67th ICFA Advanced Beam Dynamics Workshop on Future Light Sources: FLS 2023

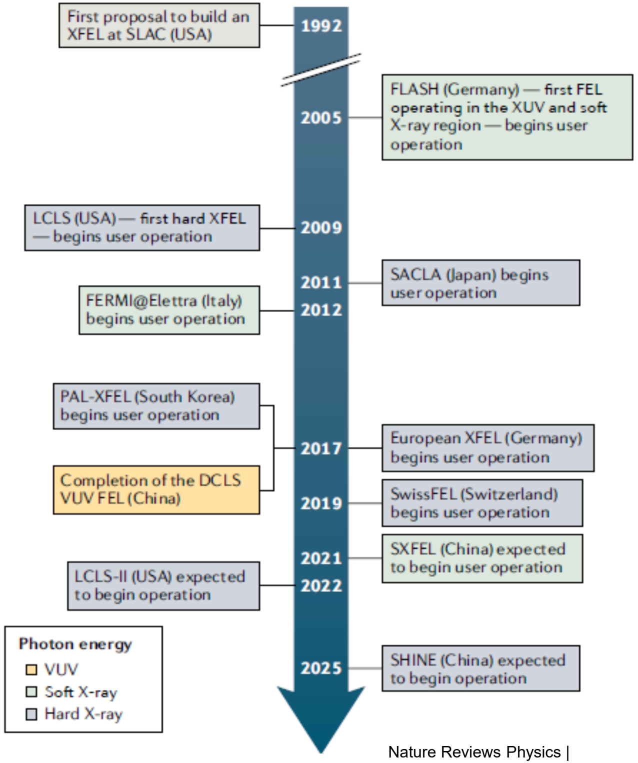
Progress of Cavity-Based XFEL

Zhirong Huang, SLAC

Outline

- Introduction
- Concepts, promises, and opportunities
- CBXFEL experiments and proposals
- Additional challenges and proposed solutions
- Summary

The first decade of XFELs



Nature Reviews Physics | https://doi.org/10.1038/s42254-020-0204-6; 3 July 2020

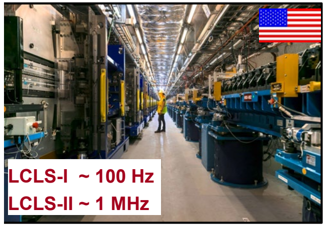
EuXFEL, Germany

FLASH

SACLA, Japan

SwissFEL, Switzerland

PAL-FEL, Korea



Under construction

SHINE, SXFEL

Approx. average pulse repetition rate is shown (note: EuXFEL is 4.5 MHz burst at 10 Hz)

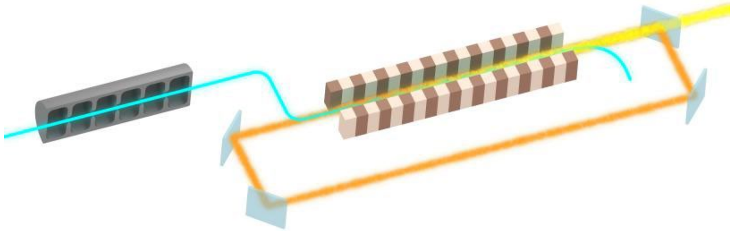
EuXFEL, SHINE and LCLS-II/HE are leading the development of high rep. rate FEL facilities

Cavity-Based XFEL (CBXFEL)

- Hard X-ray FELs are based on single-pass SASE: very flexible (fs-as pulses, self-seeding, two-color, …), but fluctuating and not longitudinally coherent.
- SASE fluctuations generally lead to excessive noise in many X-ray experiments and impede the advantages of extra flux/brightness.

- For LCLS-II and other high-rep. rate XFELs, an X-ray optical cavity can be built to filter and return X-ray pulses for repetitive interactions with e-beams, leading to much better coherence and stability.

- 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
  - Very high peak power (XRAFEL),
  - Ultrafine spectral capabilities (XFELO).



The early concept

PROPOSAL FOR A FREE ELECTRON LASER IN THE X-RAY REGION

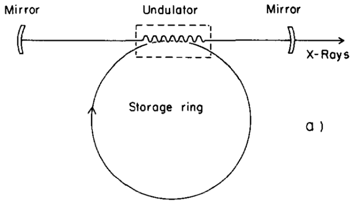
R. COLELLA
Department of Physics, Purdue University, West Lafayette, IN 47907, USA

A. LUCCIO
Brookhaven National Laboratory, National Synchrotron Light Source, Upton, NY 11973, USA

Received 13 September 1983

It is proposed that a free electron laser can be operated in the X-ray region, in the range 2–3 Å. An analysis is presented of the machine parameters and the characteristics of the mirrors that are required for operation in the Ångstrom region.

It has recently been shown that the coherence properties of the electromagnetic radiation emitted by electrons in an undulating magnetic field can be exploited to obtain laser action, by reflecting the bremsstrahlung light rays back into the electron beam by means of mirrors [1]. The most important distinction between a Free Electron Laser (FEL) and an ordinary laser is the fact that the former does not depend on the principle of optical pumping of atomic levels, and subsequent stimulated emission, which is



COLLECTIVE INSTABILITIES AND HIGH-GAIN REGIME IN A FREE ELECTRON LASER

R. BONIFACIO *, C. PELLEGRINI
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY 11973, USA

and

L.M. NARDUCCI
Physics Department, Drexel University, Philadelphia, PA 19104, USA

Received 5 April 1984

We study the behavior of a free electron laser in the high gain regime, and the conditions for the emergence of a collective instability in the electron beam-undulator-field system. Our equations, in the appropriate limit, yield the traditional small gain formula. In the nonlinear regime, numerical solutions of the coupled equations of motion support the correctness of our proposed empirical estimator for the build-up time of the pulses, and indicate the existence of optimum parameters for the production of high peak-power radiation.

Both papers in Opt. Comm. 50, 1984.

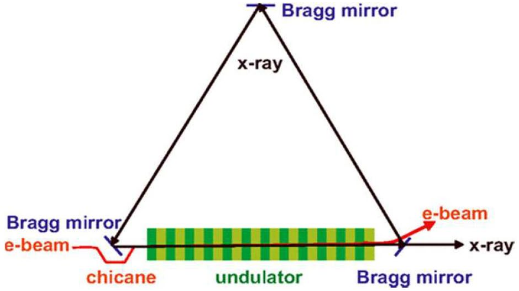
- The concept of using crystals as Bragg mirrors for X-rays was presented in 1984 at the same workshop that first suggested X-ray SASE FELs.
- While SASE took off, this concept laid dormant for more than two decades.
- It started the revival in mid to late 2000s as XRAFEL and XFELO.

XRAFEL and XFELO

Xray Regenerative Amplifier FEL (XRAFEL)

Z. Huang, R. Ruth, PRL 96, 144801 (2006)

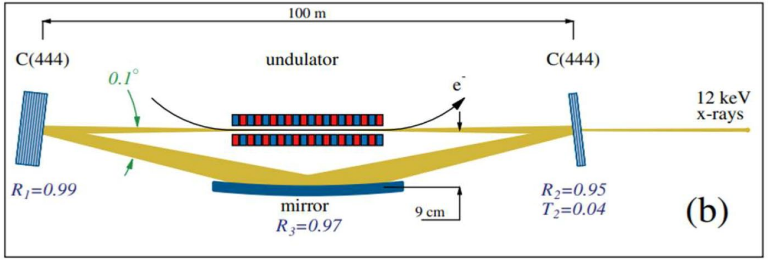
- High-gain, 10s of passes to saturation
- High-peak power
- Narrow Bandwidth
- More relaxed alignment and reflectivity tolerances
- CW or Q-switched



X-ray FEL oscillator (XFELO)

K.-J. Kim, et al., PRL100, 244802 (2008).

- Low-gain, 100s passes to saturation
- Relatively low output power
- Extremely narrow-bandwidth
- Tighter alignment and reflectivity tolerance
- CW operation

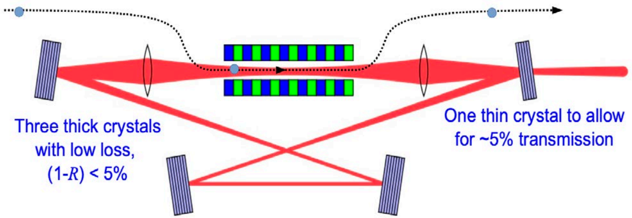


- High-rep. rate FEL facilities are coming online (Eu-XFEL, LCLS-II, SHINE,…).
- Advances in X-ray optics and nano-mechanical controls have dramatically improved these prospects.
- CBXFEL (XRAFEL+XFELO) receives renewed interests in recent years.
- Population Inversion X-ray Laser Oscillator is also proposed (A. Halavanau, WE2C1)

CBXFEL concepts unlock true potential of a HXR laser

SLAC

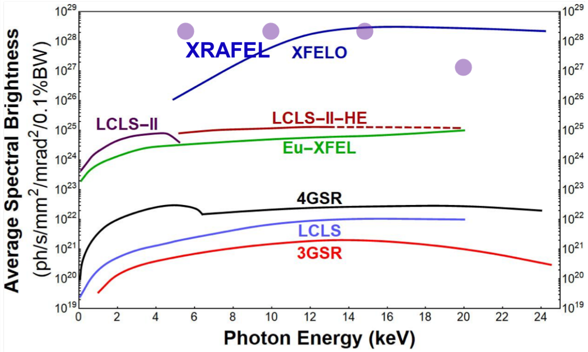
XFELO



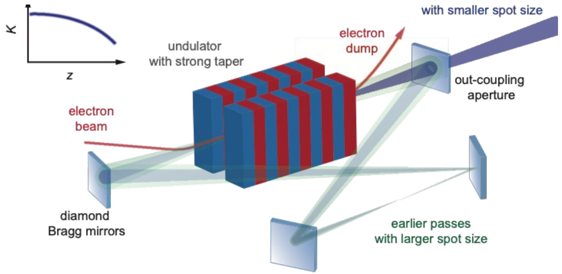
- Electron beam requirements
  - High brightness: $\varepsilon_x \leq 0.3$ μm, $\Delta\gamma/\gamma \leq$ few × 10^{-4}
  - Relatively low intensity: I_{peak} ~ 10 – 200 A
  - Moderate duration: 0.2 – 5 ps
  - Repetition rate = c/(cavity length) ~ MHz
- Undulator parameters: $K \sim 1$ and $N_u \sim 10^3$
- Low-loss optical cavity
  - Perfect diamond crystals that reflect x-rays via Bragg diffraction
  - Focusing elements to produce x-ray waist at undulator middle and optimize Rayleigh range
  - Bow-tie shape is basically a wrapped-up monochromator that allows one to tune the output wavelength[4,5]

R. Lindberg et al., PRSTAB 14, 010701 (2011).
W. Qin et al., FEL2017 (2021)

Peak and average brightness 2-3 orders of magnitude greater than single pass SASE amplifiers



XRAFEL



- **XRAFEL** source assuming LCLS-II-HE parameters + 300 m RT length cavity produces coherent, stable, narrow bandwidth hard x-rays.
- Mirror with hole for outcoupling, high-loss is compensated by high-gain FEL.
- Strong taper and refractive guiding in the postsaturation regime is found to play a key role in passively controlling the stored cavity power.

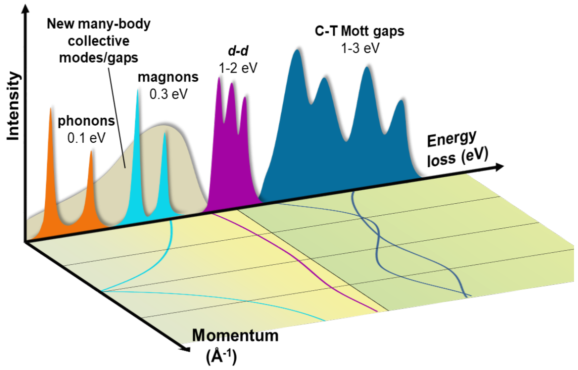
G. Marcus *et al.*, Phys. Rev. Lett. 125, 254801 (2020)

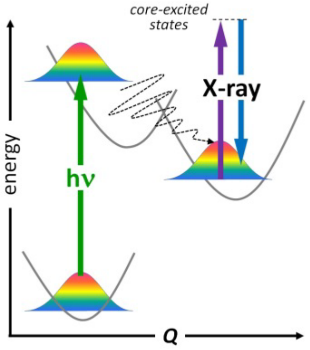
CBXFEL Science Opportunities

2021 EuXFEL workshop: https://indico.desy.de/event/25361/

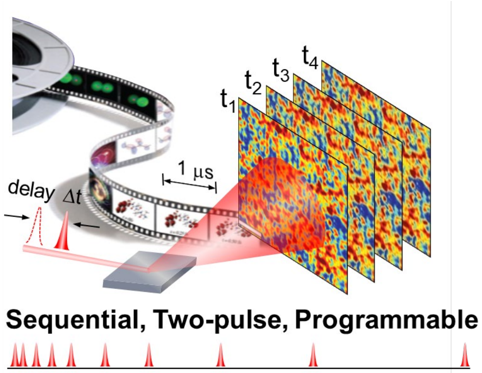
(R. Schoenlein)

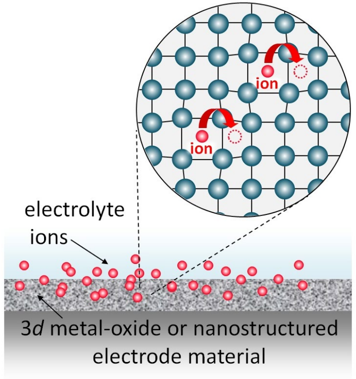
Hard X-ray Spectroscopy at the FT Limit



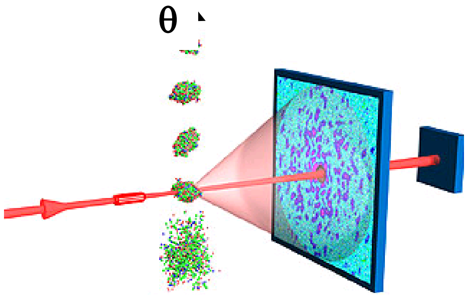


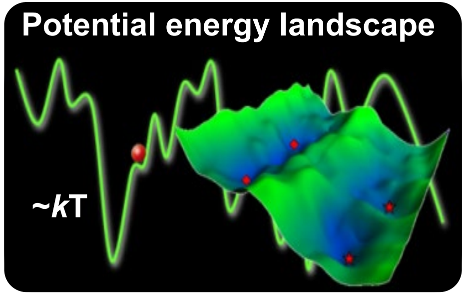
Stochastic Dynamics & Materials Heterogeneity



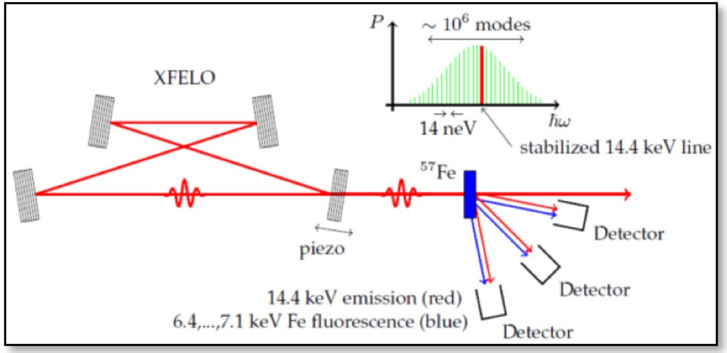


Mapping Reaction Paths & Rare Events





Quantum X-ray Optics & Extreme Metrology



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SLAC

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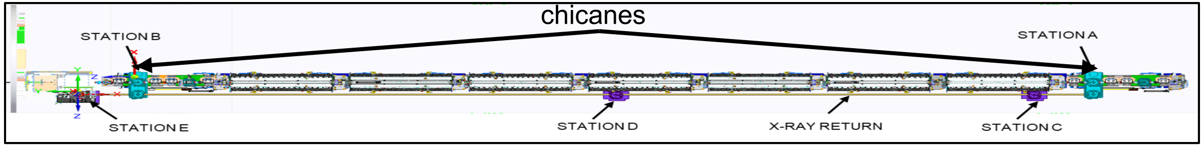
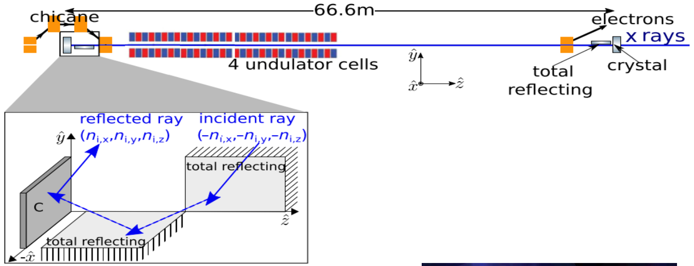
CBXFEL Proof of Principle Experiments

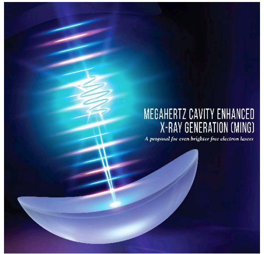
- ANL/SLAC/Spring-8 is working on a CBXFEL PoP project at LCLS-II (G. Marcus et al., FEL2019, *K.-J. Kim et al.,* TU4P14)



- Eu-XFEL is pursuing a similar project (P. Rauer et al., PRAB 26, 020701, 2023)



- SHINE MING proposal (N.S. Huang et al. NUCL. SCI. TECH. 34, 6, 2023)

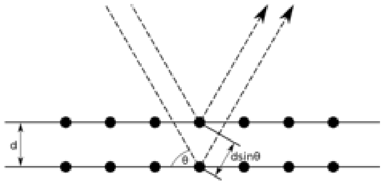


Diamond as the material for Bragg mirrors

Optics development: High-pressure high-temperature Type IIa diamonds

At select HXR energies, diamond Bragg mirrors provide ~99% reflectivity for narrow bandwidths

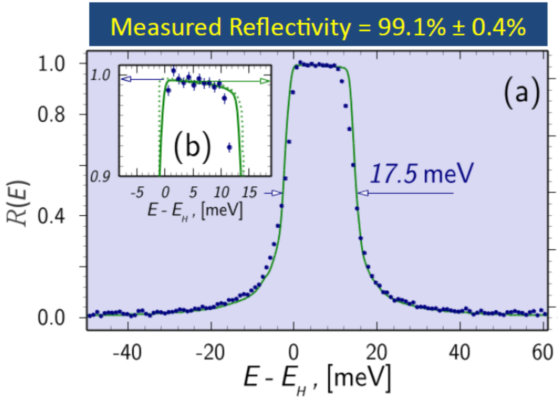
Bragg Reflection



Sample 4-bounce reflections

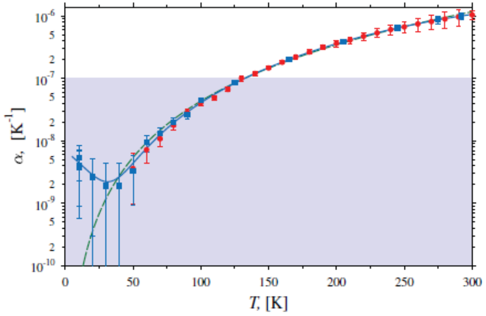
HKL	Energy 45° (eV)	4 Bounce FWHM (eV)
220	6952.3	0.139
400	9831.9	0.079
440	13904.4	0.048

Diamond has excellent thermo-mechanical properties: record high reflectivities, ultra-high thermal diffusivity, ulta-low thermal expansion at low temp., radiation hard



Y. Shvyd'ko, *et al*., Nature Photonics **5**, 539 (2011)

Diamond Linear thermal expansion coefficient



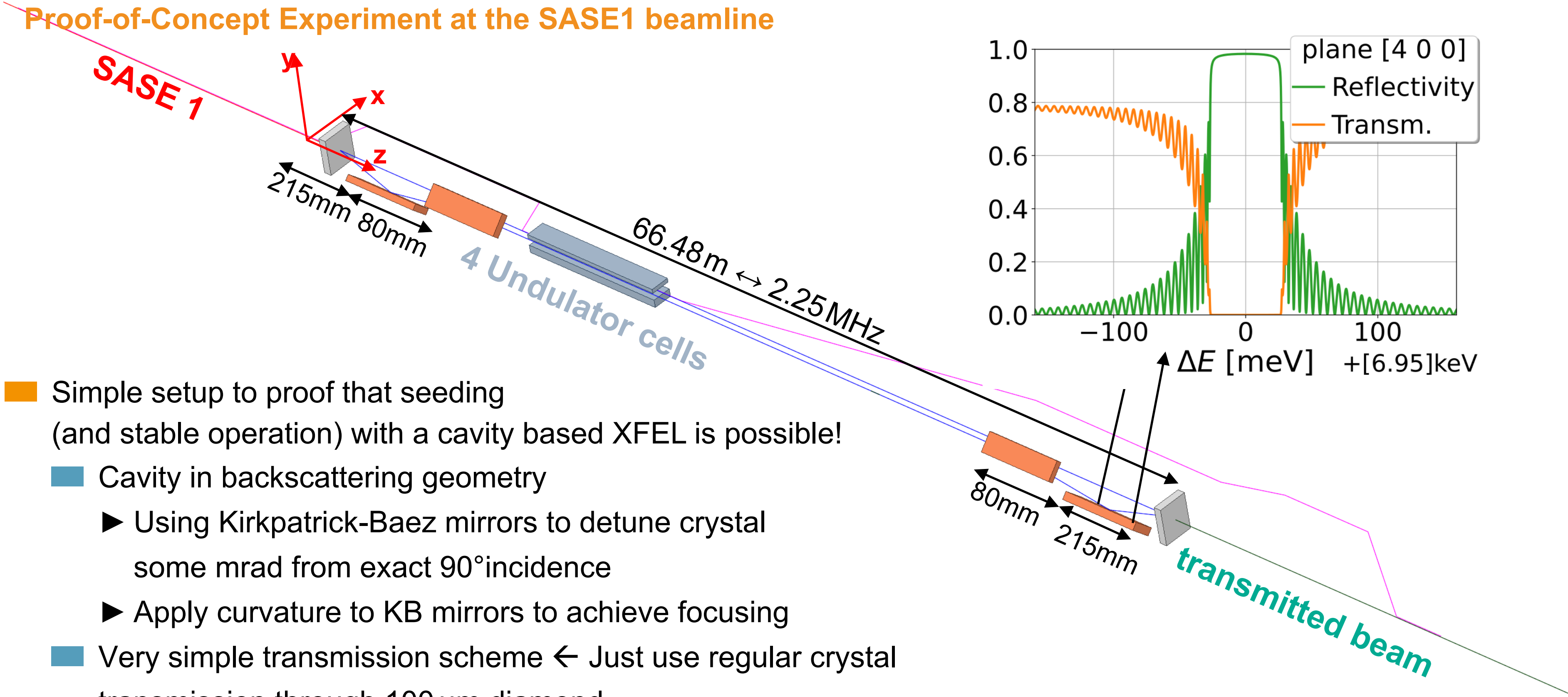
S. Stoupin, Y. Shvyd'ko, Phys. Rev. Lett. **104**, 085901 (2010)

SLAC Argonne NATIONAL LABORATORY RIKEN Since 1917

A CBXFEL Demonstrator for the European XFEL

Patrick Rauer (DESY)

Proof-of-Concept Experiment at the SASE1 beamline



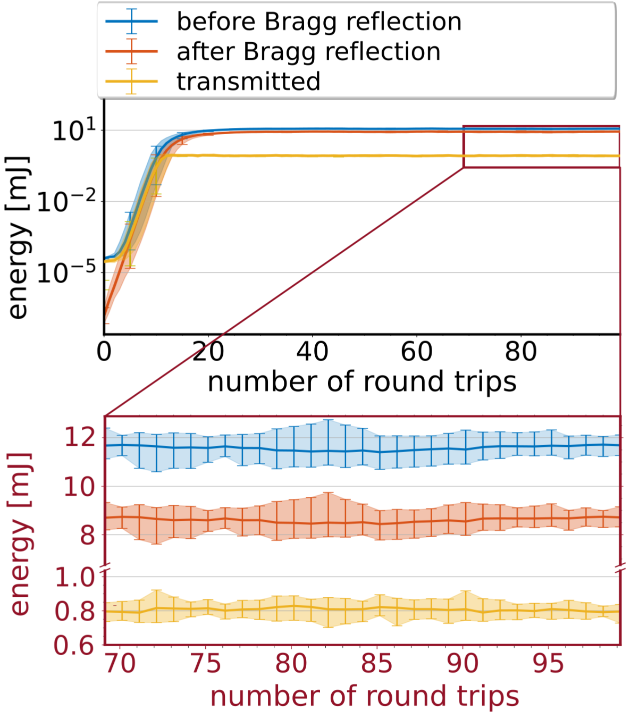
- Simple setup to proof that seeding (and stable operation) with a cavity based XFEL is possible!
  - Cavity in backscattering geometry
    - ► Using Kirkpatrick-Baez mirrors to detune crystal some mrad from exact 90°incidence
    - ► Apply curvature to KB mirrors to achieve focusing
  - Very simple transmission scheme ← Just use regular crystal transmission through 100 µm diamond

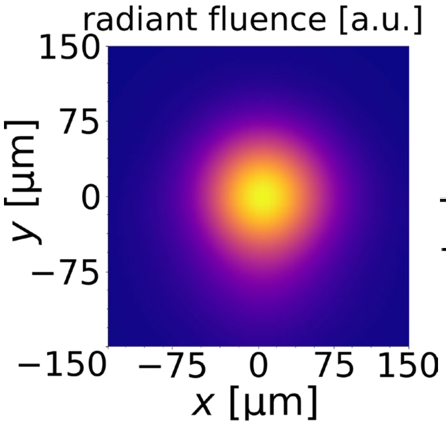
P. Rauer et al., PRAB 26, 020701, 2023

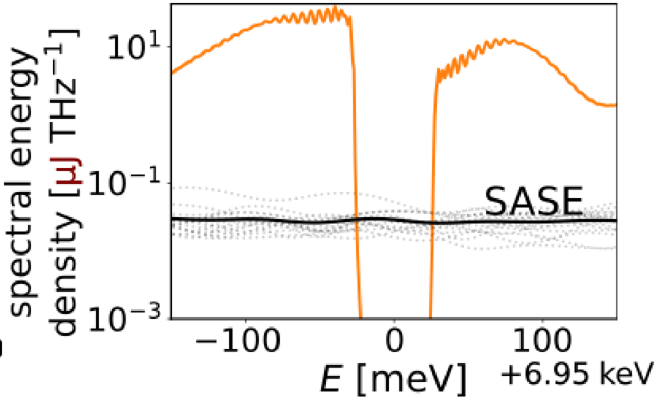
Patrick Rauer (DESY)

A CBXFEL Demonstrator for the European XFEL

Performance of Transmitted Beam Including Mirror Tilt, Electron Jitter and Surface Error







- Transverse distribution smoothed out for transmitted radiation
- Transmitted radiation 3 orders of magnitude lower spectral flux
  - Still 2-3 orders higher than SASE

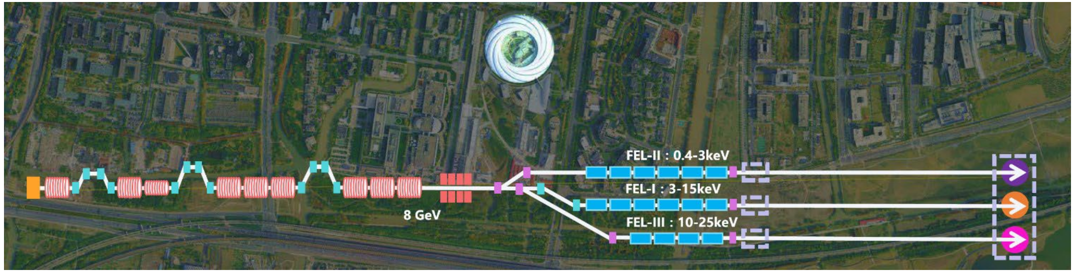
- Thermal impact of MHz x-rays on crystals could strongly destabilizes the CBXFEL!

P. Rauer et al., PRAB 26, 020701, 2023

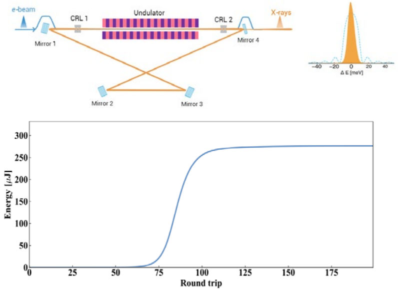
Haixiao Deng (SARI)

Megahertz cavIty enhaNced x-ray Generation (MING) at SHINE

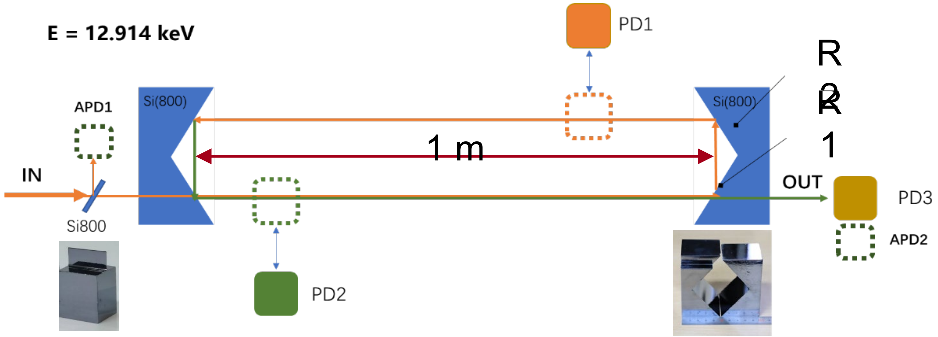
- ✓ **Beam parameters: 8GeV, 1MHz, 100pC;**
- ✓ **X-ray cavity wavelength: 0.1nm/0.085nm**
- ✓ **CDR(2023) released, TDR(2025)**

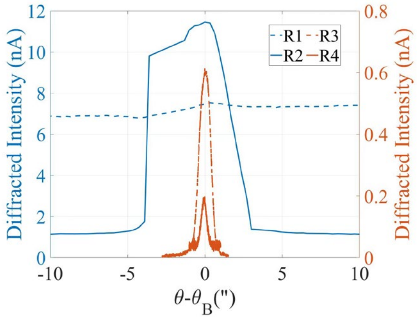


N.S. Huang *et al. NUCL. SCI. TECH.* 34, 6, 2023



X-ray cavity experiments at SSRF

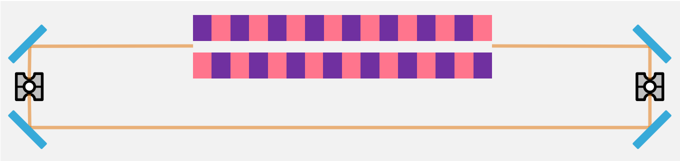


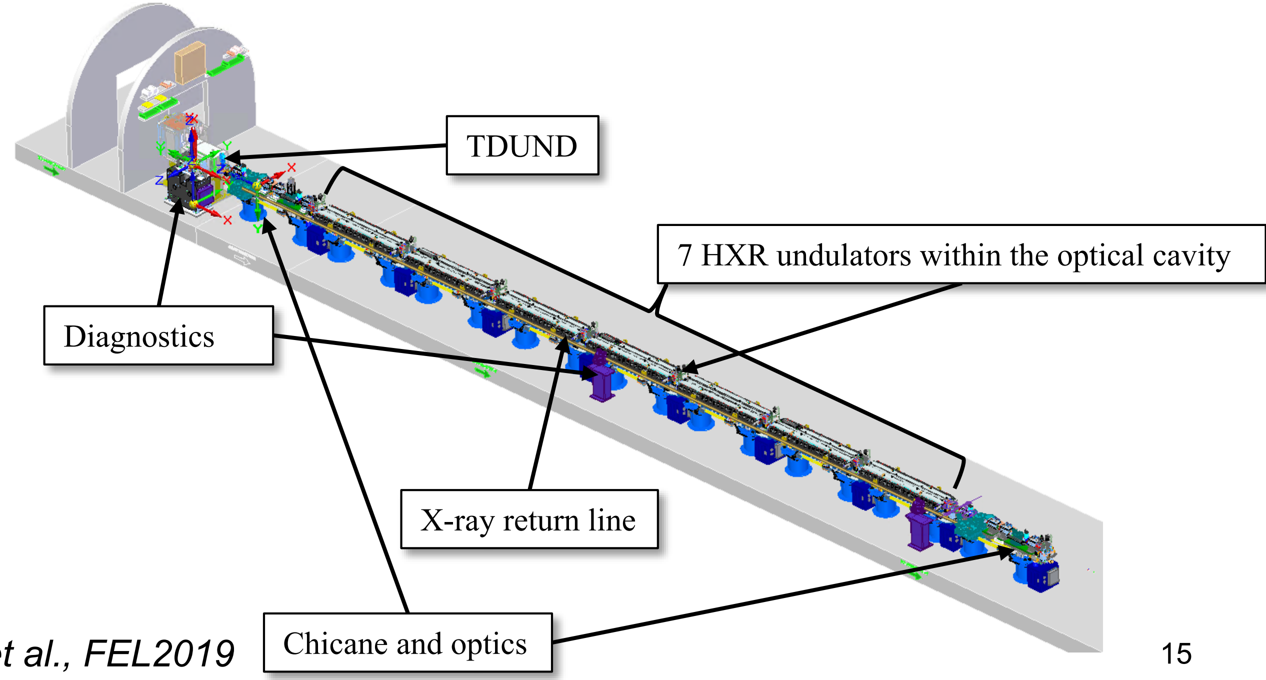


Measured four Bragg reflections with non-closed cavity

CBXFEL project – *ANL/SLAC/Spring-8 collaboration to conduct targeted R&D*

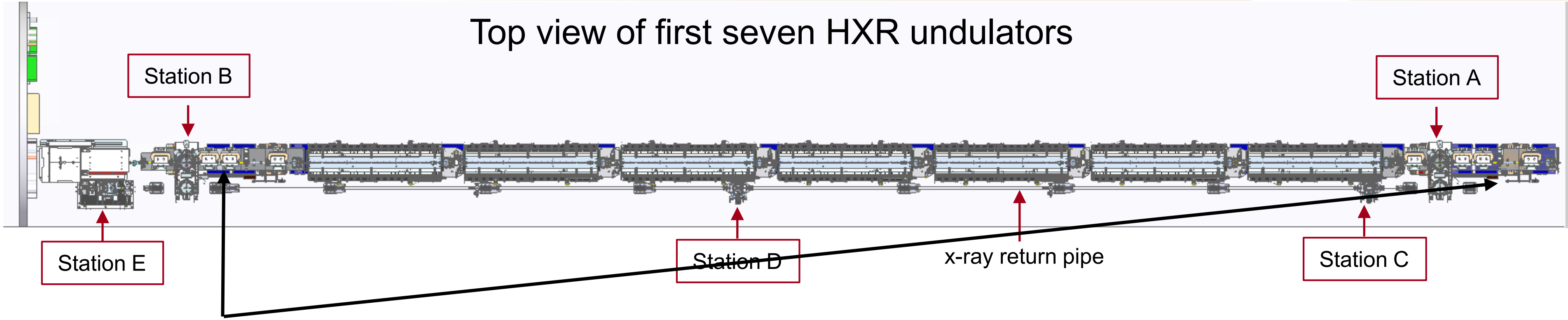
- Design and construct a **rectangular** X-ray cavity that encloses the first 7 LCLS-II HXR undulators.
- Use **double** bunches from the SLAC Cu RF linac with 624 bucket separation (218.4 ns).
- **Photon energy 9.83 keV. Cavity length 65.5 m**
- First bunch generates SASE, which is returned by cavity to interact with the second bunch.
- Initial performance goals: **measure 2nd pass gain and quantify cavity loss**.
- Characterize cavity stability and tolerances for XRAFEL/XFELO.





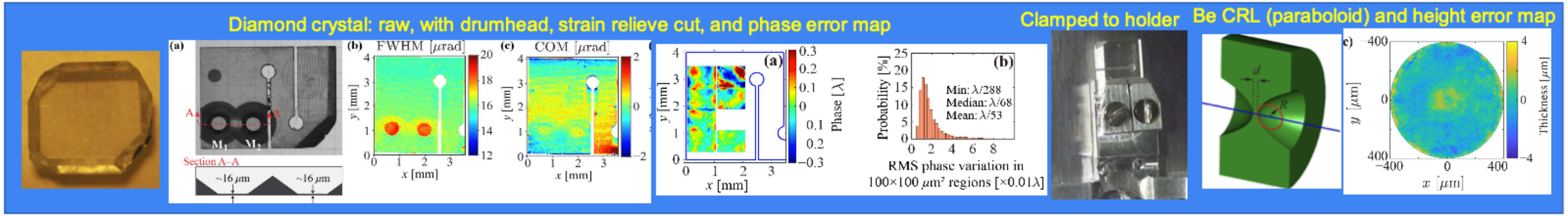
G. Marcus et al., FEL2019

CBXFEL sub-systems



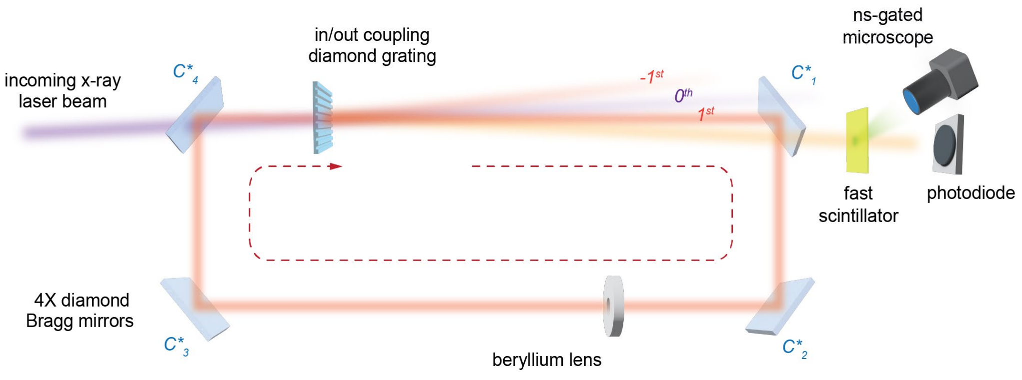
1. Chicanes to by-pass optics (including relocating undulators)
2. Stations A/B house 4-diamond crystals (including nanopositioning stages)
3. X-ray optics/diagnostics inside stations A/B/C/D/E

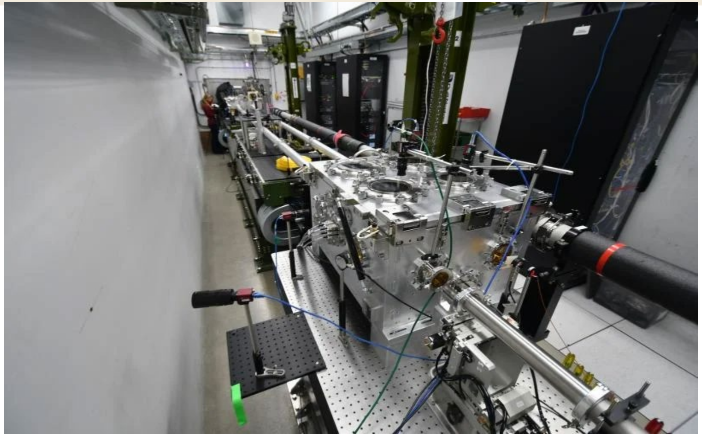
X-ray optics

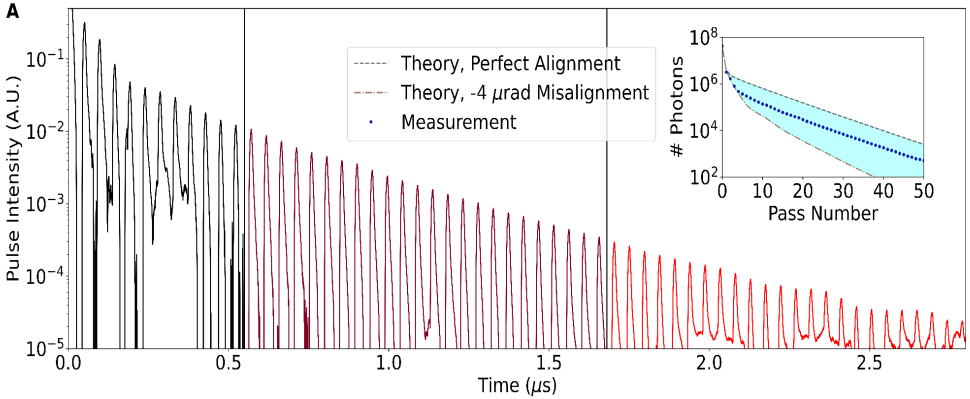


See K.-J. Kim et al., TU4P14

X-ray 'Cold' Cavity Experiment at LCLS







- X-ray ring down inside a rectangular cavity at 9.83 Angstrom with 4 C*(400) reflections.
- 14.2 m round trip length, 80 meV bandwidth.
- Transmission grating demonstrated as effective IN/OUT coupling mechanism.
- Intracavity focusing for stabilizing the beam trajectory.
- Alignment diagnostic and procedures tested.

R. Margraf, D. Zhu, et al. Nature Photonics Aug. 2023; see TU2A4

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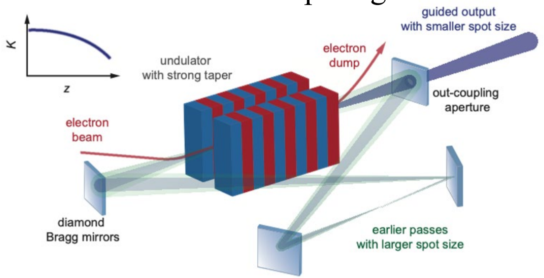
Additional Challenges

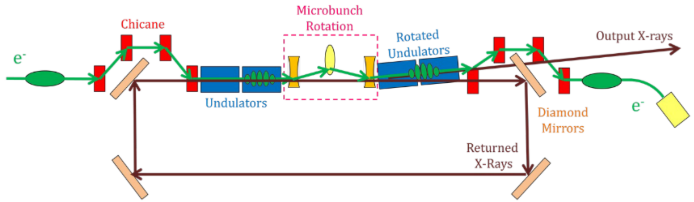
- Most CBXFEL outcoupling schemes are passive (thin diamond, grating, mirror with pinhole, μB rotation, …)

Pinhole and tapering



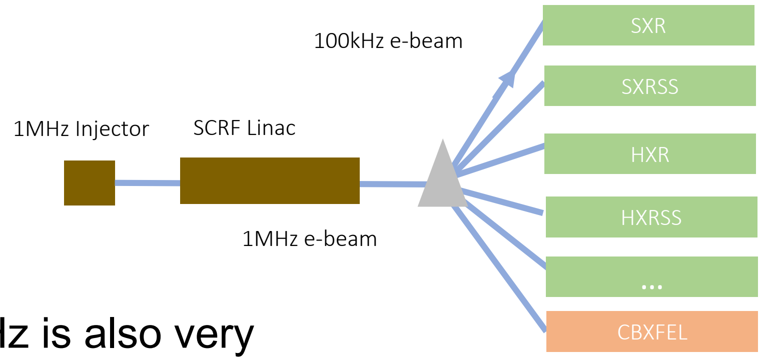
G. Marcus *et al.*, Phys. Rev. Lett. **125**, 254801 (2020)

μB rotation



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

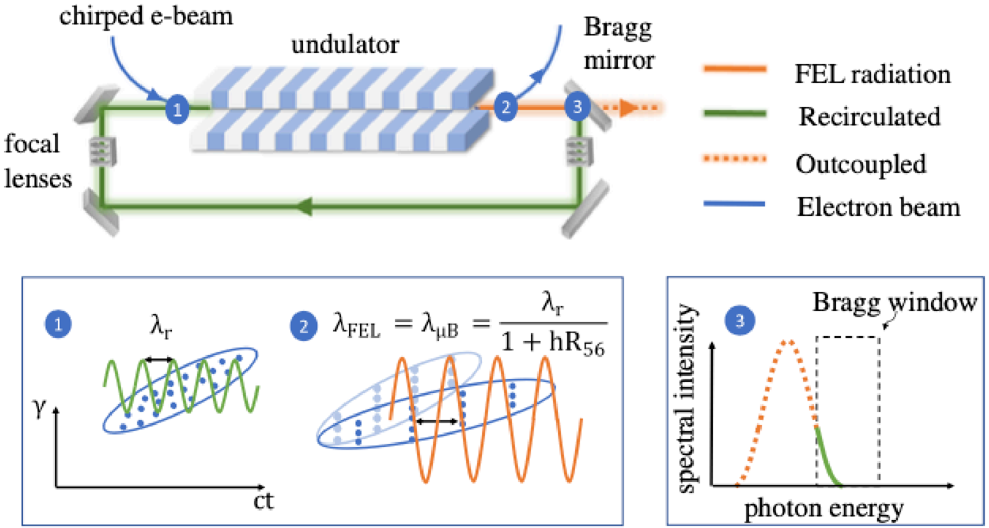
- Passive methods typically requires full machine repetition rate (1MHz) to drive a cavity
  - Repetition rate limited by beam dump power
  - Not compatible with multiplexing



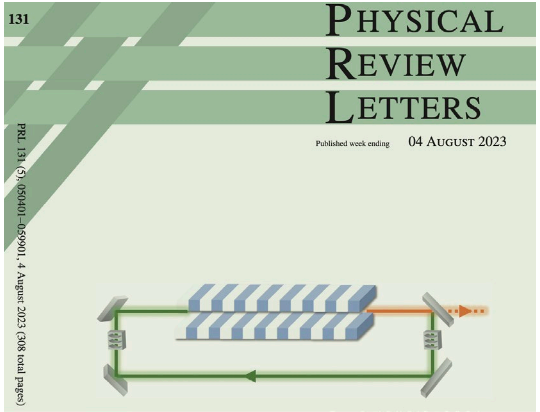
- Thermal load management for X-ray optics at MHz is also very challenging.

Chirp-based XRAFEL Q-switching scheme

- Use an energy-chirped e-beam to shift X-ray wavelength outside the Bragg bandwidth (J. Tang, TH4A3)
- Actively control the cavity Q by manipulating the e-beam energy chirp (Z. Zhang, WE3A2)
- Keep cavity optics simple and intact



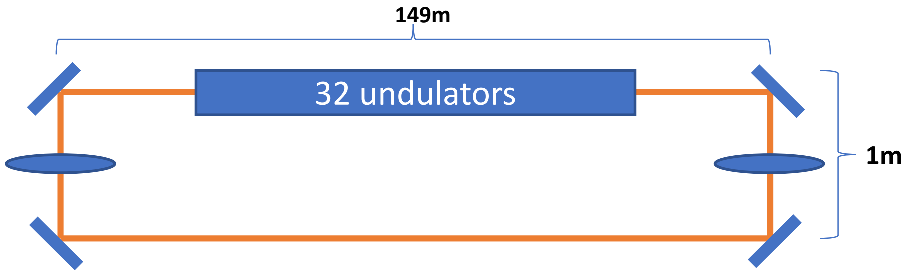
J. Tang, Z. Zhang, J. Morgan, E. Hemsing, Z. Huang, PRL **131**, 055001, *2023*



- High cavity Q ➔ fast power build-up and low circulation loss without gain
- Low cavity Q ➔ large power can be outcoupled

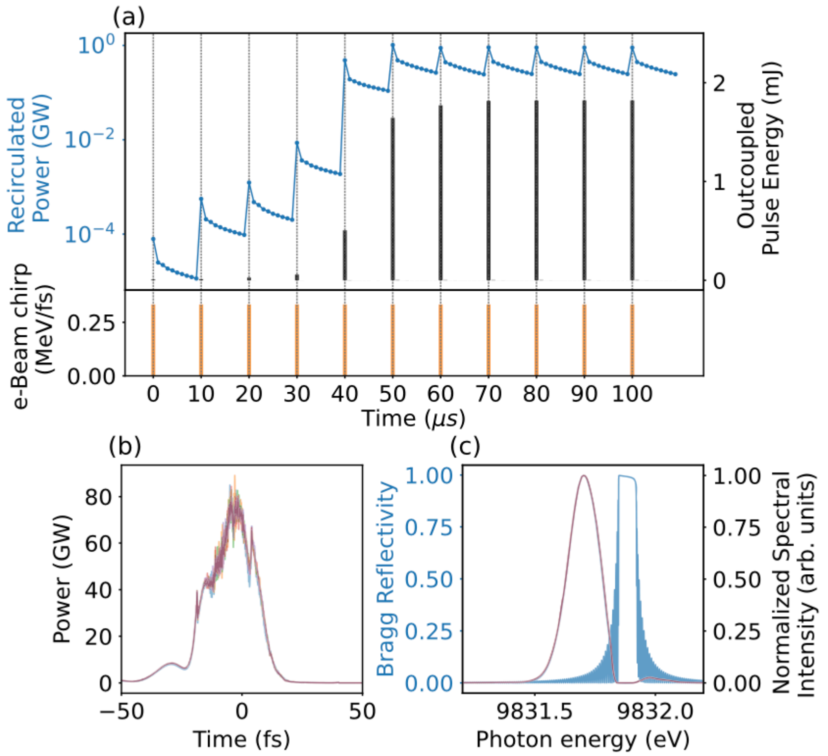
XRAFEL based on LCLS-II HE beam (100 kHz)

- Expand the current CBXFEL cavity to enclose 32 undulators (instead of 7 undulators)



Cavity: 300 m roundtrip, 10 roundtrips = 10 usec for the next bunch (at 100 kHz)

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.**



J. Tang et al, PRL 131, 055001, *2023*

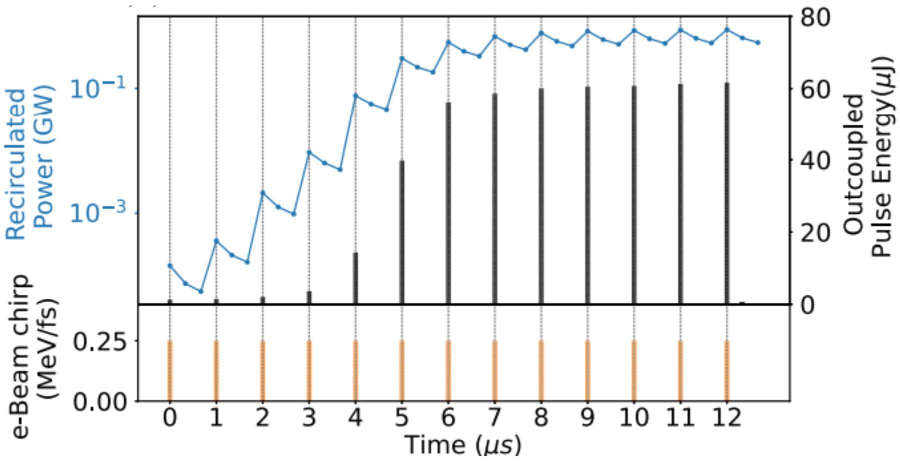
Hard X-ray RAFEL for 3 GeV SC Linac

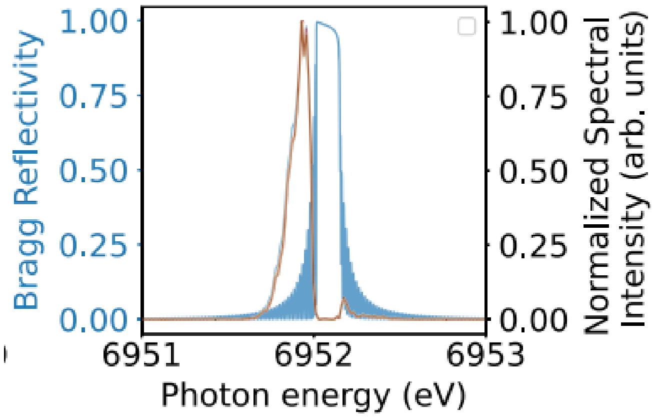
XRAFEL allows multiple passes before saturation, hence a relatively-low energy linac for Hard X-rays

Cavity: 100 m roundtrip, 3 roundtrips = 1 usec for the next bunch (at 1MHz)

E-beam: 3 GeV, current 2 kA, emittance 0.3 um

Electron beam energy	3 GeV
Undulator period	1 cm
Undulator length	3.9 m
Undulator K	0.675
Photon energy	**6.95 keV** **C (220)** at 45 deg.





J. Tang et al, PRL 131, 055001, *2023*

Summary

SLAC

- CBXFEL promises another 2-3 orders of magnitude improvement in XFEL brightness.
- High-rep. rate XFEL facilities (LCLS-II, EuXFEL, SHINE) are developing experiments and proposals to implement CBXFELs.
- A 14-m scale cold cavity at LCLS demonstrated some key technology for CBXFELs.
- A chirp-based Q-switching method is proposed for controlling outcoupled radiation, relaxing requirements on electron beam rep. rate and thermal load management.
- The Q-switching method can support multiplexing high-rep. rate FELs and can work with varieties of electron energies and cavity lengths.

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