An Active Q-switched X-ray Regenerative Amplifier Free-Electron Laser

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8/31, 2023

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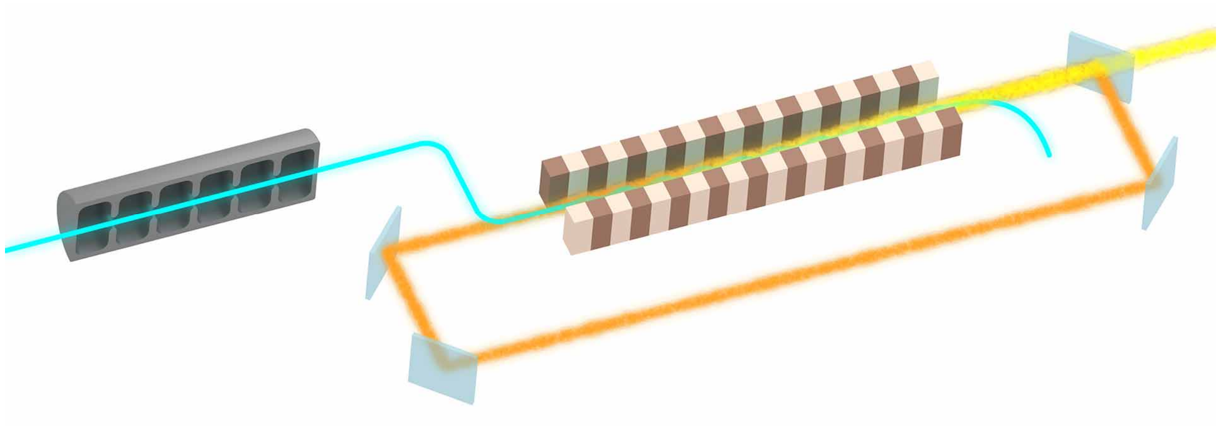
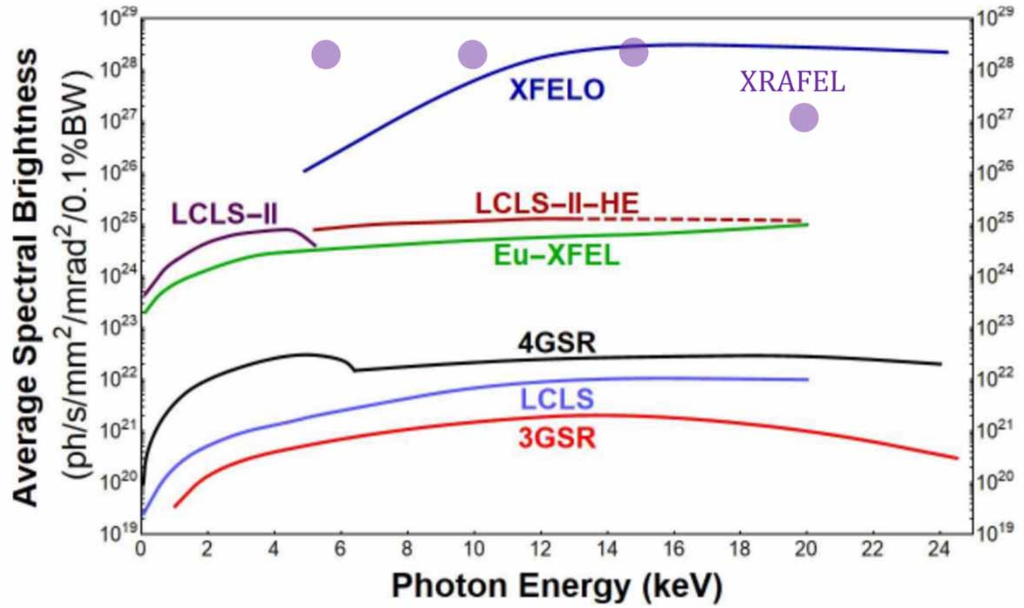
SLAC NATIONAL ACCELERATOR LABORATORY

Cavity-Based XFEL (CBXFEL)

- XFELs are based on single-pass SASE: powerful and transversely coherent, but not stable and not longitudinally coherent.
- Cavity-Based XFEL has the potential to produce highly stable, fully coherent X-ray pulses at a high repetition rate, and hence achieve higher average and peak brightness (by 2 to 3 orders than SASE) → **A True X-ray Laser**



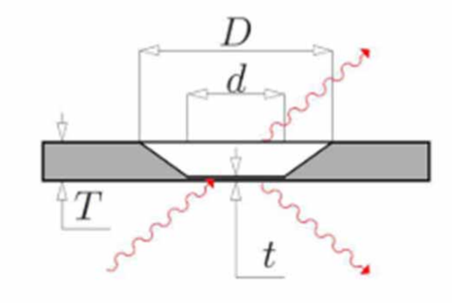


Outcoupling Methods for XRAFEL

- **Like optical laser, the outcoupling method is one of the most critical components for CBXFELs**

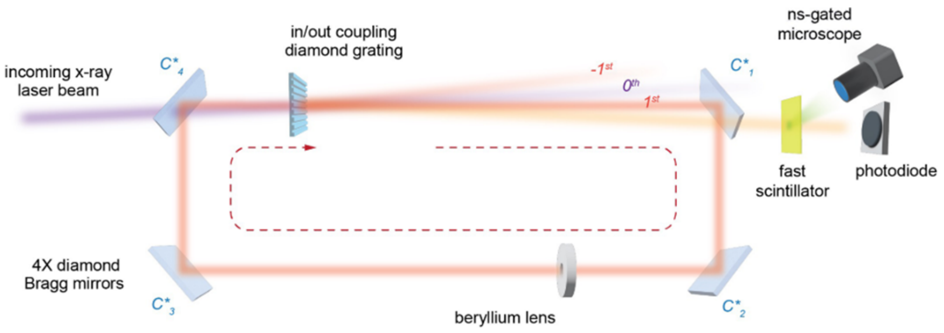
Passive methods

Thin (Drumhead) Crystal



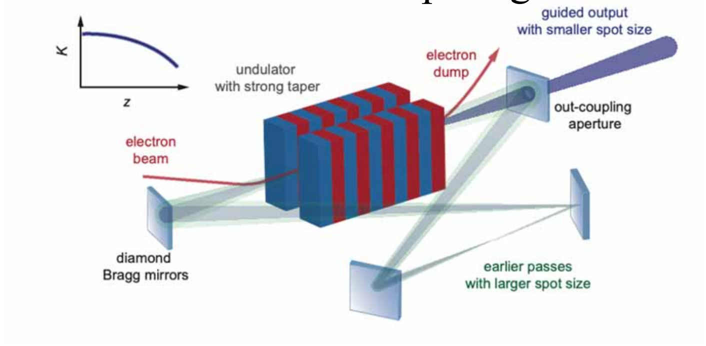
Kolodziej, et al. (2016) J. Appl. Cryst., 49: 1240-1244

Grating Splitter



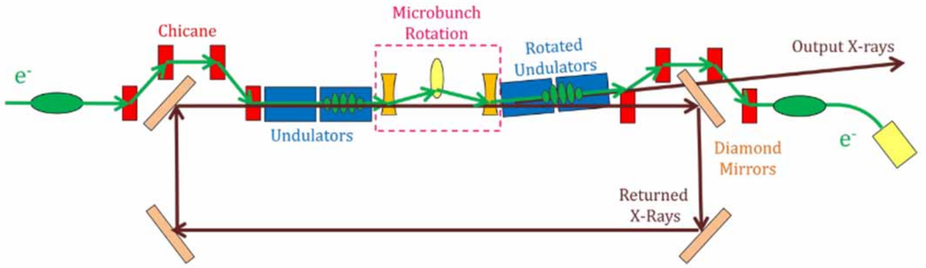
Margraf, Rachel, et al. Nature Photonics (2023): 1-5. TU2A4

Pinhole and tapering



G. Marcus *et al*., Phys. Rev. Lett. **125**, 254801 (2020)

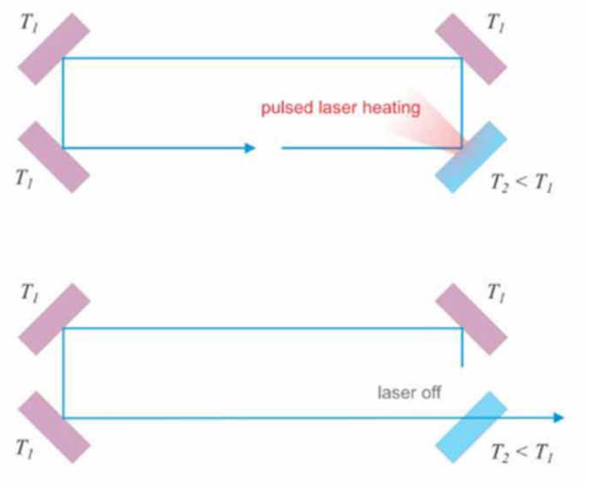
μB rotation



J. P. MacArthur, et al. Phys. Rev. X, 8, 4, 41036, (2018)
R. Margarf et at., Proc. FEL'22, (2022)

Active methods

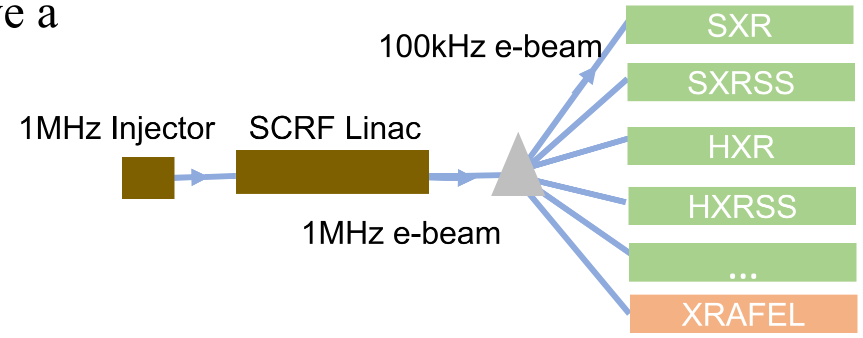
Q-switching with doped diamond



J. Krzywiński et al., Proc. FEL'19, 122125, (2019)
R. Margraf et al., Proc. IPAC'22, (2022)

Outcoupling Methods for XRAFEL

- **Most outcoupling schemes for XRAFEL are passive and/or reply on cavity optics manipulation.**
  - Passive methods require full machine repetition rate (1MHz) to drive a cavity
    - Repetition rate limited by dump power
    - Not compatible with multiplexing FEL
  - Cavity optics manipulation may lead to degradation of the crystal quality and may be subject to various thermal distortions



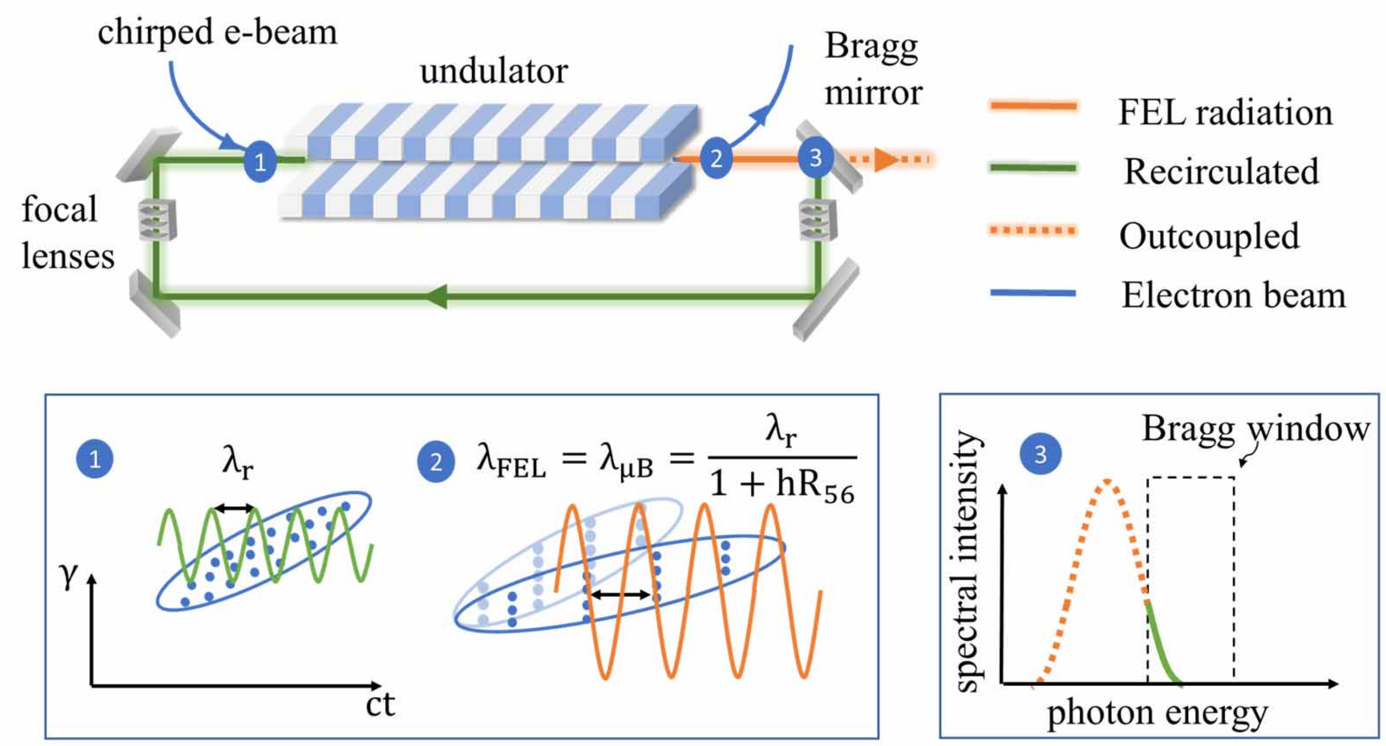
- **Unlike optical lasers, the gain medium of CBXFELs is a relativistic electron beam.**
  - Electron beams are relatively simple and flexible for manipulation

A simple, beam-based, active Q-switching method

Outline

- Chirp-based XRAFEL Q-switching Scheme
- Examples
    - XRAFEL driven by e-beams at a reduced rep. rate
    - XAREFL with a more compact footprint
    - XRAFEL generating higher photon energy with relaxed requirements on e-beams

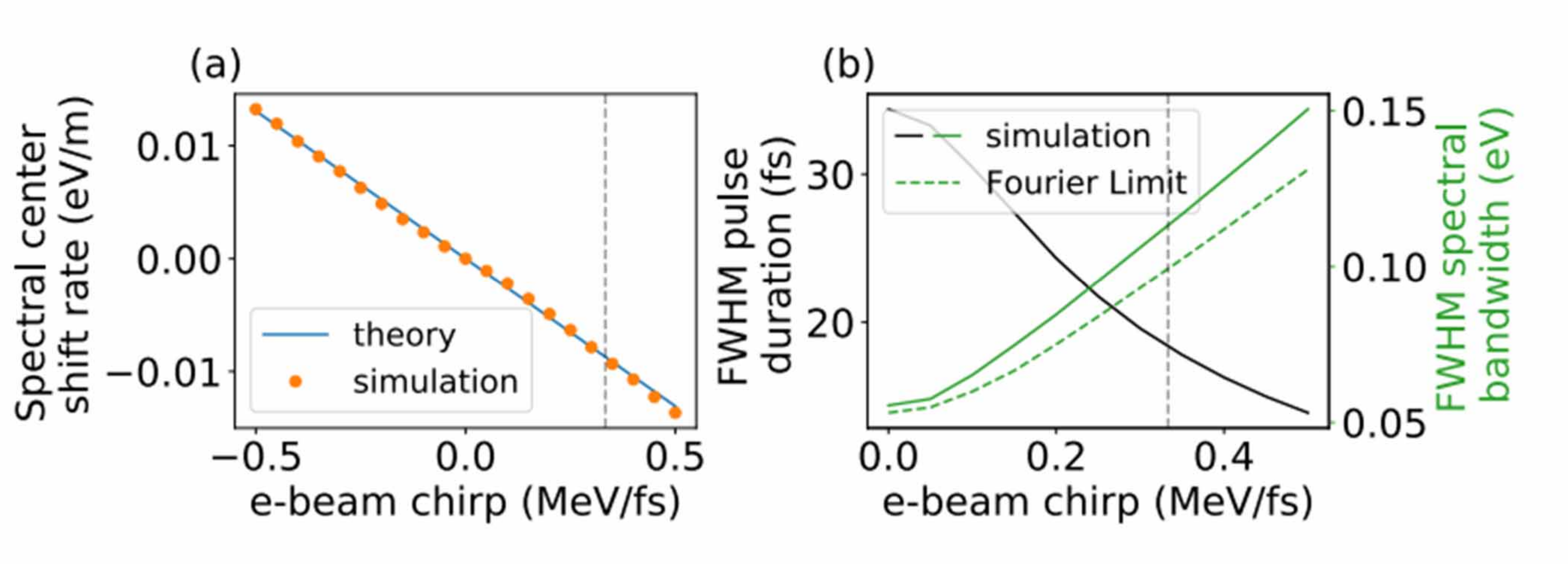
Chirp-based XRAFEL Q-switching scheme



- Use an energy-chirped e-beam to shift X-ray wavelength (slightly) outside the Bragg bandwidth
- Actively and flexibly control the cavity Q by manipulating the e-beam energy chirp

Tang, Jingyi, Zhen Zhang, Jenny Morgan, Erik Hemsing, and Zhirong Huang. *Physical Review Letters* 131, no. 5 (2023): 055001.

Chirp-based XRAFEL Q-switching scheme



$$h = \frac{d\gamma/\gamma_0}{cdt}$$

$$\frac{\Delta\omega}{\omega_r} = \frac{4}{3} h \lambda_r N_u$$

- Only a moderate level of energy chirp is required to shift the spectrum out of the Bragg window.

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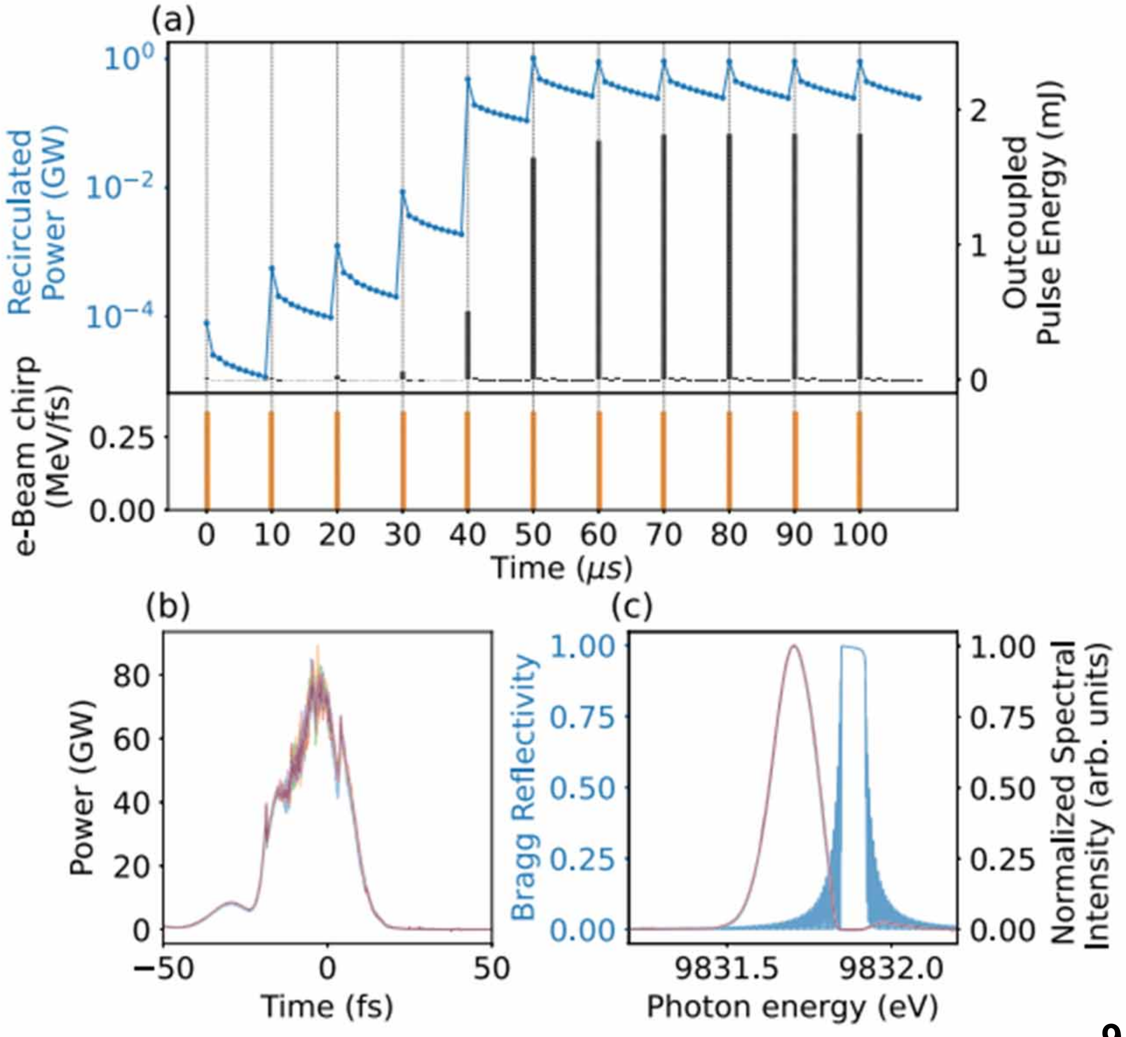
Driven by e-beams at reduced rep. rate

- **300 m** cavity roundtrip, 128m undulators embedded
- **100kHz** e-beam repetition rate
- 10 roundtrips = 10 usec for the next bunch

nominal LCLS-II HE parameters

Electron beam energy	8 GeV
Peak current	2 kA
Normalized emittance	0.3 um
Undulator period	2.6 cm
Undulator length	3.9 m
Undulator K	1.657
Photon energy	9.83 keV C (400) at 45 deg.



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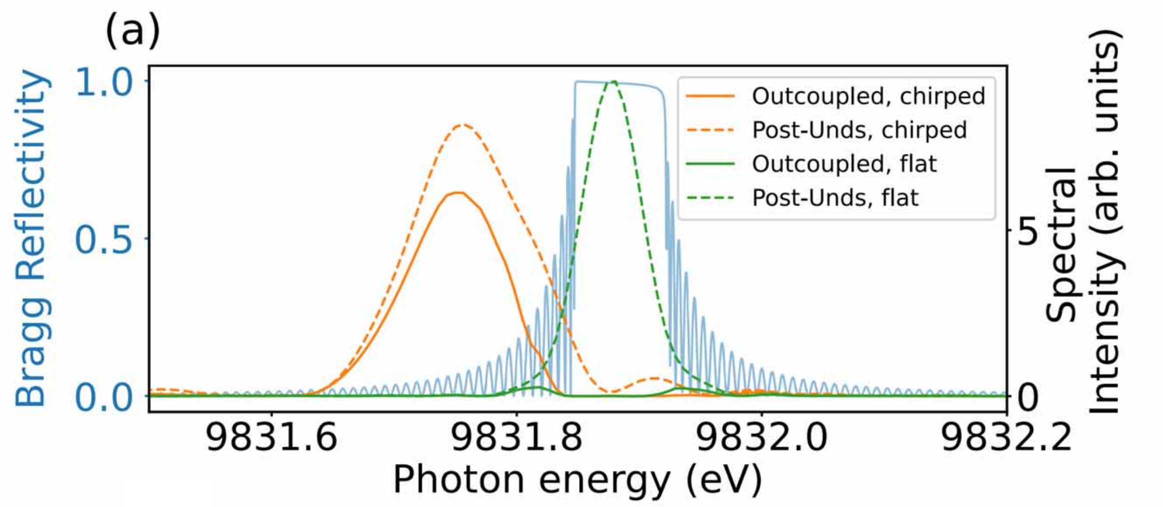
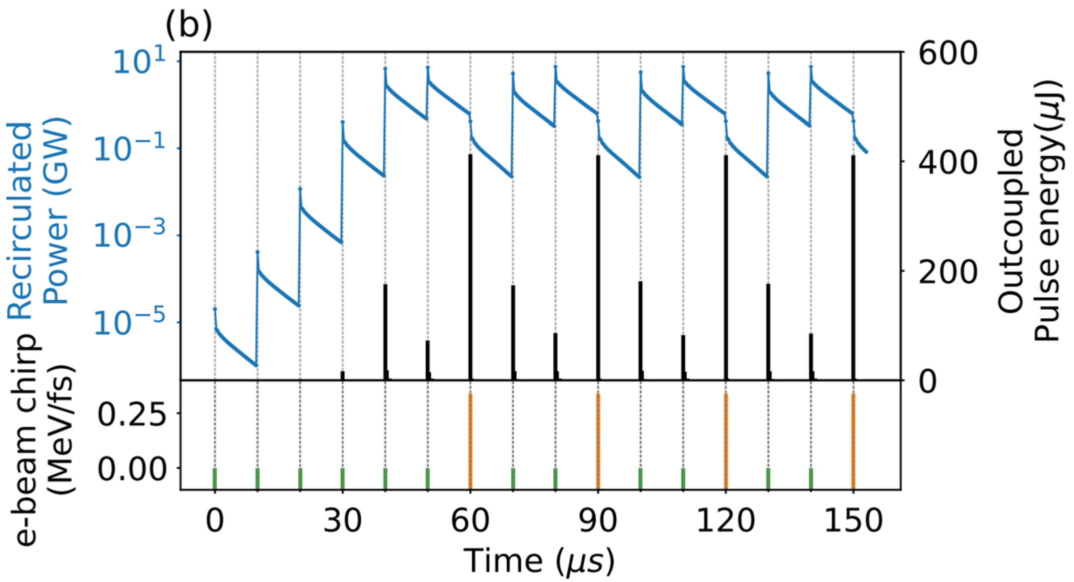
More Compact XRAFEL Footprint

- **100 m roundtrip length**, 46m undulators embedded
- 100kHz e-beam rate
- 30 roundtrips = 10 usec for the next bunch.





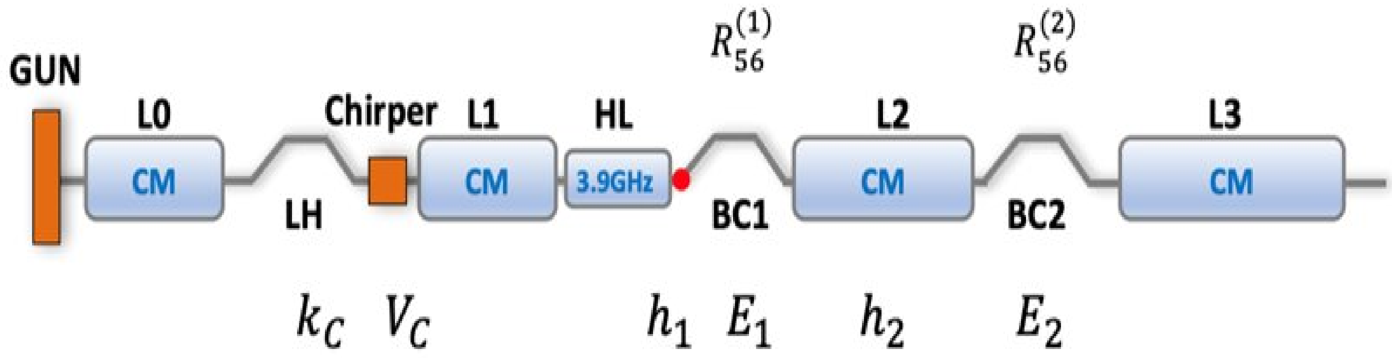
no e-beam / flat e-beam ➡ high cavity Q ➡ fast power build-up and low circulation loss

chirped e-beam ➡ low cavity Q ➡ power outcoupling

More Compact XRAFEL Footprint

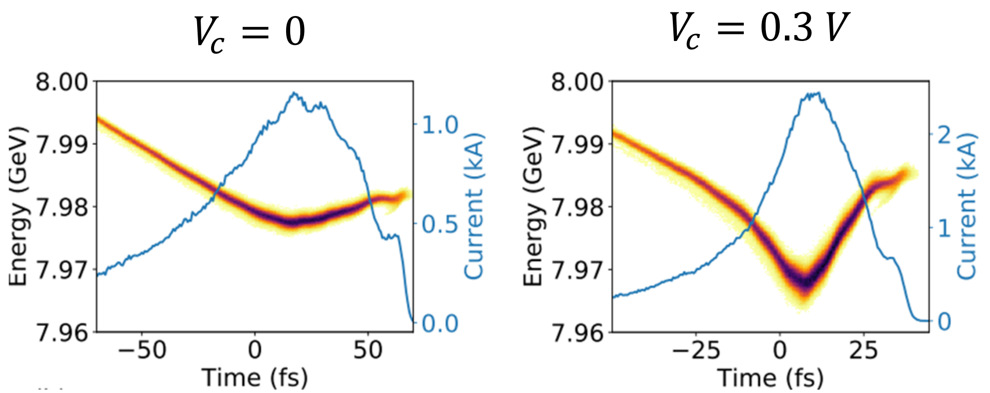
- Fast control of e-beam chirp with normal conducting chirper cavity

Z. Zhang, WE3A2



Nasr, Mamdouh H. et al. *IPAC'16*
Zhang, Zhen, et al. *Review of Scientific Instruments* 94.2 (2023).

- Start-to-end beam of LCLS-II HE



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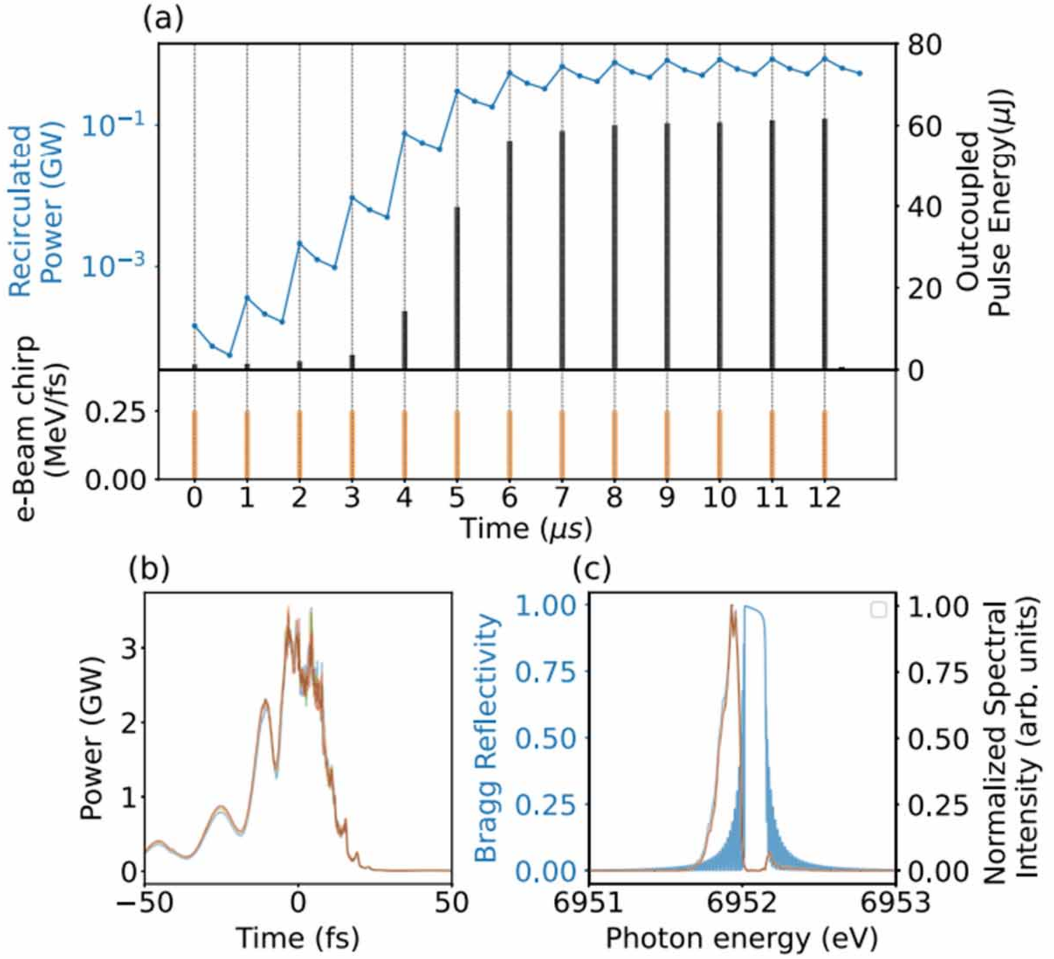
Higher Photon Energy with Low E-beam Energy

- **XRAFEL allows multiple passes before saturation, hence a relatively-low energy linac for Hard X-rays**

  - UK XFEL [1]
  - Shenzhen XFEL [2]

Electron beam energy	**3 GeV**
Electron beam rate	1 MHz
Normalized emittance	**0.3 um**
Photon energy	**6.95 keV**
Bragg Mirror	C(220)
Cavity Roundtrip Length	100 m
Undulator Length	46 m



[1] D. J. Dunning et al., Facility concept outlines for a UK XFEL, in Proc. 40th International Free Electron Laser Conference
[2] X. Wang et al., Physical Design For Shenzhen Superconducting Sof X-Ray Free-electron Laser (S3FEL), 14th International Particle Accelerator Conference, Venezia,

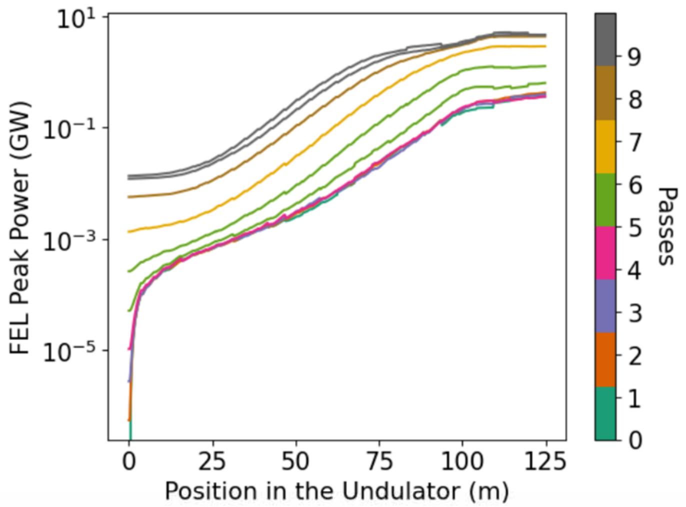
20keV XRAFEL with LCLS-II baseline injector and undulator

SLAC

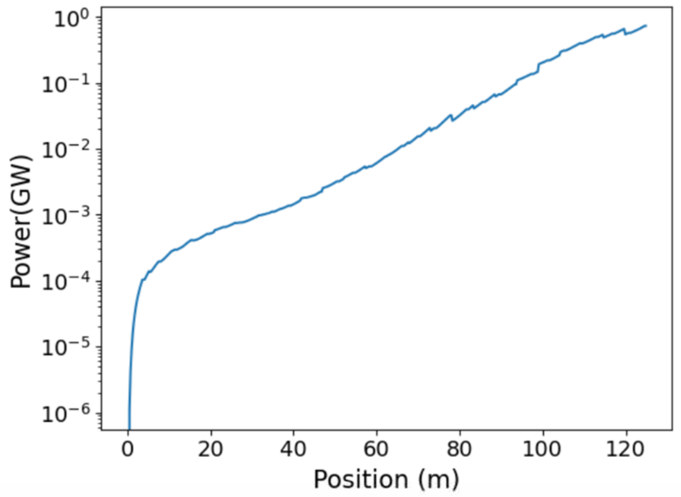
Electron beam energy	**8 GeV**
Electron beam rate	100 kHz
Normalized emittance	**0.3 um**
Photon energy	**19.7 keV**
Bragg Mirror	C (800)
Cavity Roundtrip Length	300 m
Undulator Length	125 m
Pulse energy	**200 uJ**

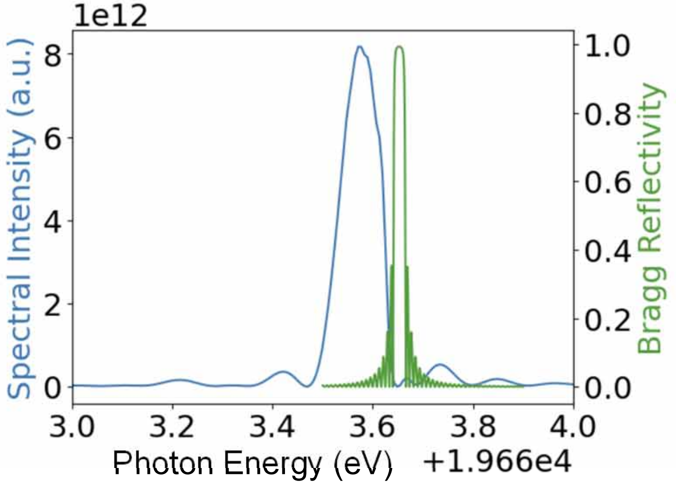
- 3-4 orders of magnitude increase in spectral brightness
- emittance reduction not required

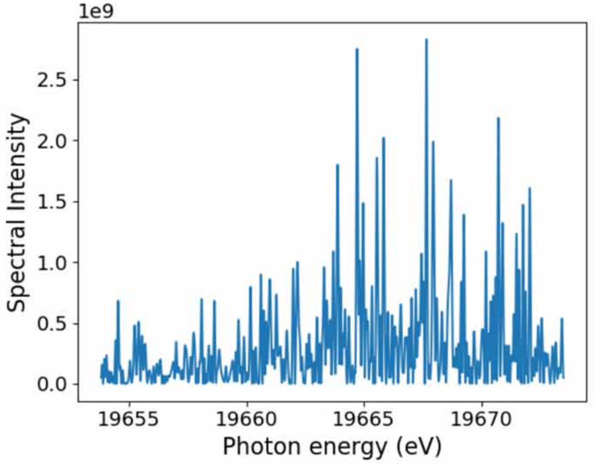
20keV XRAFEL



20keV SASE







Summary

We describe a flexible, efficient Q-switched schemes for XRAFEL

- Simple and straightforward to implement. It only requires simple manipulation of electron beams

- Can be driven by lower e-beam rep rate
  - Pave ways for practical operation of a steady-state XRAFEL
  - Compatible with multiplexing FEL
  - Allows smaller XRAFEL footprint

- Can be driven by e-beams with much lower energy than what is typically required for hard X-ray FELs. This can lead to significant cost savings for future X-ray FEL facilities.

- Thanks for the funding support from DOE BES - Accelerator and Detector Research

- Thanks for you attention