Arrival Time and Energy Jitter Effects on the Performance of X-ray Free Electron Laser Oscillator

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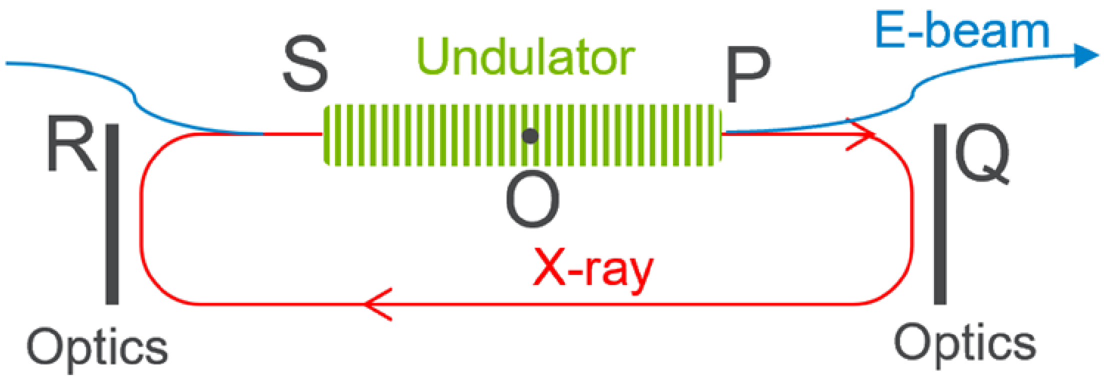
NAPAC2022: THYD6

08/11/2022

Concept of X-ray laser: The X-ray FEL oscillator (XFELO)



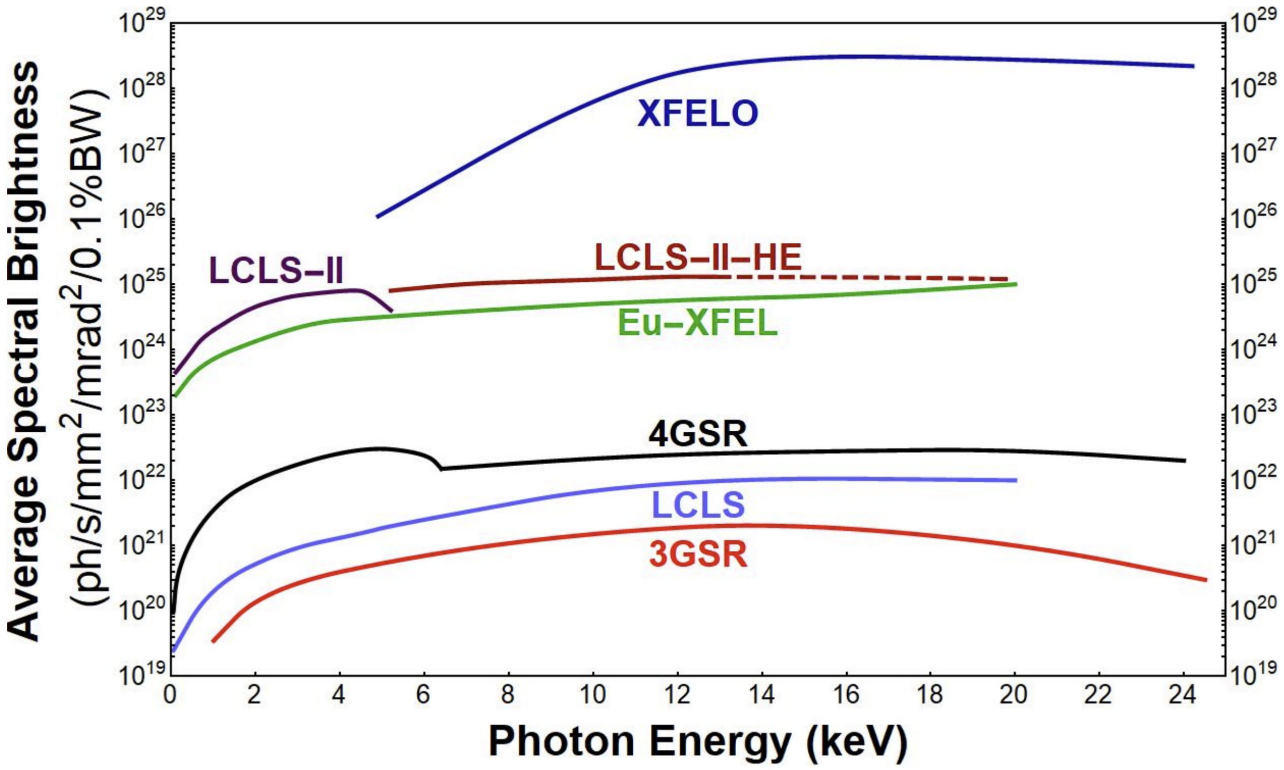
Schematic of cavity-based X-ray FEL. Not drawn to scale.

- When the FEL gain and outcoupling are HIGH, the oscillator is referred to as **X-ray regenerative amplifier FEL (XRAFEL)** [1].

- The configuration with low-gain FEL and low outcoupling is called **X-ray FEL oscillator** [2, 3].

[1] Z. Huang and R.D. Ruth, Phys. Rev. Lett. **96**, 144801 (2006).
[2] R. Colella and A. Luccio, Opt. Comm. 50, 41 (1984).
[3] K.-J. Kim, Y. Shvyd'ko, and S. Reiche, Phys. Rev. Lett. 100, 244802 (2008).

Application domains of X-ray FEL oscillator (XFELO)



Photon brightness from XFELO and other light sources [5].

- Science applications and extensions [4]:
 - Inelastic x-ray scattering
 - Nuclear resonant scattering
 - X-ray photoemission spectroscopy
 - Hard x-ray imaging
 - X-ray photon correlation spectroscopy
… and more

- XFELO opens the possibility of adopting advanced optical techniques such as **Q-switching** [5]**, mode-locking** [6]**, parametric amplification** [7] and so on, thereby bringing atomic laser properties to the X-ray regime.

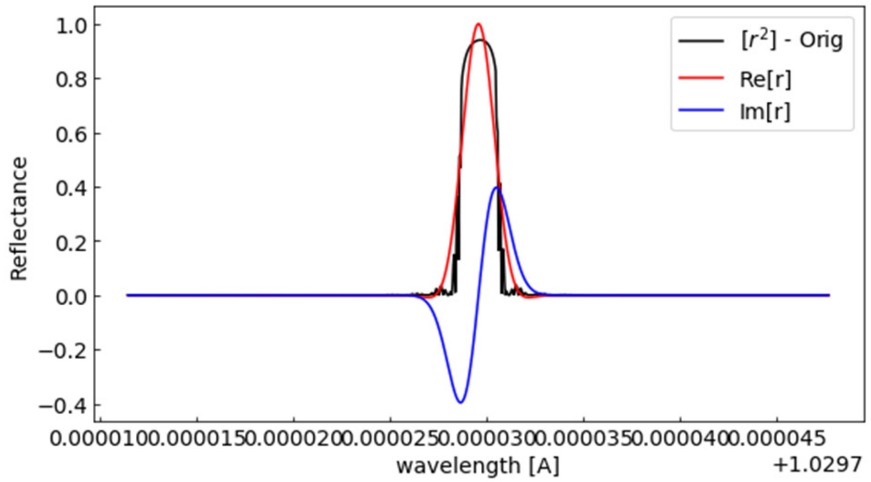
[4] arXiv:1903.09317v2.
[5] J. Krzywinski et al., Proc. of the 39th International Free-Electron Laser Conf. (2019) [TUP033].
[6] B. W. Adams and K.-J. Kim, Phys. Rev. ST Accel. Beams **18**, 030711 (2015).
[7] K.-J. Kim, Z. Huang, and R. Lindberg, Synchrotron Radiation and Free-Electron Lasers: (Cambridge University Press, Cambridge, 2017) and references within.

Moving from concept to design tolerances in XFELO

- XFELO's performance depends on the quality and alignment of e-beam and optical cavity.
- Effects of transverse spatial misalignment on XFELO performance is reported elsewhere [8].
- Fluctuations in arrival time and energy of the e-beam can affect XFELO throughput.
- For simplicity, we approximate the reflectivity of the bragg-crystals (or of the optical cavity) by

$$\mathcal{R}(\omega) = \sqrt{R}\, e^{-\frac{(\omega-\omega_c)^2}{4\sigma_{refl}^2} + i\,\mathrm{atan}\left(\frac{\omega-\omega_c}{2\sigma_{refl}}\right)}$$

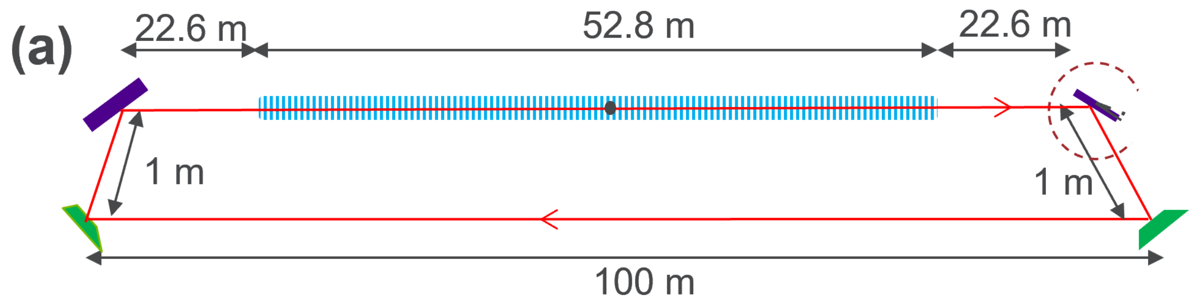
where *R* is the effective power reflectivity of the cavity.



- *A net rms bandwidth of 6.87 meV introduces a delay of ~40 fs per turn, which is compensated by shortening cavity length by the same amount.*

[8] G. Tiwari and R. R. Lindberg, PRAB, submitted.

XFELO configuration and parameters for simulations



2-crystal cavity configuration with two focusing mirrors for XFELO based on C444 crystal. Not drawn to scale. Geometry is only approximate.

- The generic optical cavity has 15% power loss per turn, defining its **quality factor,** $\hat{q} = \frac{R}{1-R} \cong 5.67$.

Parameter	Symbol (Unit)	A [12 KeV]
Electron beam		
Energy	$\gamma_0 mc^2$ (GeV)	7
Energy spread	σ_γ (MeV)	1.4
Energy shift	δE (MeV)	2.3
Normalized emittance	ε_n (mm. mrad)	0.2
Peak current	I (Amp)	10
Pulse length	σ_t (ps)	0.2
RMS width	σ_x (μm)	12.67
Undulator/Radiation		
Undulator periods	N_u	3000
Undulator length	L_u (m)	52.8
Radiation wavelength	λ_r (Å)	1.0298
Optical Cavity		
Rayleigh range	Z_R (m)	10
Cavity Length	L_{cav} (m)	200
Stability parameter	$\|A + D\|/2$	0.704
Ideal FEL Gain	G_0	0.44

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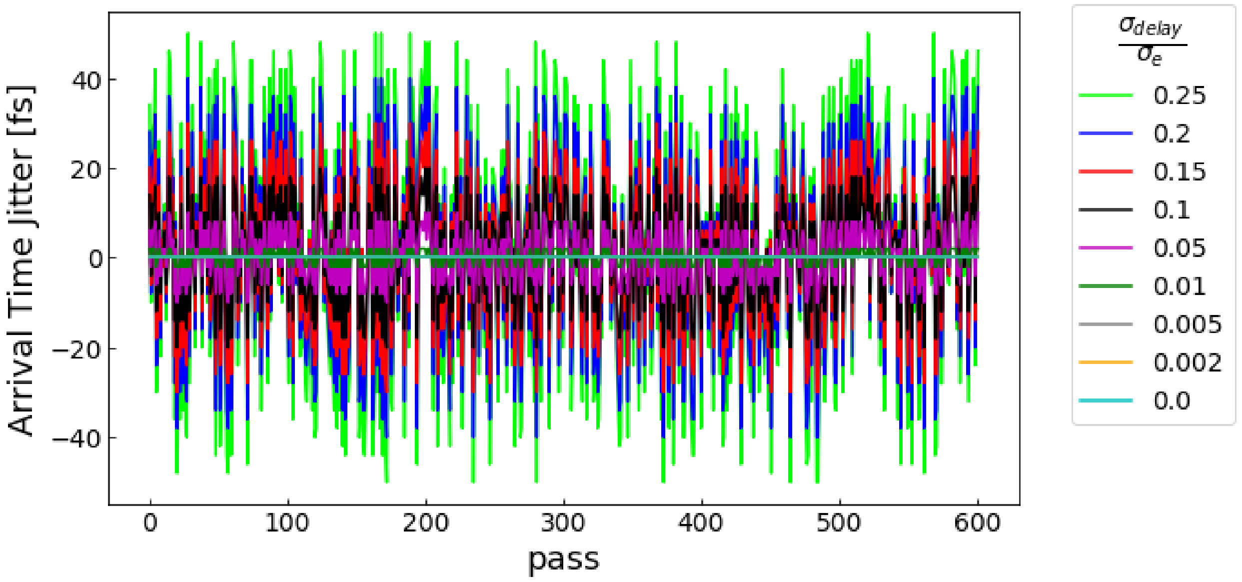
Jitters in Arrival Time and Energy of Electron Beams

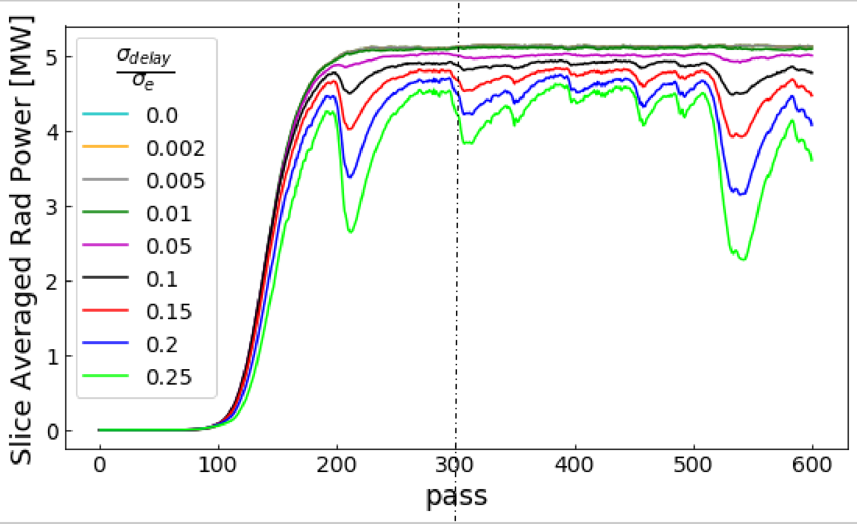
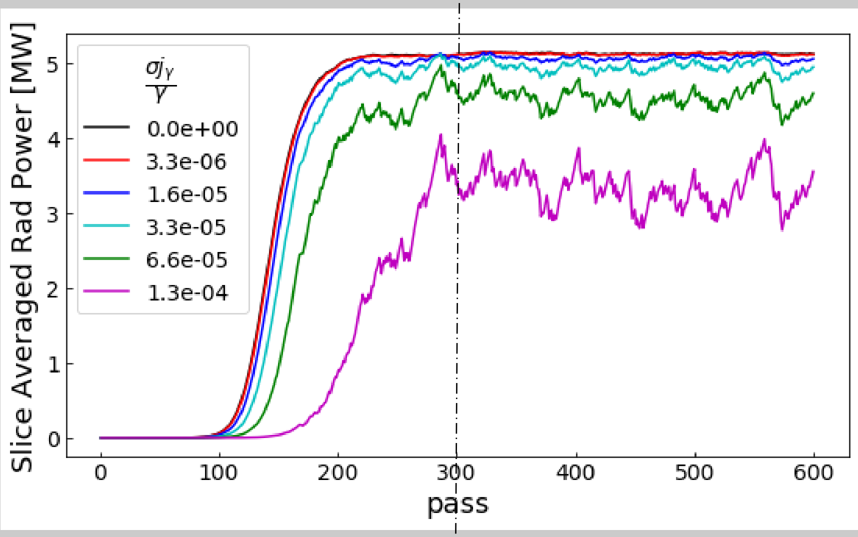
- Turn by turn arrival time jitters (ATJ) and energy jitters (EJ) are artificially generated using random number generation with pre-determined rms values as shown below:



ATJ from 0 to 25% of rms temporal width of e-beam.

- Likewise, rms EJ values ranged from 0 to 0.013% of e-beam energy .
- We observed how jitters affected power output and rms pulse widths after saturation (at steady-state).

Jitter effects in generic cavity (*R*=85%)

<table>
<tr><th></th><th>Arrival Time Jitter (ATJ)</th><th>Energy Jitter (EJ)</th></tr>
<tr><td>Power (6% at users' end)</td><td>
</td><td>
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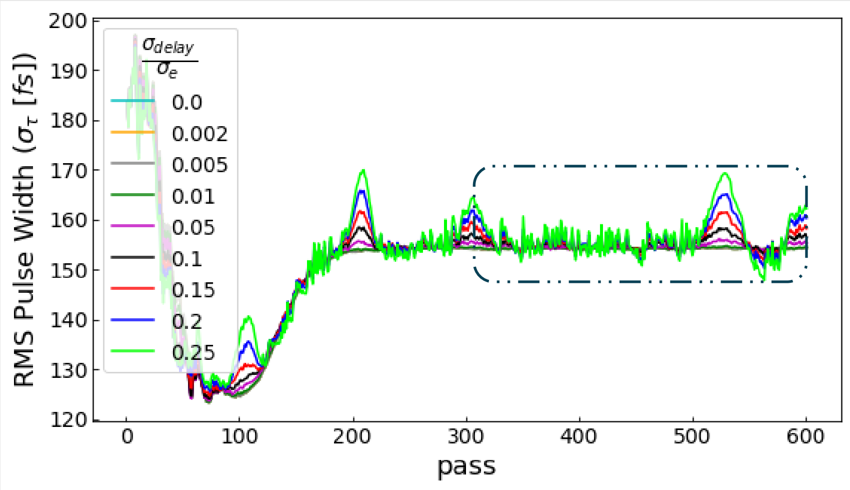
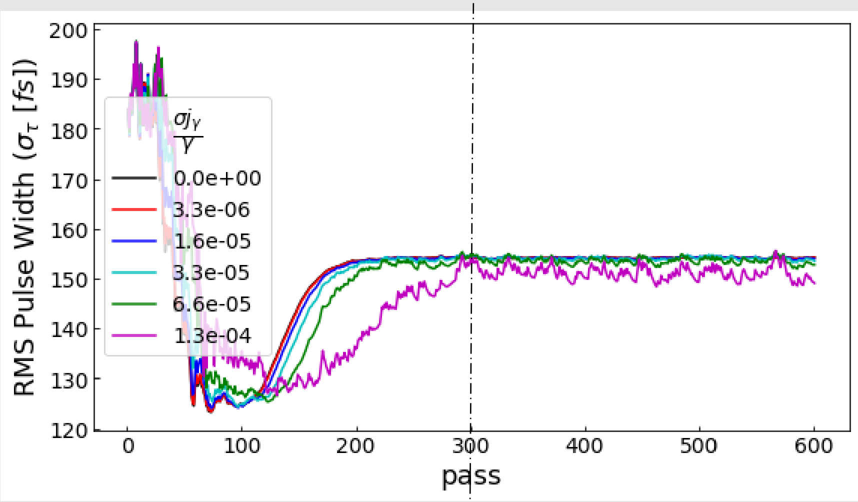
<tr><td>RMS Pulse Width</td><td>
</td><td>
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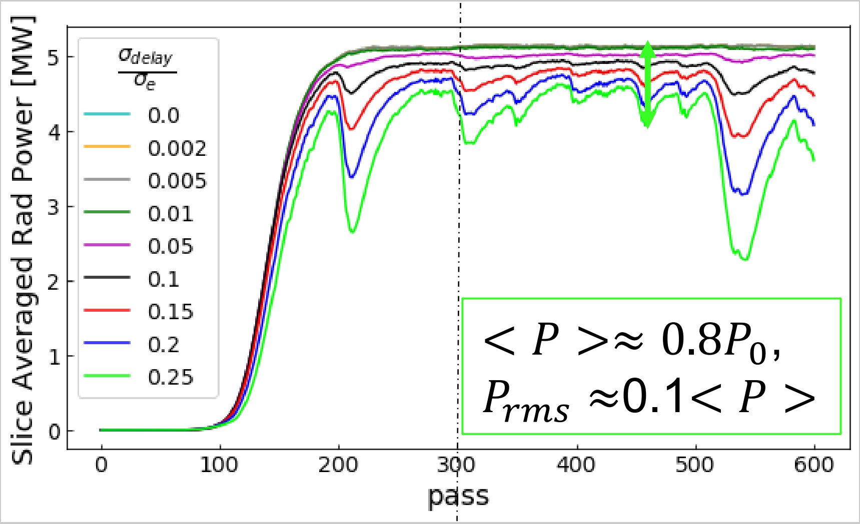
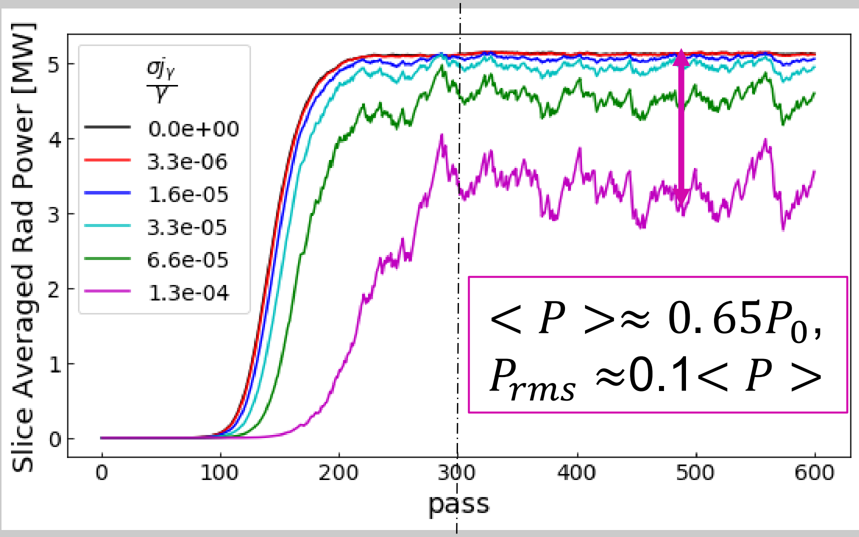
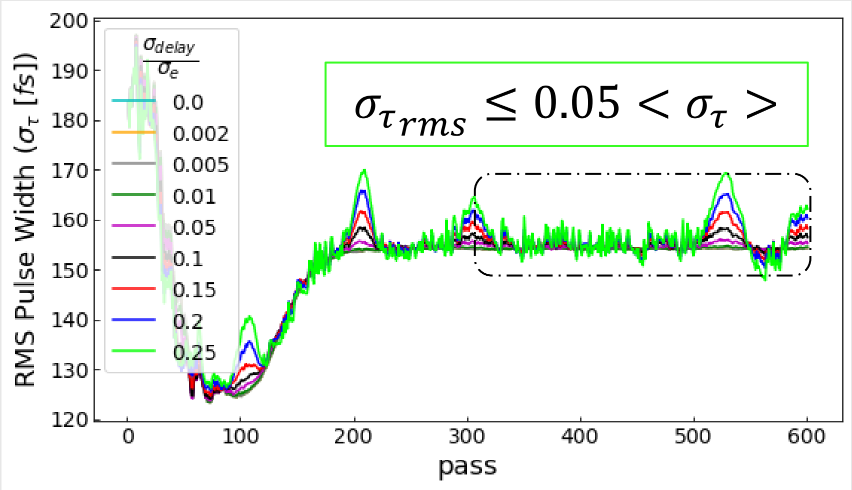
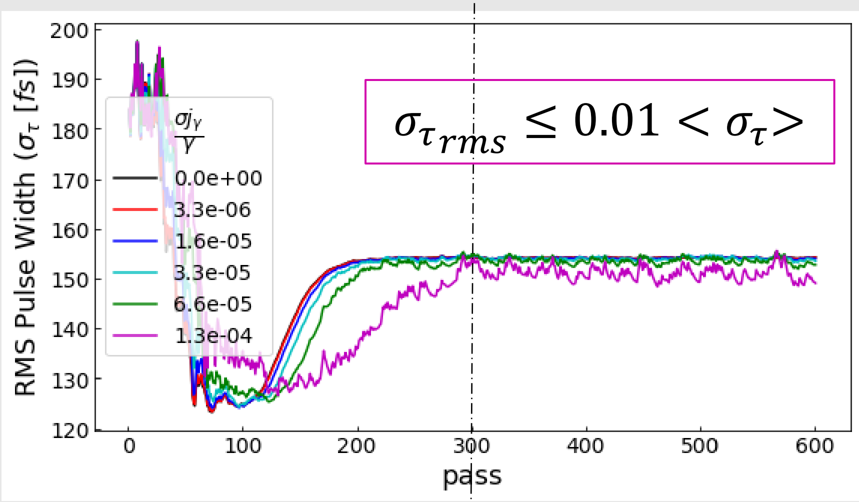
Jitter effects in generic cavity (R=85%)

	Arrival Time Jitter (ATJ)	Energy Jitter (EJ)
Power (6% at users' end)		
RMS Pulse Width		

What can we do about the jitters or their effects?

- Superconducting linacs can (are expected to) achieve [9]
  - energy jitter $\Delta E/E \leq 0.01\%$ and
  - timing jitters of 20 fs (i. e. $\Delta T/T \leq 10\%$ for e-beam with 200 fs rms width).

- However, electron beam jitters become unavoidable for XFELO operation.

- In what ways can we minimize the jitter effects in XFELO performance?

- For an XFELO to sustain lasing, it must satisfy:

$$R(1+G) \geq 1$$

where *R* is net power reflectivity of the cavity and *G* is FEL gain.

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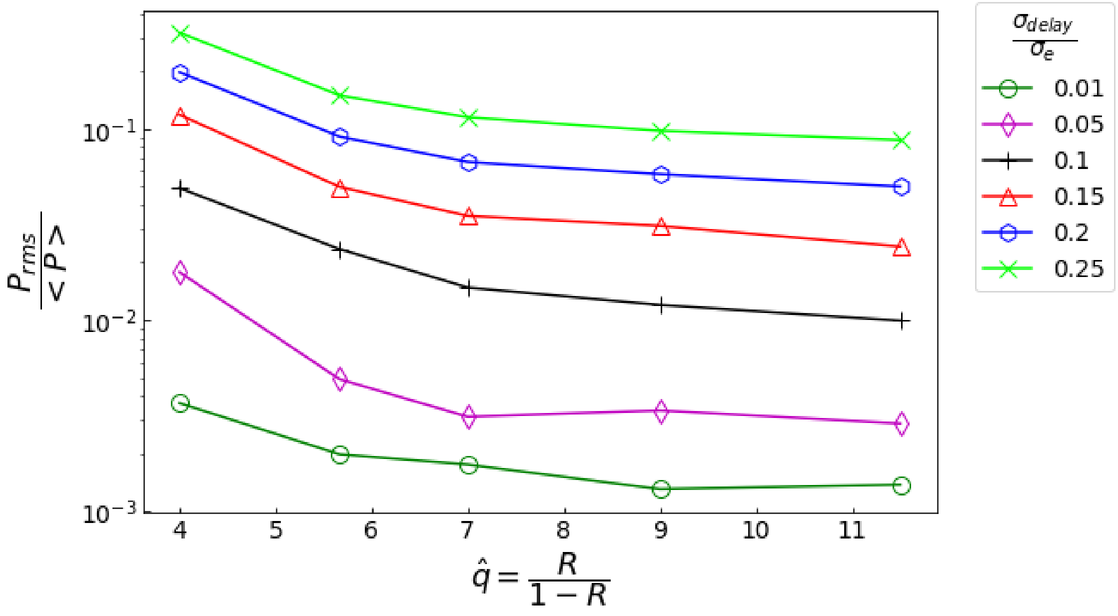
[9] https://lcls.slac.stanford.edu/parameters.

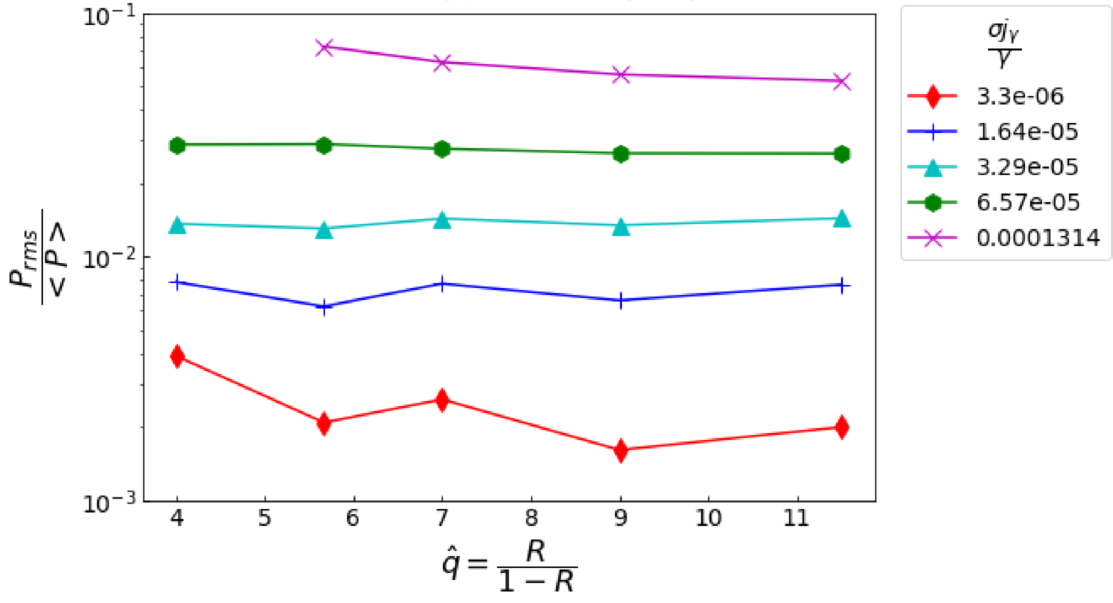
Case I: Jitters and Reflectivity (quality) scan

- We changed the net power reflectivity of the cavity to observe power fluctuations with jitters ON.

Arrival Time Jitter (ATJ)



Energy Jitter (EJ)



- ATJ within 5% yield fluctuations within 1%.
- ATJ above 15% induce fluctuations >5%.
- Higher reflective (HR) cavities are favorable.

- EJ within 0.005% yield fluctuations within 5%.
- EJ at/above 0.006% generate fluctuations >5%.
- HR cavities favored for mean output, but not fluctuations when EJ is ON.

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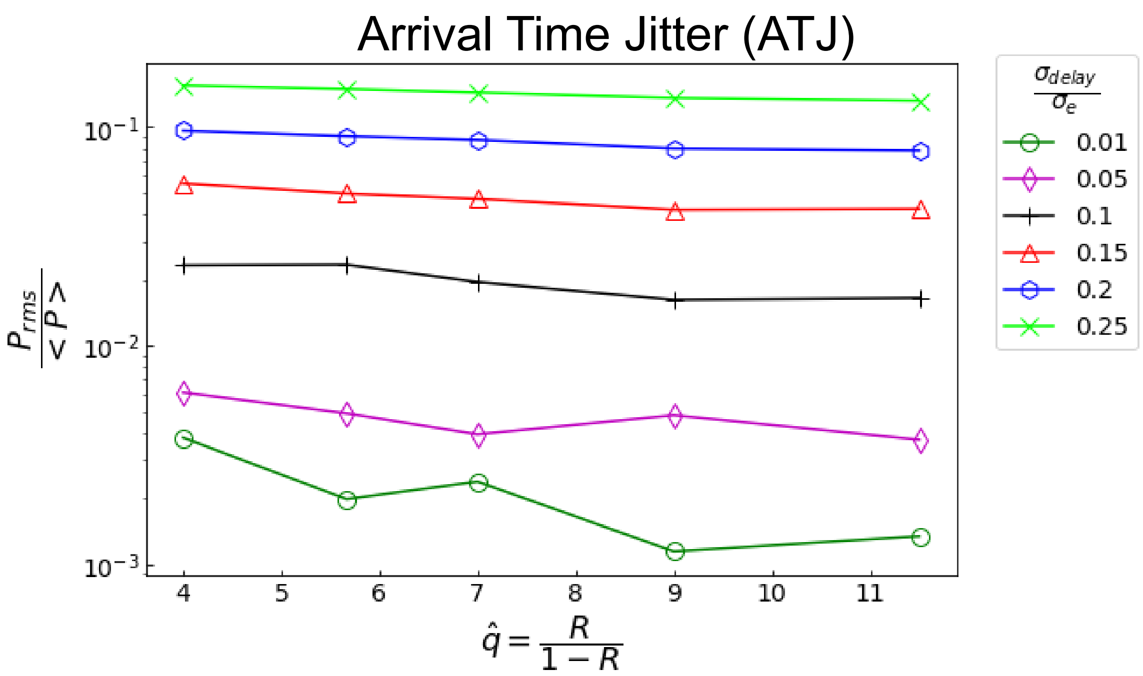
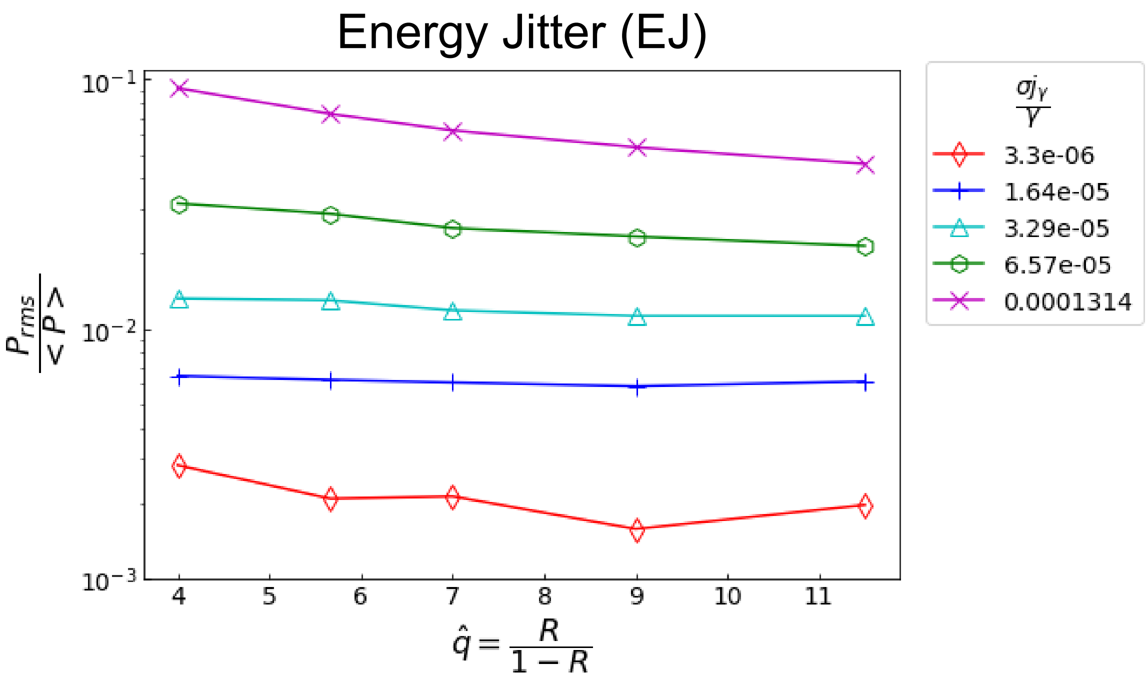
Case II: Jitters and Reflectivity scan with gain compensation

- Reflectivity scan is now accompanied with a constraint R(1+G) = constant = 1.224.
- Gain is increased (for lossy cavities) or decreased by adjusting beam current.





- Gain compensation brings fluctuations to the same level for all cavities with ATJ ON.
- ATJ within 5% yield fluctuations within 1%.
- ATJ above 15% induce fluctuations >5%.

- Gain compensation had minimal effect.
- EJ within 0.005% yield fluctuations within 5%.
- EJ at/above 0.006% generate fluctuations >5%.

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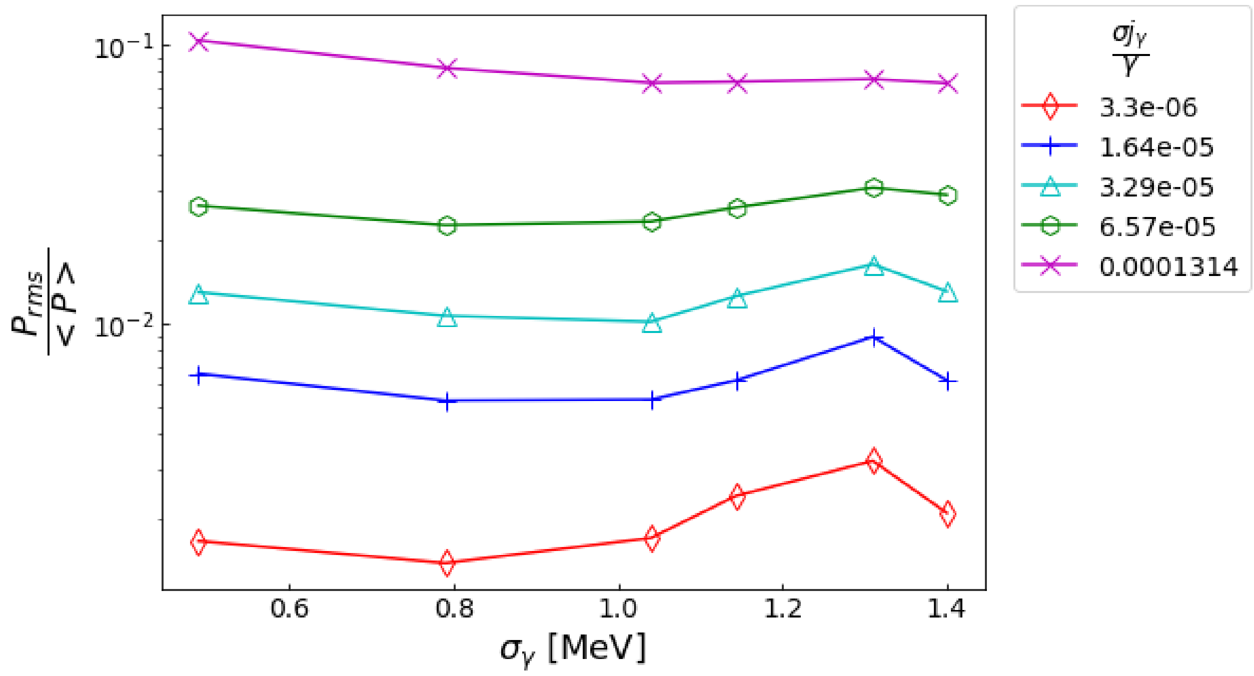
Case III: Energy Jitter and FEL efficiency scan

- Finally, both FEL gain and reflectivity are kept constant.
- Energy spread and Number of Undulator Periods are chosen to keep the FEL gain constant.

$\sigma_E\ (MeV)$	N_u
1.4	3000
1.31	2500
1.143	2000
1.04	1800
0.79	1500
0.49	1300



- No significant change in fluctuations is observed for different FELs.
- We plan to investigate this further.

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To sum up:

- **Arrival Time Jitter (ATJ):**

  - ATJ above 10% is worrisome and is not preferred for XFELO.
  - Sensitivity to ATJ effects can be reduced to certain extend by FEL gain compensation.
  - RMS pulse width fluctuations due to ATJ is minimal.

- **Energy Jitter (EJ):**

  - EJ < 0.005% of e-beam energy is required to maintain fluctuations within 5%.
  - EJ $\geq$0.01% of e-beam energy is troublesome for desired XFELO performance.
  - Role of FEL efficiency in mitigating EJ effects require further studies.
  -EJ does not induce fluctuations in bandwidth of the radiation pulse.

- We hope to extend this study for an accurate prediction of jitter effects on XFELO performance.

Acknowledgments

- Funding:

U.S. DOE BES Funding Contract No. DE-AC02-06CH11357.

THANK YOU!