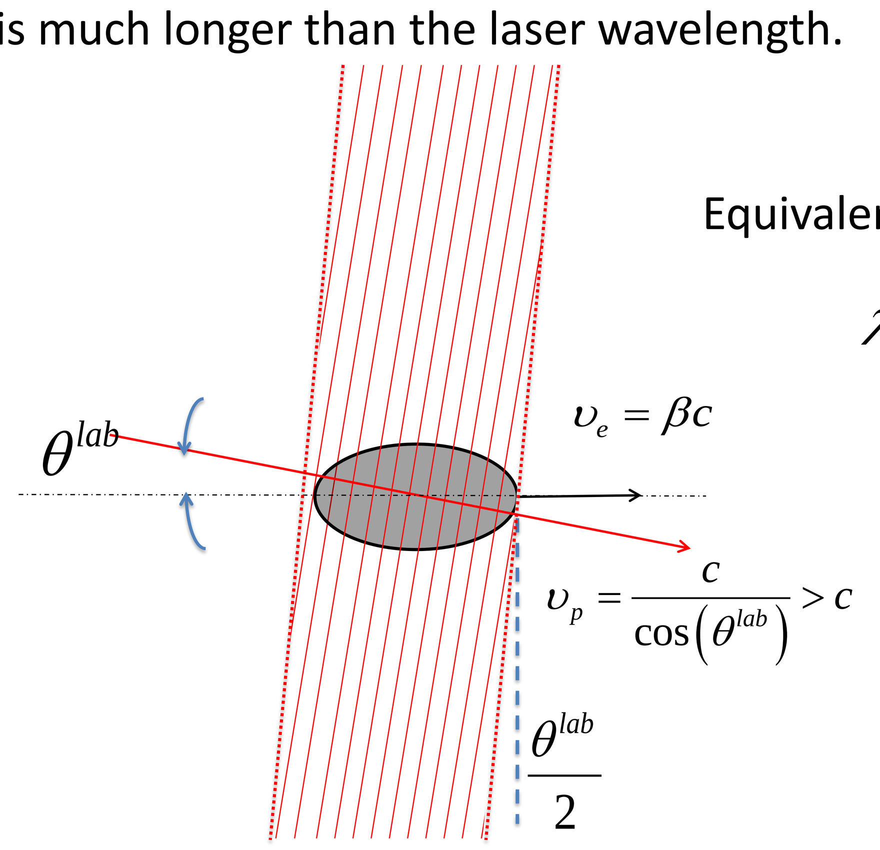
$$K^2 = \frac{2r_e I \lambda_L^2}{m_0 c^3 \pi}$$

Laser wavelength in electron rest frame

$$\lambda_L' \approx \frac{2\lambda_L}{\gamma\left(\theta^{lab}\right)^2}$$

SHEARED WAVEFRONT LASER PULSE

The laser direction of propagation is tilted at an angle θ^{lab} with respect to the electron beam axis. The equivalent undulator period is much longer than the laser wavelength.

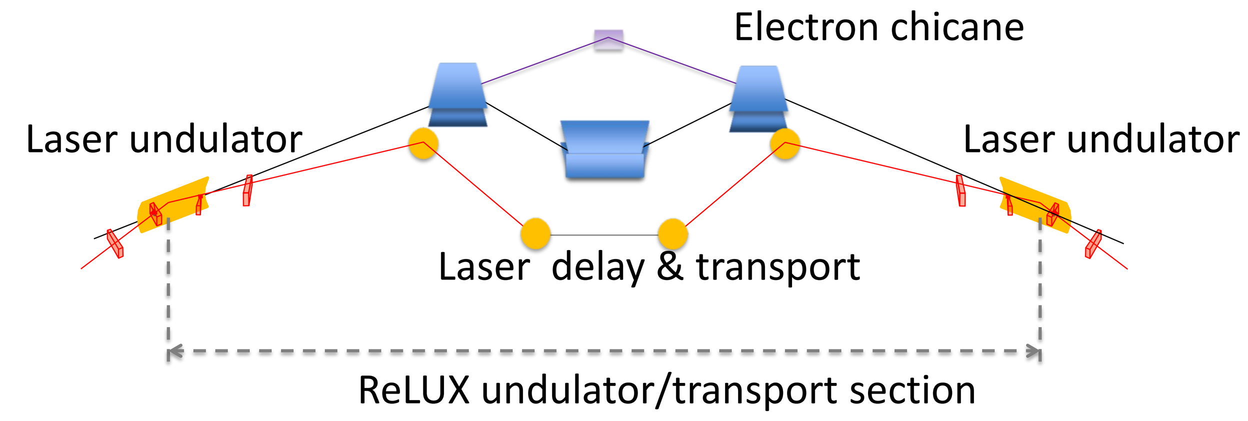


Equivalent undulator period

$$\lambda_u^{eq} \approx \frac{2\lambda_L}{\left(\theta^{lab}\right)^2}$$

A single multi-TW laser pulse can be used repeatedly as multiple laser undulators to provide large FEL gains over many transport sections.

UNDULATOR/TRANSPORT SECTION



Bragg angle

$$\vartheta = \sin^{-1}\left(\frac{\lambda}{2d}\right) = 9.5^\circ$$

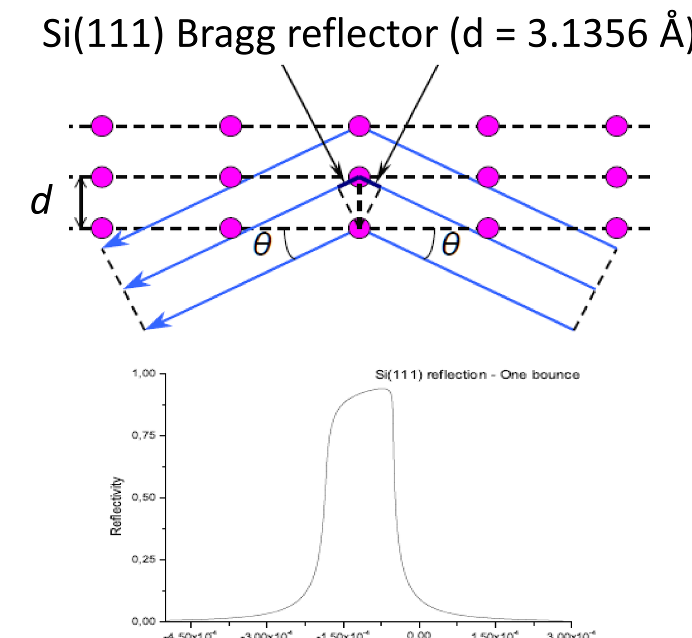
FEL angular divergence

$$\Delta\vartheta = \frac{\lambda}{\pi\sigma_r} = 15\,\mu rad$$

Relative linewidth

$$\frac{\Delta\lambda_X}{\lambda_X} = \Delta\vartheta\cot\vartheta = 9\times10^{-5}$$

Si(111) Bragg reflector (d = 3.1356 Å)

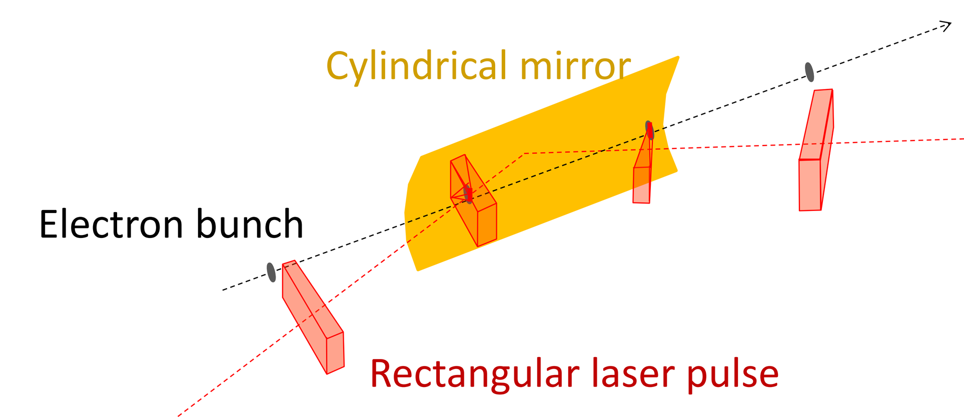


ReLUX FEL DESIGN PARAMETERS

ReLUX FEL Parameter	Symbol	Value	Unit
Electron beam energy	E_b	2	GeV
Peak current	I_{pk}	3	kA
rms normalized emittance	ε_n	0.1	µm
rms relative energy spread	σ_γ / γ	0.01%	
rms bunch length	σ_z	2.5	µm
rms transverse size	σ_x	7	µm
Laser wavelength	λ_L	1.05	µm
Lab-frame angle	θ^{lab}	1.5	deg
Laser power	P_L	500	TW
Laser 1/e² radius in y	w_0	7	µm
Laser full width in x	W^{lab}	7	cm
Equivalent undulator period	λ_u	3.06	mm
rms dimensionless undulator strength	K	0.203	
Equivalent undulator length	L_u	2.67	m
Number of oscillations (periods) per undulator	N_u	873	
X-ray wavelength	λ_X	1.04	Å
FEL rho parameter (1D)	ρ_{1D}	0.054%	
3D Gain length	L_{G3D}	0.39	m
Single-pass gain / undulator	G_{SS}	12x	
# of passes to saturation	N_{pass}	10	
Power at saturation	P_S	0.6 (TD) 5 (TI)	GW
Relative linewidth	$\Delta\lambda/\lambda_X$	8 x 10^{-5}	

LASER BEAM FOCUSING OPTICS

Only a portion of the 7-cm wide laser beam is focused to 7-µm 1/e² radius spot by a cylindrical mirror. The laser focused spot moves along the 2.6-m length of the cylindrical mirror such that the electron beam always interact with a 7-µm radius spot.



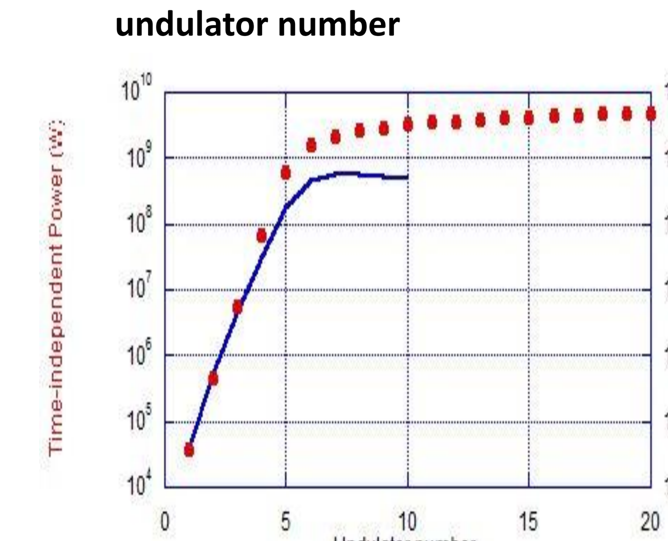
The number of undulator periods is best calculated by dividing the interaction length by the laser wavelength in the electron rest frame

$$N_u = \frac{W^{lab}\left(\theta^{lab}\right)}{\lambda_L}$$

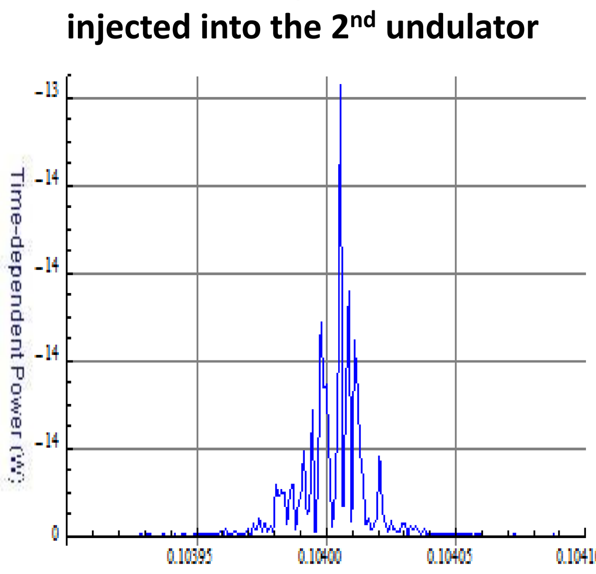
GENESIS SIMULATIONS

1. Time-dependent SASE Genesis simulation for the first undulator.
2. Spectral filtering of the SASE signal with a Si(111) Bragg reflector.
3. Time-independent Genesis simulations for subsequent sections, using energy spread from the previous section with no initial microbunching (assumed to be washed out in the chicane).

Time-independent & time-dependent Genesis simulation: peak power vs undulator number



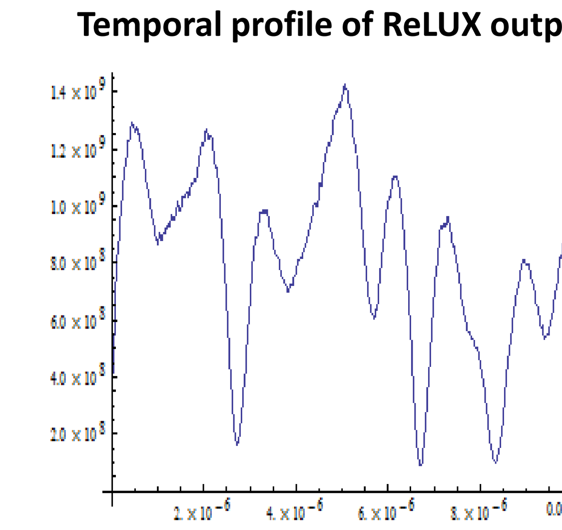
Filtered SASE spectrum to be injected into the 2nd undulator



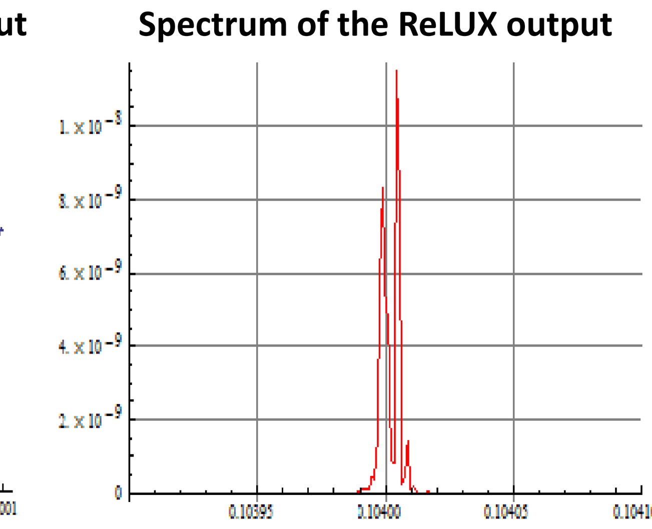
TIME-DEPENDENT SIMULATIONS

1. Time-dependent Genesis simulation with spectral filtering with a Si(111) Bragg reflector between sections (no retuning).
2. The re-injected electron bunch has energy spread from the previous section and no initial microbunching.
3. The ReLUX output spectrum shows fewer spikes and narrower linewidth than SASE.

Temporal profile of ReLUX output



Spectrum of the ReLUX output



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