A Low-Loss 14 m Hard X-ray Bragg-reflecting Cavity, Experiments and Analysis

Rachel Margraf on behalf of:

River Robles, Alex Halavanau, Jacek Kryzywinski, Kenan Li, James MacArthur, Taito Osaka, Anne Sakdinawat, Takahiro Sato, Yanwen Sun, Kenji Tamasaku, Zhirong Huang, Gabriel Marcus, Diling Zhu

ICFA Future Light Sources 2023

August 29, 2023

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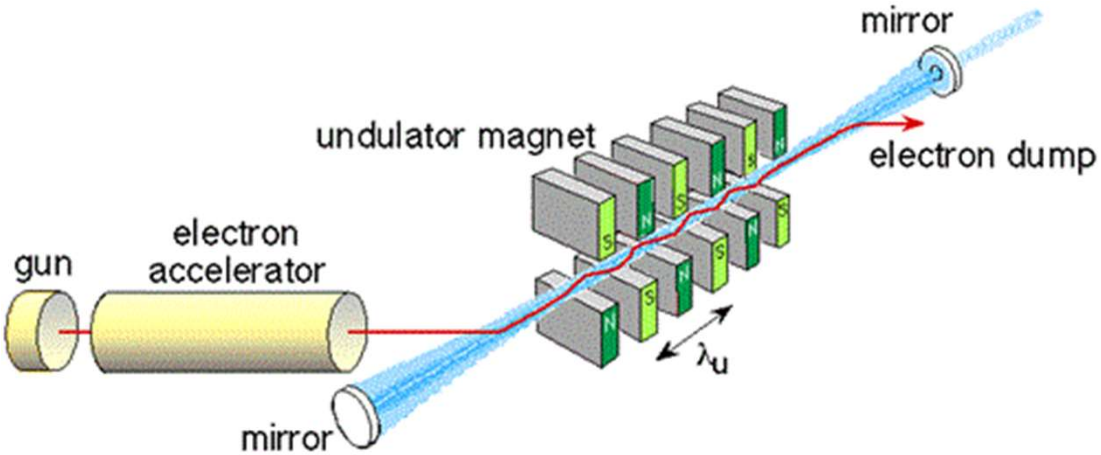
Cavity-Based FELs



(https://www.ru.nl/felix/about-felix/about-felix/fel-operating-principle/)

- FEL Oscillators (FELOs) widely used at Infrared Wavelengths
  - Optical properties well defined by cavity.

- Current X-ray FELs are single-pass, SASE machines
  - Transversely coherent, longitudinally chaotic
  - X-ray cavities difficult to build – lack of broad bandwidth, high-angle, high reflectivity mirrors.

- Cavity-based XFELs will extend oscillator schemes to X-ray regime.

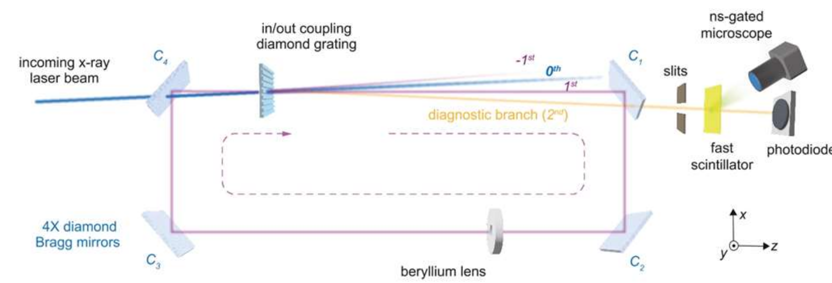
Cavity-Based XFEL Installations at LCLS

0

SLAC LDRD-Funded Cavity Ringdown Test

- 14 m X-ray "Cold Cavity" (no gain)
- Operated Feb-Apr 2022 in the LCLS XPP hutch

→**Focus of Today's talk!**



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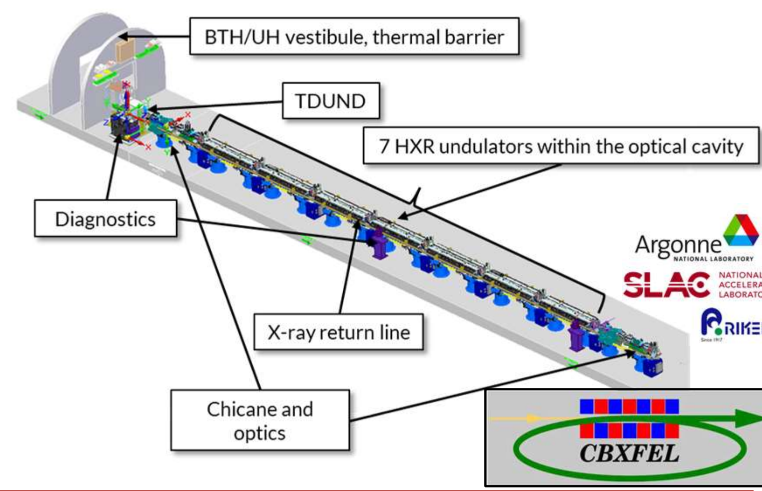
The Optical Cavity-Based X-Ray Free-Electron Laser Project (CBXFEL) a collaboration between SLAC, Argonne and RIKEN.

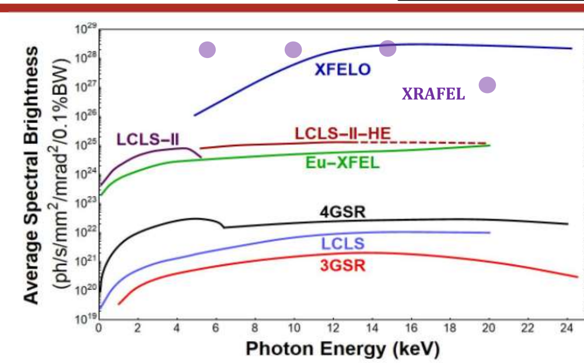
- 66 m 2-pass Gain test cavity, uses NC Accelerator
- To be installed in LCLS Hard X-ray Undulator Hall within a year



X

Large-Scale CBXFEL to deliver X-rays to Users

- Use 8 GeV e$^-$ at MHz repetition rate from LCLS-II-HE to provide gain over many passes
- TBD - lots of possibilities!



G. Marcus *et al.*, Phys. Rev. Lett. **125**, 254801 (2020)
K.J. Kim et al., Proc. of IPAC2019, (2019)

Cavity-Based XFEL Installations at LCLS

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SLAC LDRD-Funded Cavity Ringdown Test

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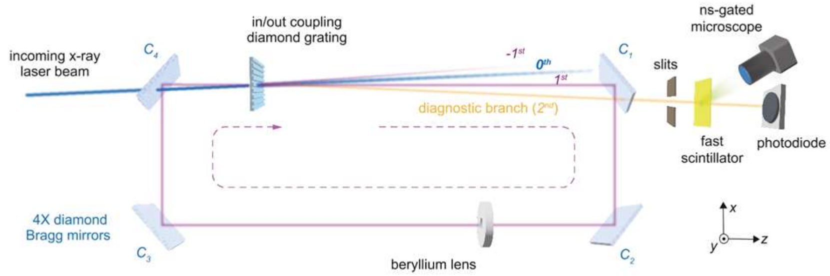
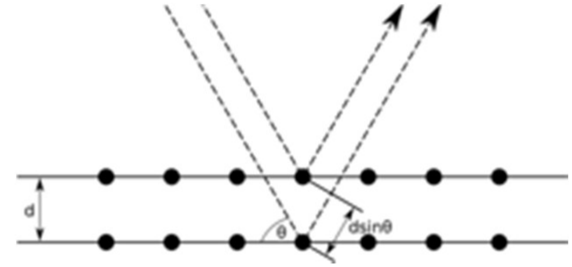
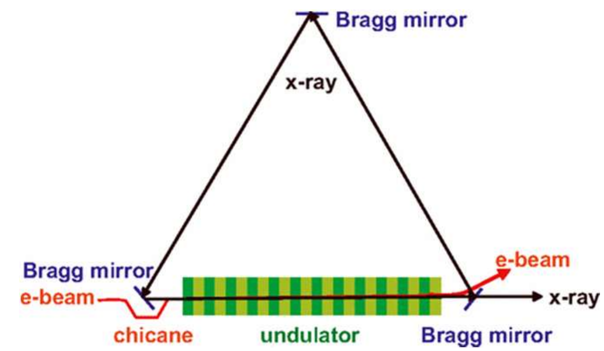


→ First step – build a cavity suitable for a CBXFEL.
What type of cavity do we need?

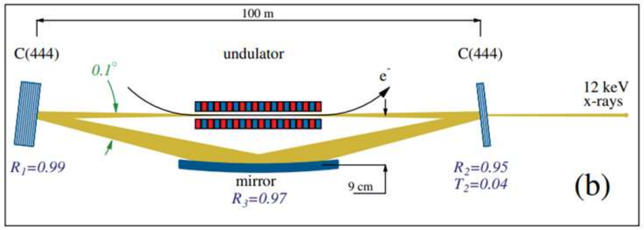
Cavity-Based XFEL Cavity Requirements

- Bragg-Reflecting Cavity
  - High angle, high reflectivity, narrow bandwidth mirrors
- High Thermal Load Tolerance
  - Influences crystal choice – eg. Diamond better dissipation than Silicon
- Large (10-200 m) Stable Cavity
  - Set by round trip time of MHz electron beam
  - Challenging Alignment
  - Crystals need to be independently actuated with angular precision and stability *much* better than beam divergence (~2 μrad) and width of the Bragg curve (eg. 8.8 μrad FWHM diamond 400 @ 9.83 keV)
  - Crystal miscuts and defects reduce cavity efficiency
- Out-coupling Capable
  - Needs to deliver high power X-rays to the end user





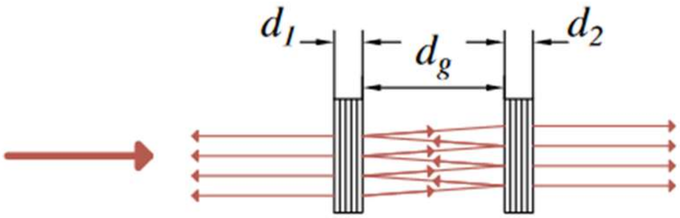
Z. Huang and R. Ruth, PRL, 96, 144801 (2006)



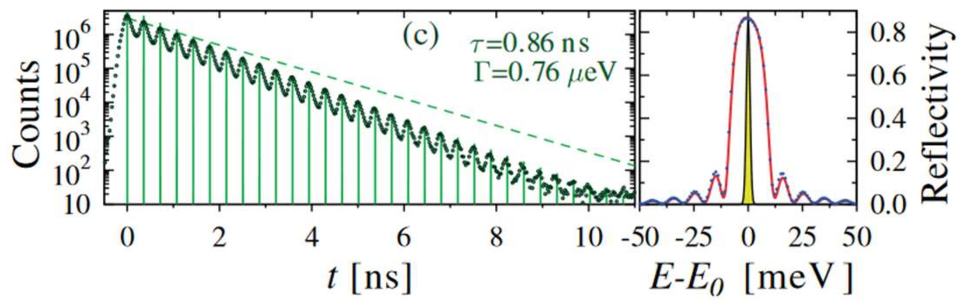
K.-J. Kim, Y. Shvyd'ko, S. Reiche, PRL, 100, 244802 (2008)

Past Bragg-Reflecting X-ray Cavities

Fabry-Pérot Cavities at APS, SPring-8

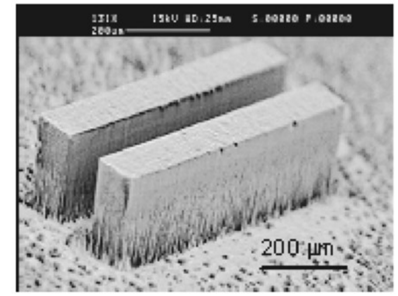


$d_g = 5.37\ cm$

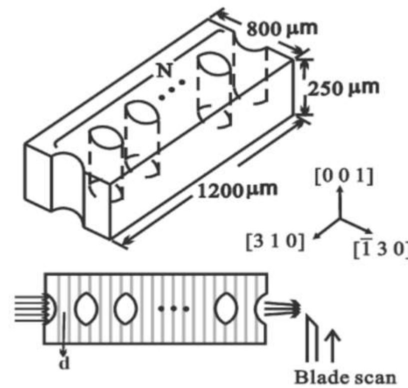


Shvyd'ko et al., PRL, Vol. 90, No. 1 (2003)

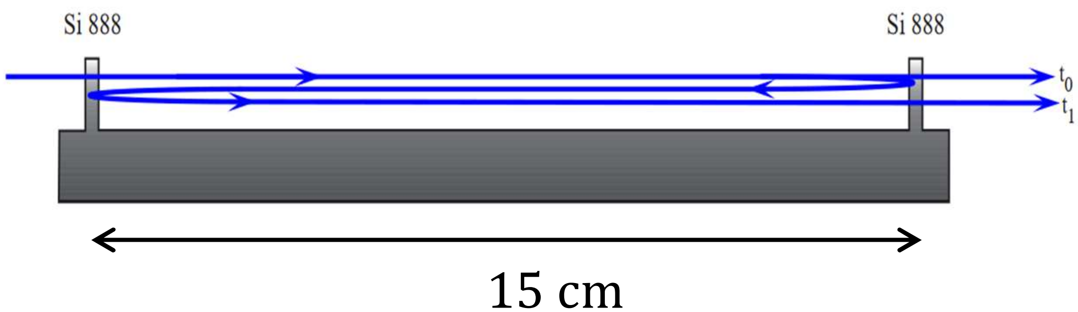
Chang et al., PRB 74, 134111 (2006)

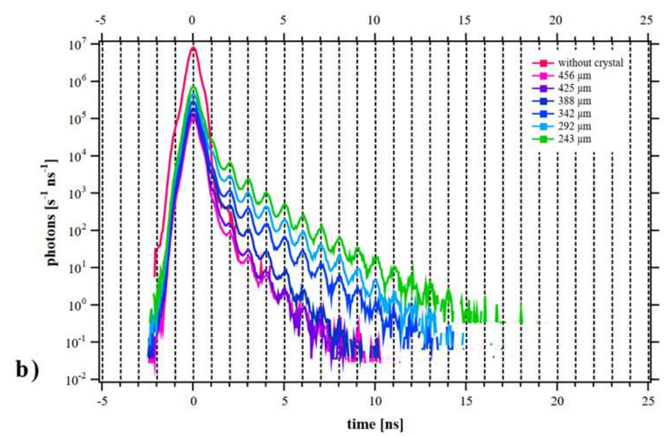


Chang et al., Optics Express 7886 Vol. 18, No. 8 (2010)



Backscattering at ESRF



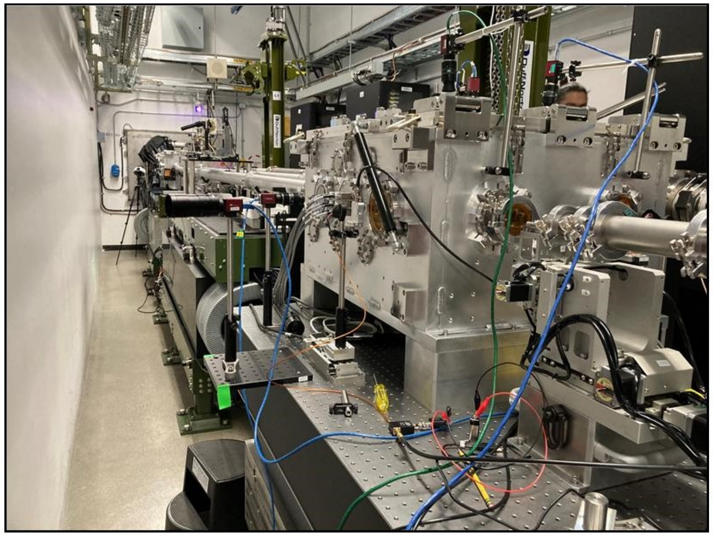


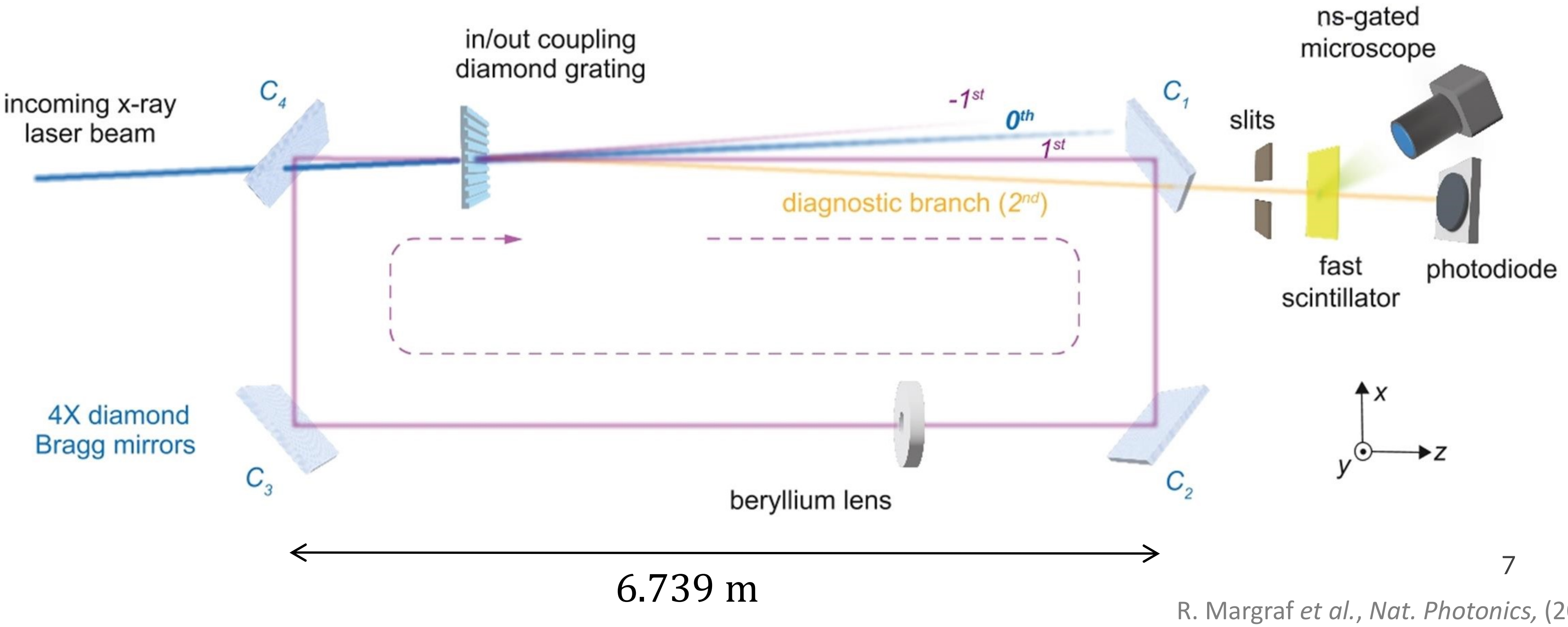
K.-D. Liss et al., Nature, vol. 404, no. 6776, pp. 371–373, (2000). Color figs from: Liss *et al.*, *Proc. SPIE 4143*, (2000)

Small-scale, utilizing Si or Sapphire. Want to test a large-scale (10s of m) diamond cavity.

Stage 0: 14 m Cavity at LCLS XPP

"Cold Cavity" – No Gain
Operated Feb-Apr 2022 in LCLS XPP hutch



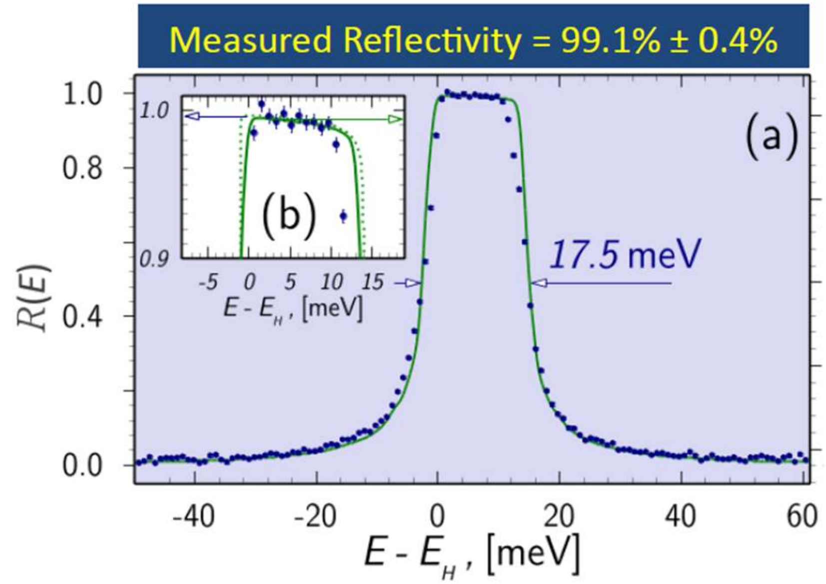


R. Margraf *et al.*, *Nat. Photonics*, (2023)

Bragg-Reflecting Diamond Mirrors

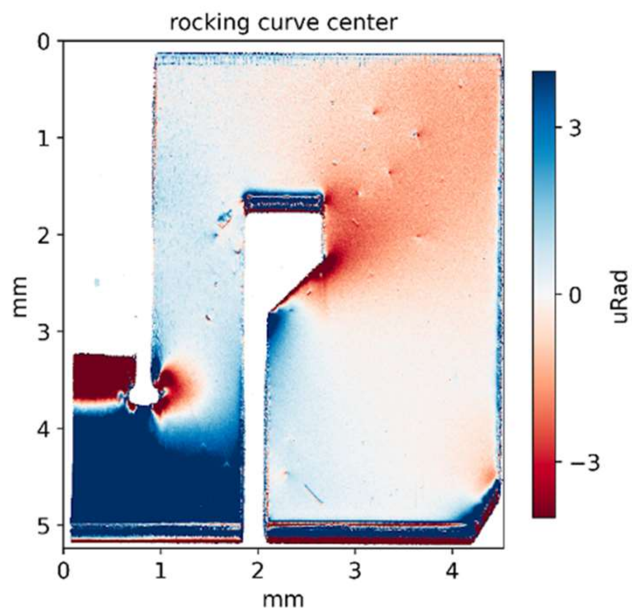
HPHT Type IIa Diamond

- \+ High Reflectivity
- \+ High Thermal Diffusivity
- \- Perfect crystals less available than Silicon



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

Crystals grown by Sumitomo Electric, characterized at SSRL, APS and SPring-8

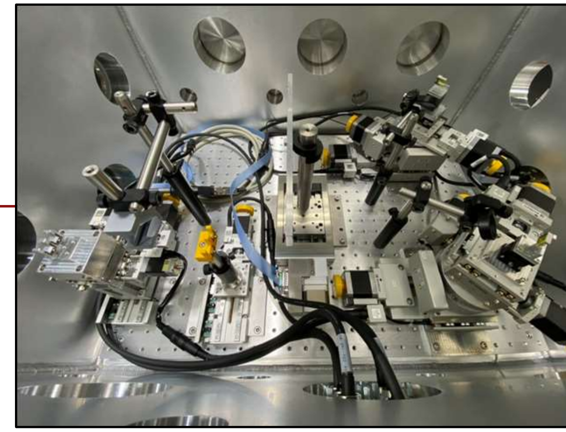


Example 4-bounce Options

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

R.C. Burns *et al., J. Phys.: Condens. Matter,* **21,** 364224, (2009)
H. Sumiya, K. Harano, and K. Tamasaku, *Diamond and Related Materials*, vol. 58, 221–225, (2015)
P. Pradhan, *et al.*, J. Synchrotron Rad. **27**, 1553 (2020)
A. Halavanau et al., *Journal of Appl Crystallography*, vol. 56, no. 1, Feb. 2023.

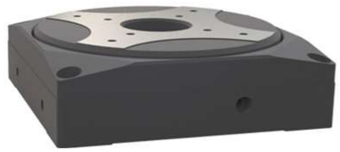
Cavity Alignment Mechanics



Stage 0 Cavity

For Diamond Positioning and Orientation

Off-the-Shelf Solution for Stage 0
(X-rays Only)
→1-10 μrad alignment precision

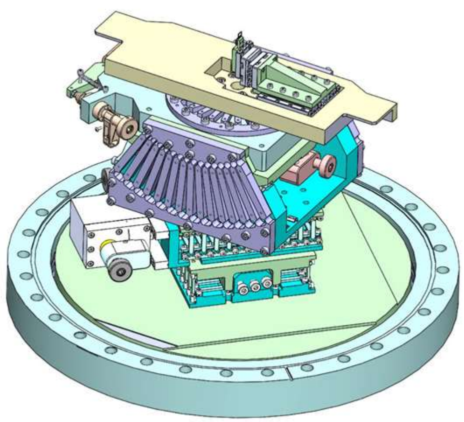


Kohzu (RA10A-W, Axis ∥ cavity plane)
Microstepping Step: .2 mdegrees (3.5μrad)
Angular Repeatability: 2 mdeg (35 μrad)

Attocube (ECR5050hs, Axis ⊥ cavity plane)
Step: 1 μdegree (~20 nrad)
Short Term Angular Repeatability: 2 mdeg (35 μrad)

Need higher precision for even larger cavities:

Custom Flexure Stages for Stage 1,
(Full 2-pass gain Experiment)
→10s of nrad alignment precision

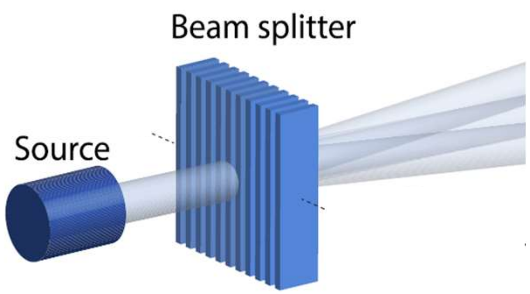


D. Shu *et al*, MEDSI2020.
D. Shu *et al*, SRI2021

Axes ∥ and ⊥ cavity plane:
Step: ~1 μdegree (20 nrad)
Angular Repeatability: 3 μdeg (50 nrad) or better

Outcoupling Methods

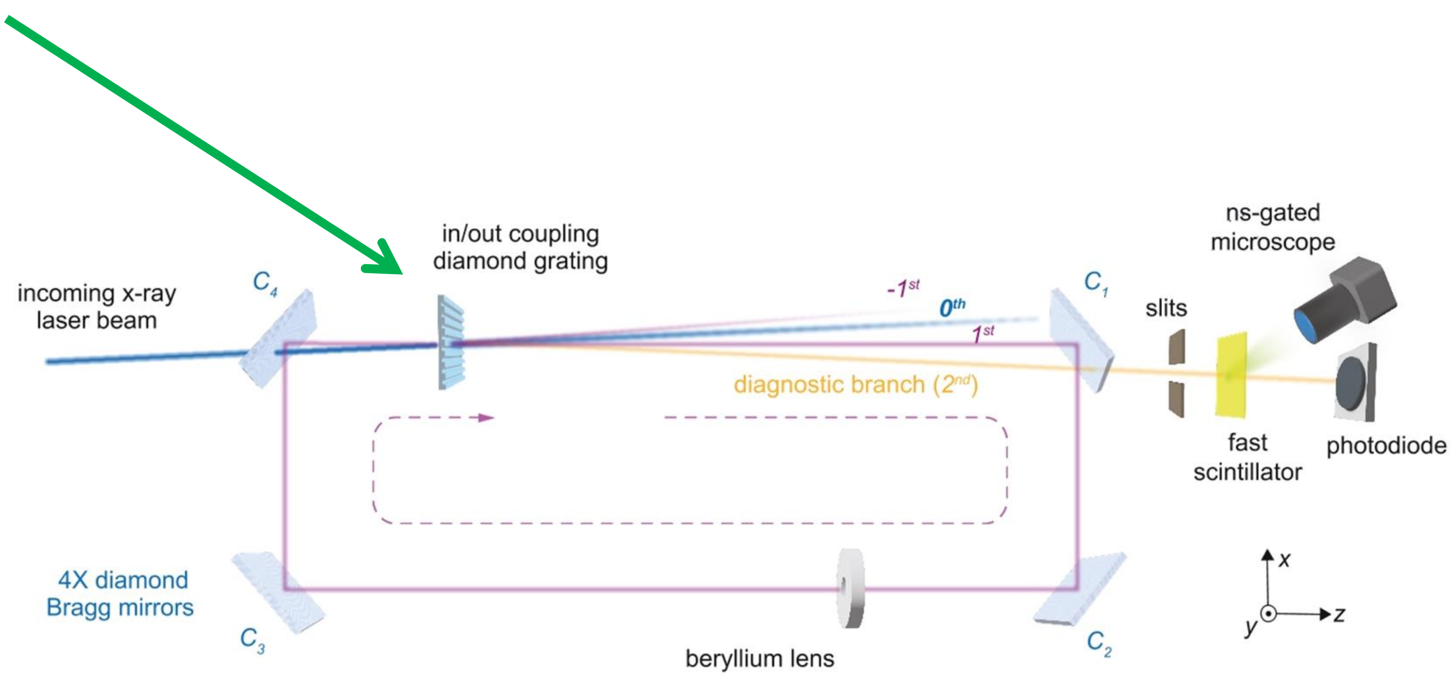
- Grating Beamsplitter



K. Li *et al. Opt. Express, OE*, 28, **8**, 10939–10950, (2020)

Pros: (For this Scheme)
- Performs both in-coupling and out-coupling
- Additional diffraction orders useful for diagnostics

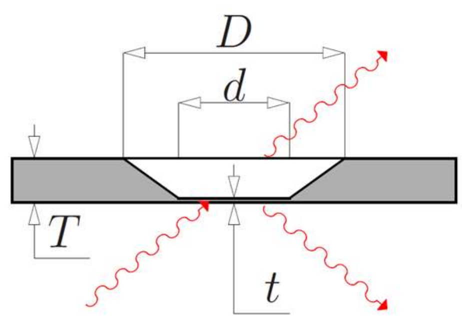
Cons: (For a future CBXFEL)
- Losses due to absorption, additional diffraction orders. Can only out-couple small fraction of beam.



Outcoupling Methods

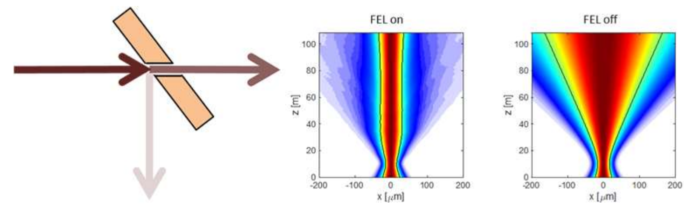
There are many additional out-coupling methods being studied!

- Thin (Drumhead) Crystal



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

- Mirror with Pinhole

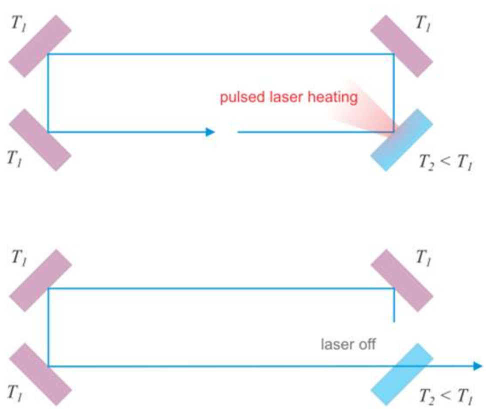


H.P. Freund, P. van der Slot, and Y. Shvyd'ko, arXiv:1905.06279, (2019)

… & Strong Taper

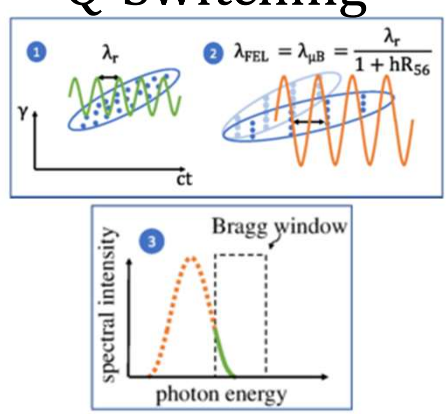
G. Marcus *et al.*, Phys. Rev. Lett. **125**, 254801 (2020)

- Bragg Q-Switching



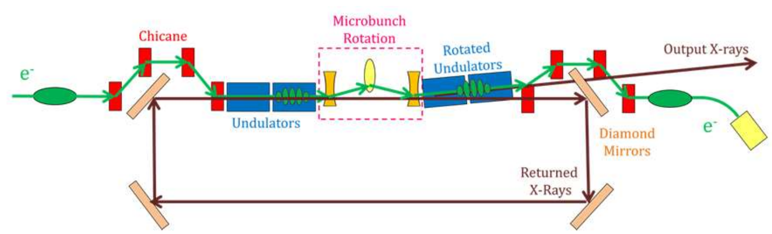
J. Krzywiński *et al.*, *Proc. FEL'19*, 122-125, (2019)
R. Margraf *et al.*, *Proc. IPAC'22*, (2022)

- Chirped E-Beam Q-Switching



J. Tang *et al.*, Phys. Rev. Lett., vol. 131, no. 5, p. 055001, (2023)

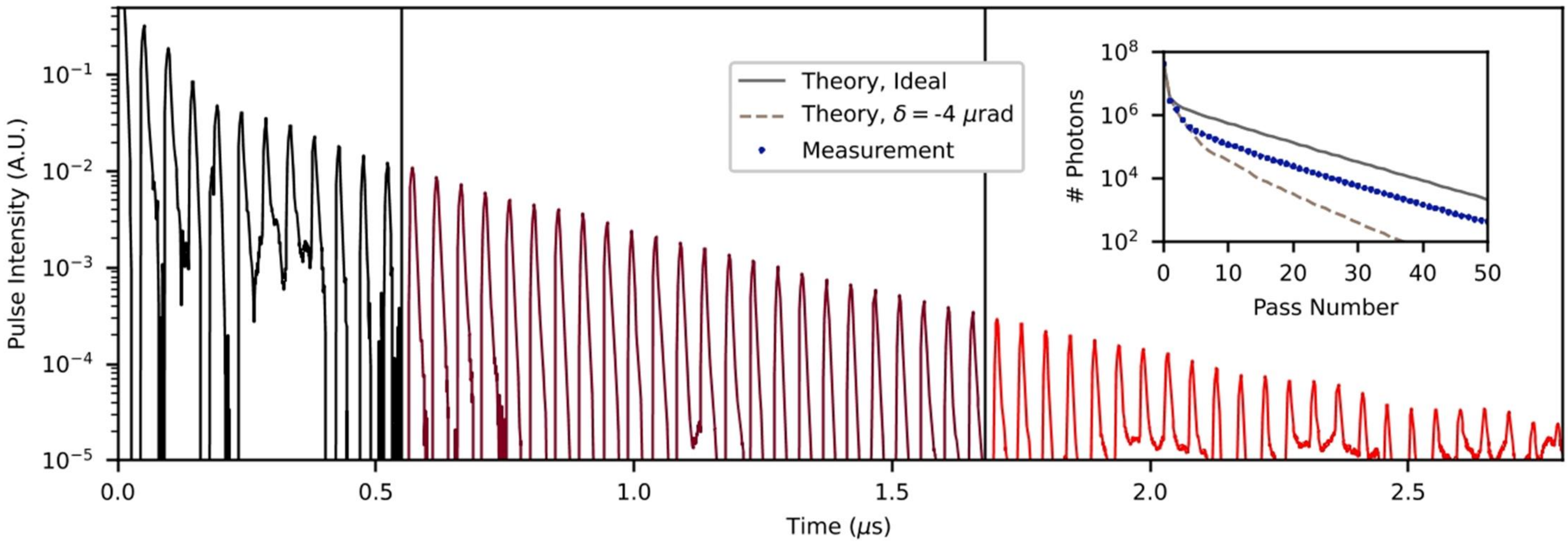
- Microbunch Rotation



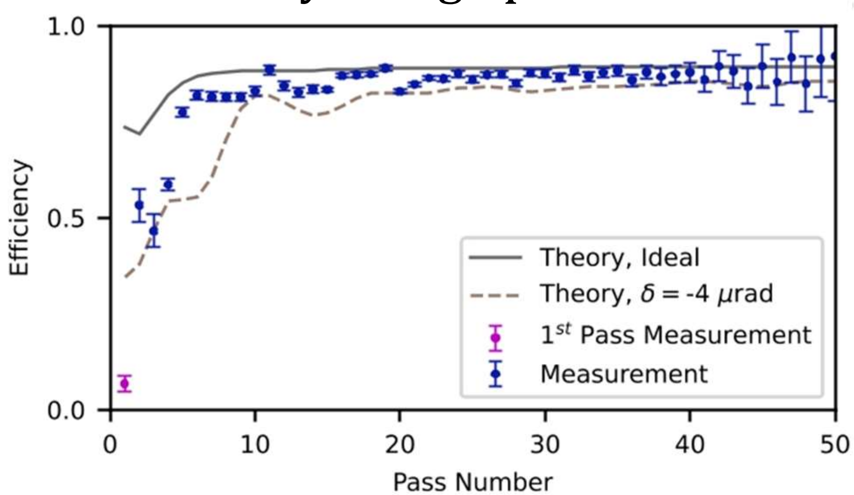
J. P. MacArthur, *et al., Phys. Rev. X,* **8**, 4, 41036, (2018)
R. Margraf et al., Proc. FEL'22, (2022)

Cavity Ringdown

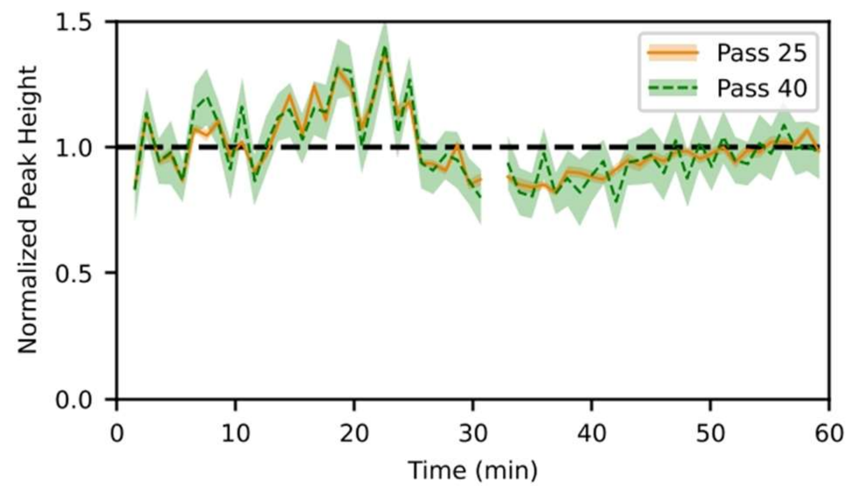
R. Margraf *et al.*, *Nat. Photonics*, (2023)



88% efficiency at high pass numbers!



Stable over 1 hour!

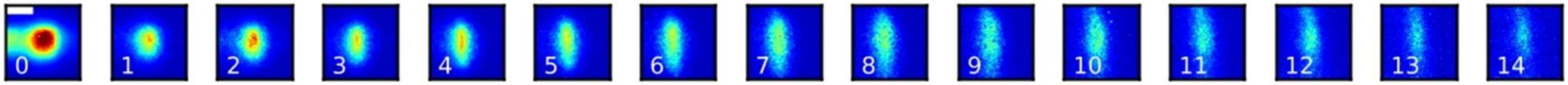


>96% efficiency if remove loss from in-coupling grating and lens!

Transverse Oscillations

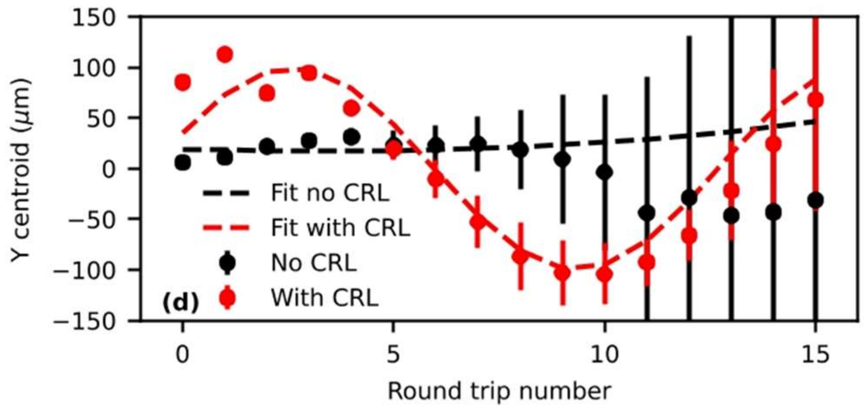
R. Margraf *et al.*, *Nat. Photonics,* (2023)

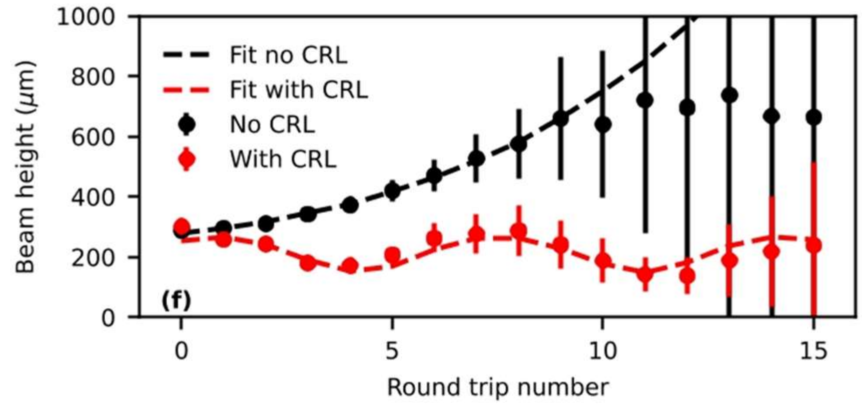
No Focusing – Beam spreads out in Y



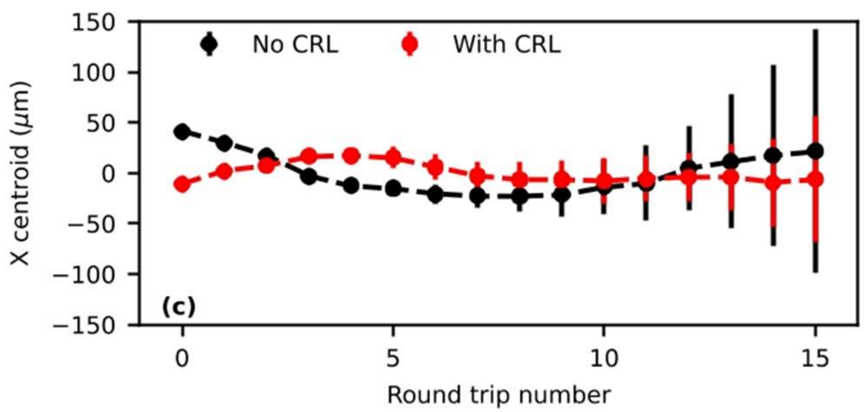
With Focusing – Beam oscillates in Y

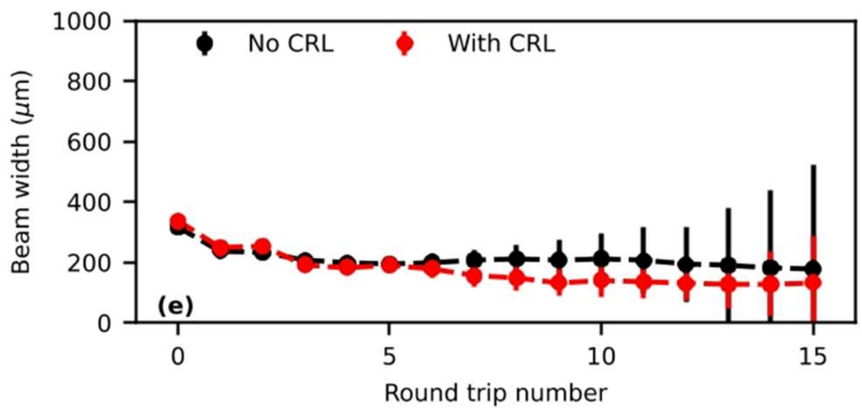
Y Plane (Out of the Plane of the Cavity): With Focusing, Beam Oscillates





X Plane (In the Plane of the Cavity): Less Oscillation due to Angular Filtering





Next, we will apply this experience to building cavities with gain!

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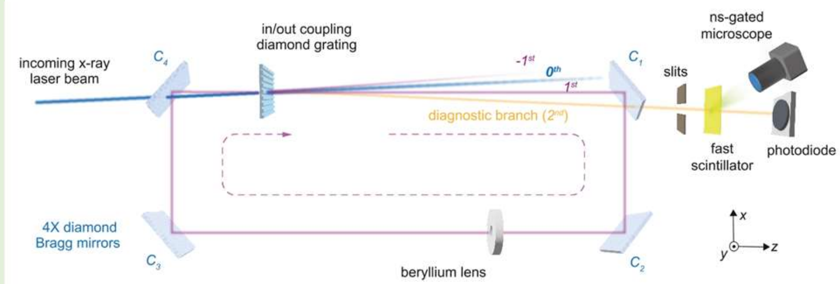
SLAC LDRD-Funded Cavity Ringdown Test

- Demonstrated Cavity Ring-down and Stability
- Tested Diagnostics, Grating Out-Coupling, Focusing and Alignment Techniques



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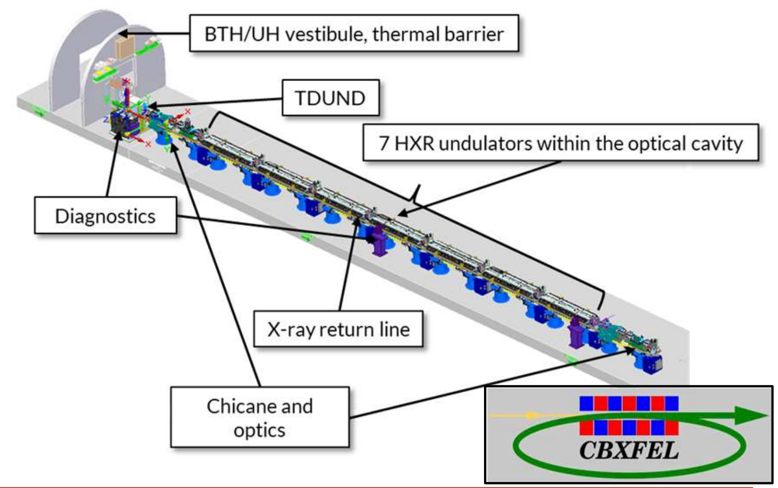
- 66 m 2-pass Gain Test-Bed cavity
- To be installed in LCLS-II HXU within a year



X

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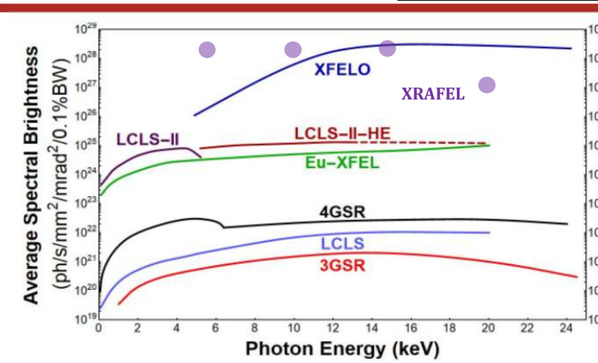
- TBD - lots of possibilities!



G. Marcus *et al.*, Phys. Rev. Lett. **125**, 254801 (2020)
K.J. Kim et al., Proc. of IPAC2019, (2019)

Acknowledgements

Thanks to our sponsors
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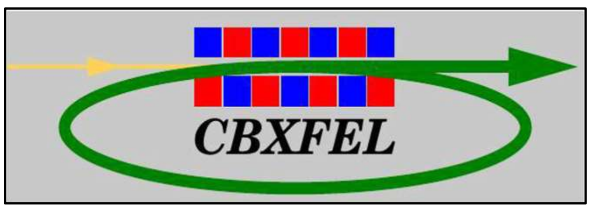
And to our CBXFEL Collaboration



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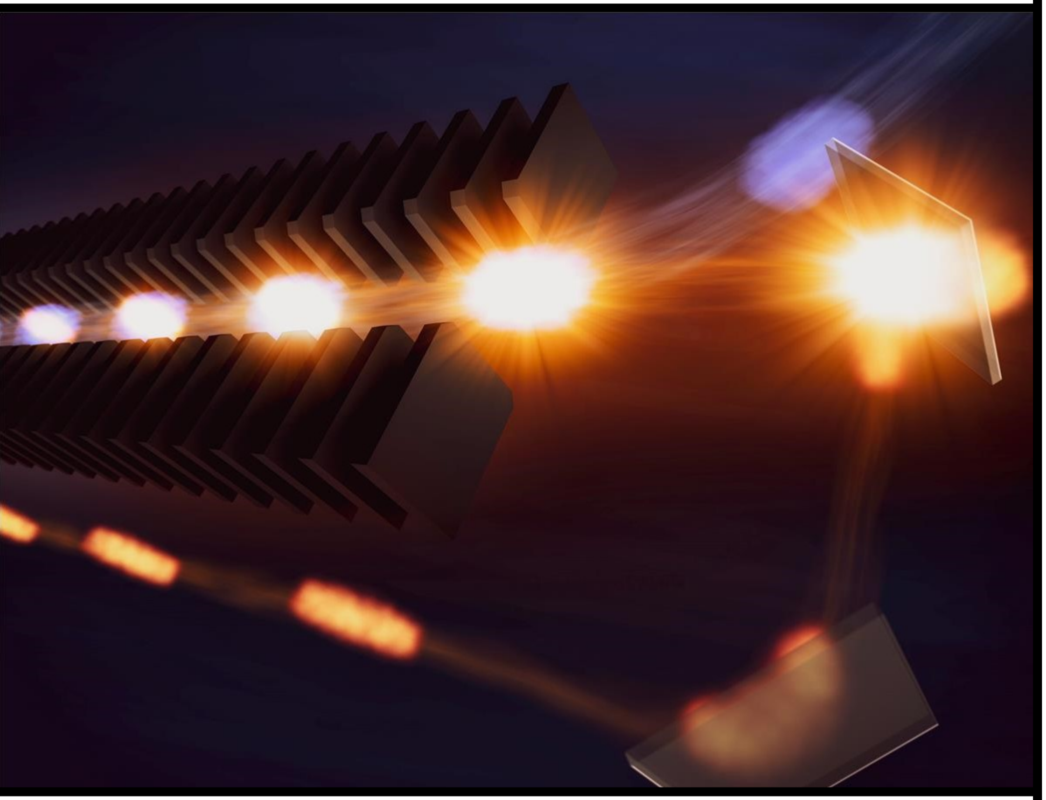
Questions?



Lots of Detail on Cavity-Based XFELs, and X-ray Laser Oscillators in other Presentations! →

Tuesday:

4:30 pm, Kwang-Je Kim, TU4P14 (poster)

Cavity-based XFEL R&D Project

Wednesday:

9:00 am, Zhirong Huang, WE1L2

Progress of Cavity-based X-ray Free-electron Lasers

11:00 am, Kwang-Je Kim, WE2A1

Modified Maxwell-Bloch Equations for X-ray Amplified Spontaneous Emission in X-ray Lasers

11:00 am, Aliaksei Halavanau, WE2C1

Population Inversion X-ray Laser Oscillator at LCLS and LCLS-II

Thursday:

3:00 pm, Kwang-Je Kim, TH3B3

Transverse Gradient Undulator for a Storage Ring X-Ray Free-Electron Laser Oscillator

5:00 pm, Jingyi Tang, TH4A3

An Active Q-switched X-ray Regenerative Amplifier Free-electron Lasers