Multi-FELOs Driven by a Common Electron Beam

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Outline

§1 Motivation & Concept of the scheme

- ⇒ For single-pass high-gain FEL amplifier, impact on the beam can be abrupt and violent, compared to relatively mild process for low-gain FEL
- ⇒ Possible reuse of the electron beam

§2 Model description

- ⇒ Modified 1-D FELO model

§3 Simulation results

- ⇒ Preliminary feasibility study
- ⇒ Ignore practical technical challenges

§4 Summary & Discussion

Motivation

- High-brightness FEL/e-beam is very expensive
- Low-repetition-rate FEL facilities can only support one or few experiment stations
- High-repetition-rate high-gain FEL is presently a hot and active topic, initiate many ongoing projects, and can potentially support more experiment stations
- Simultaneous, in-parallel operation of multiple undulator lines may compromise the repetition rate
- For single-pass high-gain FEL amplifier, impact on the beam can be abrupt and violent, compared to relatively mild process for low-gain FEL
- Idea: High-repetition-rate e-beam to drive low-gain FELOs, in-serial operation

Concept of the scheme

- Use the same e-beam to drive multiple XFELOs
- Spent e-beam may still be able to drive other oscillator
- Inherit high repetition rate, if the idea works
- Total photon flux $\leq k \times$ photon flux per oscillator

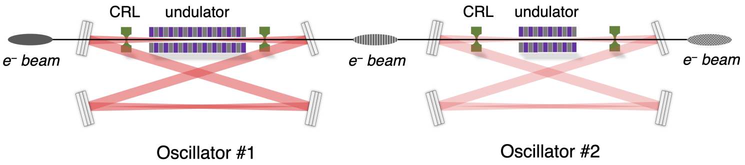


Figure: Conceptual schematic layout for the two-oscillator scheme. Bragg mirrors, consisting of three high-reflectivity mirrors and one mirror used for outcoupling, and two compound refractive lenses (CRLs) used for focusing are employed to form the oscillator. This design allows two independent users to conduct experiments

1-D FEL model

$$\begin{cases} \frac{d\theta_j}{d\tau} = p_j, \quad \frac{dp_j}{d\tau} = -\left(Ae^{i\theta_j} + A^* e^{-i\theta_j}\right) \\ \frac{dA}{d\tau} = \left\langle e^{-i\theta_j} \right\rangle + i\delta A \end{cases}$$

Scaled gain parameter $G \equiv 4\pi\rho N_u \Rightarrow \begin{cases} G > 1 & \text{high-gain} \\ G < 1 & \text{low-gain} \end{cases}$

Intensity gain per pass $\mathcal{G} \equiv \frac{|A_G|^2 - |A_0|^2}{|A_0|^2}$

where $A_G = A(\tau = G), A_0 = A(\tau = 0)$

Radiation output power $P_{\text{out}} = \rho |A|^2 P_b \frac{\alpha}{\mathcal{L}}$

where $\mathcal{L} = \alpha + (1 - R)$, with the reflectivity R and α the outcoupling ratio[3]

[3]B.W.J. McNeil et al., FEL2006 (MOPPH011).

After leaving the oscillator #1 and serving the oscillator #2

$$\theta_j \to \theta_j + k_{R_{56}} \rho_1 p_j$$

with $k_{R_{56}} = 2\pi R_{56}/\lambda_r$. For simplicity, consider isochronous transport $k_{R_{56}} = 0$.Oscillator radiation fields develop by the following iteration

$$A_{i,0}^{(n+1)} = r_i A_{i,G}^{(n)}, \quad r_i = \sqrt{R_i}, \quad i = 1, 2$$

For oscillator #2, the e-beam quality degradation is reflected on Pierce parameter $\rho \to \rho_{\text{eff}} = \rho \left(F_{\text{inh}} F_f\right)^{\frac{1}{3}}$, taking into account energy spread increase.For oscillator #2, ρ_{eff} is updated every pass, and phase space coordinates re-scaled

$$\begin{cases} \theta_j \left(\tau_2 = 0\right) = \theta_j \left(\tau_1 = G_1\right) + k_{R_{56}} \rho_{\text{eff},1} p_j \left(\tau_1 = G_1\right) \\ p_j \left(\tau_2 = 0\right) = \left(\frac{\rho_{\text{eff},1}}{\rho_{\text{eff},2}}\right) p_j \left(\tau_1 = G_1\right) \end{cases}$$

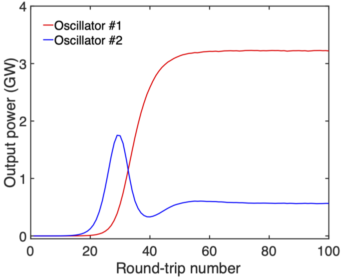
Numerical example[4]

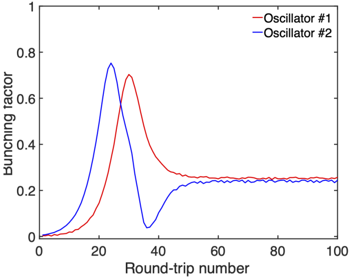
Name	Value	Unit
Resonant electron energy $E = \gamma_r mc^2$	5.7	GeV
Bunch length, rms σ_t	0.55	ps
Bunch charge	380	pC
Bunch current I_b	300	A
Normalized emittance ϵ_{nx}	0.3	μm
Energy spread σ_δ	0.3×10^{-4}	
Undulator period λ_u	1.88	cm
Number of undulator periods N_{u1}, N_{u2}	100/68	
Undulator parameter K	1.5	
Resonant wavelength λ_r	1.6	Å
Round-trip reflectivity R	0.8	
Outcoupling ratio α	0.04	

[4] Largely based on Y. Zhang et al., IPAC 2022 (TUPOPT042).

- Parameters only for illustration purpose, not optimized
- Injected 5.7-GeV beam may come from CEBAF after 2.5 passes
- Oscillator #2 has smaller number of undulator periods because driving electron beam is already microbunched
- Relatively short undulator length ≤ 2 m, compared to common XFELO designs ≥ 50 m
- Relatively lower single-pass gain can be compensated by a larger bunch charge
- Single-pass gain cannot be too small to compensate round-trip loss; cannot be too large to avoid early saturation
- Reflection & focusing: three high-reflectivity Bragg mirrors, two CRL, and one 4% outcoupling $\Rightarrow R \approx 0.96^3 \times 0.997^2 \times 0.92 \approx 0.8$
- Initial detune for two oscillators: $p_0 = \delta \approx 2.6/G_{1,2}$, where $G_{1,2} = 4\pi\rho_{1,2}N_{u1,u2}$ (not optimized for #2)

Evolution of output power and bunching factor





The output power of oscillator $\#1$ is consistent with the rough estimate formula[5] $P_{\text{sat}} \approx \frac{\alpha P_{\text{beam}}}{N_u(1-R)} \approx 3.4$ GW. Scaled gain parameters $G_{\#1} \approx 1.42, G_{\#2} \approx 0.96$. Initial Pierce parameter $\rho_{\text{eff}} \approx 1.126 \times 10^{-3}$. For simplicity, $kR_{56} = 0$

[5]Kim, Huang, and Lindberg, SR and FEL, Cambridge University Press (2017).

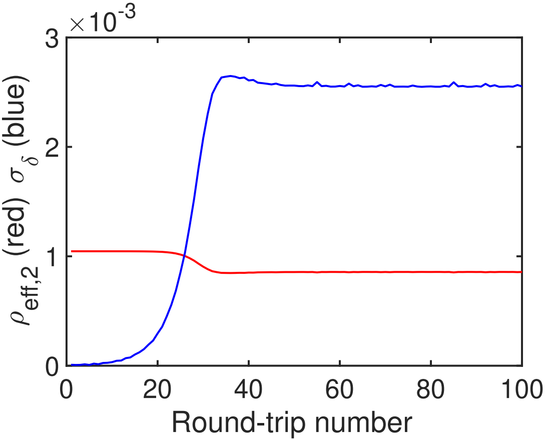


Figure: Beam energy spread and Pierce parameter at the entrance of oscillator #2.

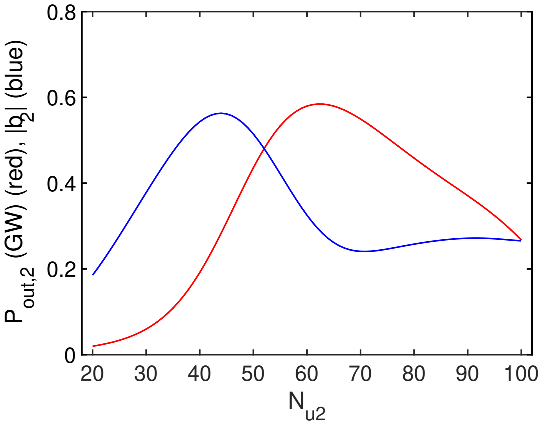


Figure: Output power and bunching factor of oscillator #2 as a function of N_{u2}. For oscillator #2 the radiation field can well incubate at $N_{u2} = 68$. As a reference, the oscillator #1 output power is 3.22 GW and the exit bunching factor is approximately 0.24.

Summary & Discussion

- Investigated the feasibility of using the same electron beam to drive two XFELOs by the modified 1-D FEL model. More detailed, 3-D time-dependent simulation ongoing
- Assume a CEBAF-like e-beam with 5.7 GeV and peak current 300 A, simulated output powers of approximately 3.2 GW and 0.6 GW, peak brightnesses of $\sim 10^{32\sim31}$ and average brightnesses of $\sim 10^{27\sim26}$ photons/sec/(mm mr)$^2\times$(0.1% BW), assuming a repetition rate of ~ 0.5 MHz
- Concept may enable a potential, economic application using a circulator ring such that an oscillator can be driven alternately by fresh linac bunches or from used bunches, while providing competent peak and average brightness

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Thank you for your attention