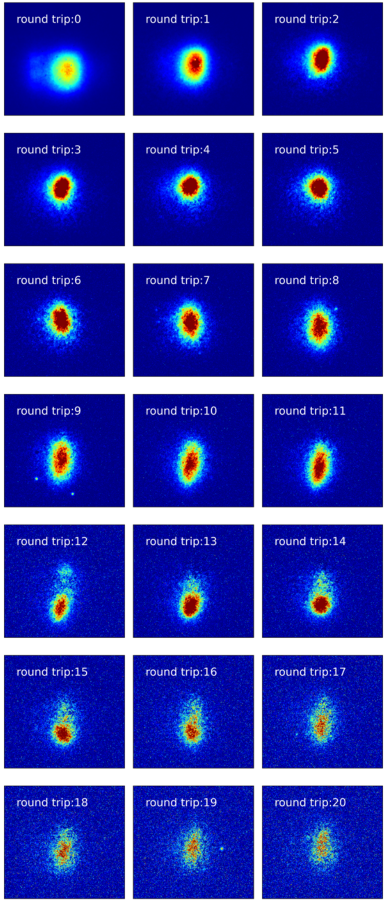
Research and Development Towards Cavity-Based X-ray Free-Electron Lasers



Gabriel Marcus, on behalf of the CBXFEL collaboration

IPAC 2022

14 June 2022

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U.S. DEPARTMENT OF ENERGY | Office of Science

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Outline

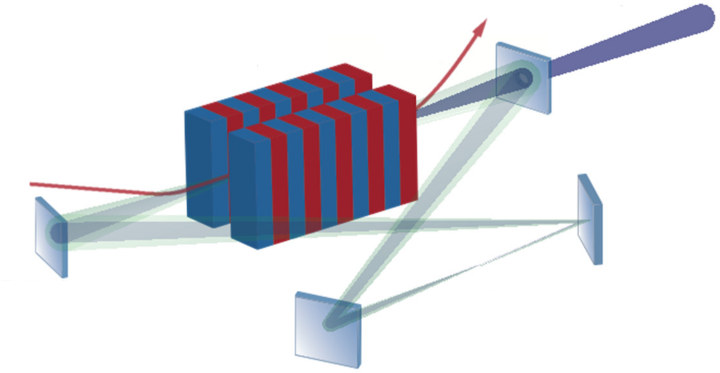
The need for a cavity-based x-ray free-electron laser (CBXFEL)

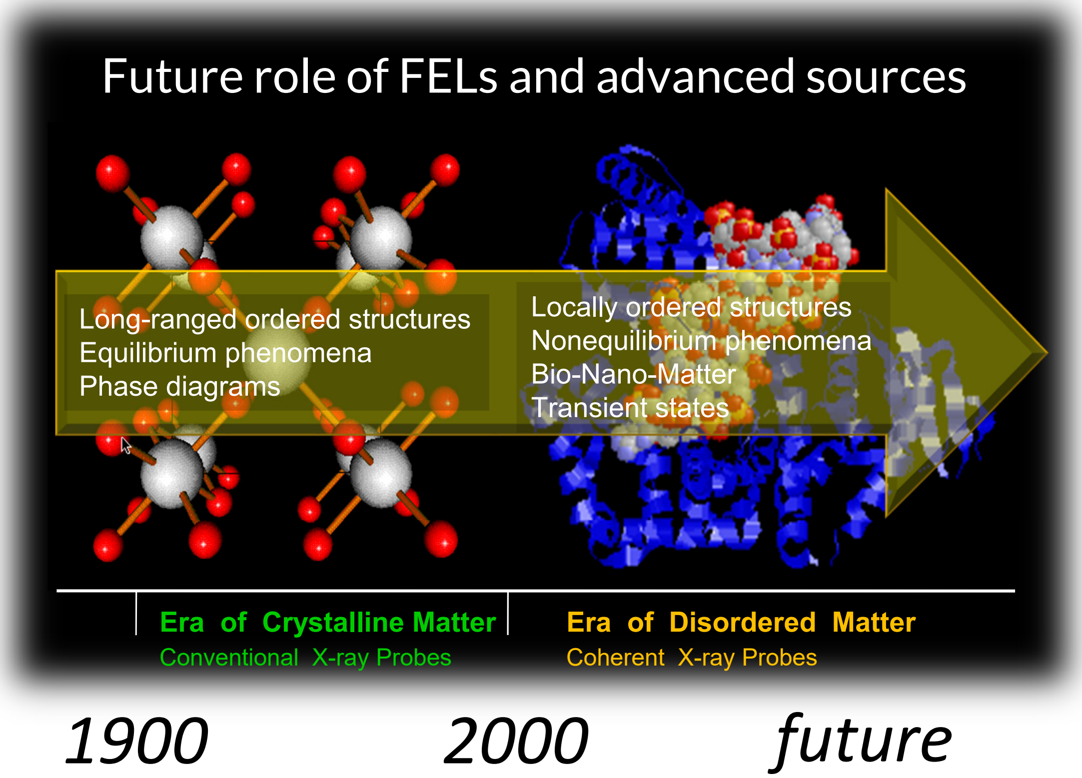
CBXFEL concepts and enabling technologies

‘Cold’ x-ray cavity experiment at the LCLS XPP instrument

SLAC/ANL/Spring-8 CBXFEL R&D project update

Summary





H. Dosch (DESY)

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Conventional x-ray sources are long and incoherent.

Nanoscale dynamics take place at femtosecond timescales → 4th generation FEL sources

Hard x-ray FELs largely based on SASE

- Transverse coherence ✓
- Short pulses ✓
- Stochastic temporal/spectral structure ✗

How to obtain a fully coherent and stable hard x-ray source?

A few lasing schemes at FELs

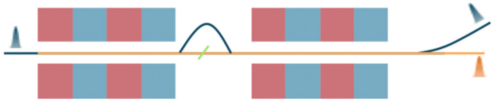
Single-pass SASE amplifier

- Implementations: All operating XFEL facilities
- Advantages: Easy alignment, tunability (γ, λ_u, K), transverse coherence
- Disadvantages: limited longitudinal coherence, stochastic temporal/spectral content, large bandwidth $\Delta E/E \approx \rho\ (10^{-3} - 10^{-4})$, fluctuations.

External seeding

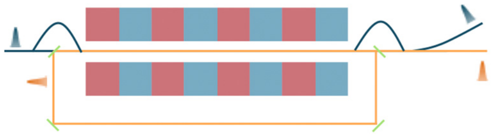
- I: Direct seeding with High-Harmonic Generation (HHG) laser, indirect seeding with sub-harmonic laser: High-Gain (HGHG), Echo-Enabled (EEHG). FERMI, FLASH, SXFEL.
- A: Full coherence, tunability (where coherent seed available), adopts stability properties of seed
- D: HHG limited to 10s of nm, HGHG/EEHG demonstrated down to ~4 nm, but e-spread growth and other limitations create challenges toward 1 nm.

Self-seeding



- I: Channel-cut seed (SACLA), Forward Bragg Diffraction wake (PAL/LCLS/EXFEL), multi-stage (EXFEL), SXR grating-based (LCLS).
- A: Wavelength tunable, can be nearly fully coherent, multiple colors possible, narrow bandwidths.
- D: Power fluctuations, spent electrons in second stage (without fresh bunch), SASE dependent.

Cavity-based



- I: No implementations at XFEL facilities
- A: Fully coherent pulses, stable output, highest spectral brightness
- D: *Requires ~MHz rep-rate*, limited wavelength tunability, alignment challenges, *cavity optics development needed*.

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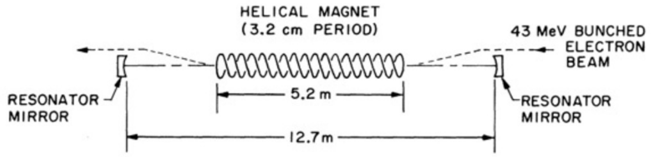
Historical cavity FEL developments

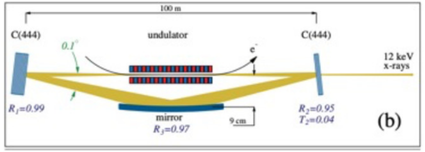
FEL Oscillators (FELO): High Q Cavity

- 1977: First FEL was an oscillator at 3.4 um. Low-gain, 500 kW stored power, 1.5% outcoupling ($Q \approx 70$).



[D.A.G. Deacon et al., PRL **38**, 892 (1977).]

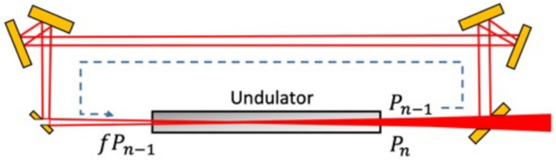
- Distinguishing features
  - High Q cavity, 10s – 100s of passes to saturation, high stored power
  - Narrow bandwidth determined by Q and e-beam
  - Cavity optics govern transverse mode
  - Sensitive to angular and temporal alignment
- Early x-ray proposal: Low gain from 19 pC, 2 ps e-beam. 400 passes to saturation, 2 meV bandwidth.



[Kim, Shvyd'ko, Reiche, PRL **100**, 244802 (2008).]

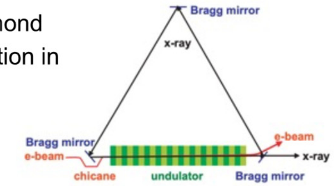
Regenerative Amplifier FEL (RAFEL): High-Gain Cavity

- 1999: Los Alamos Advanced FEL used a holey mirror to outcouple 16 um light. ~10 passes to saturation.



[D. Nguyen et al., Nucl. Instrum. Methods Phys. Res. **429,** 125 (1999).

- Distinguishing features
  - High gain, < 10 passes to saturation, low stored power
  - Bandwidth determined by SASE or mirror bandwidth
  - Gain-guiding governs transverse mode
  - Gain-guiding accepts some angular and temporal mis-match
- Early x-ray proposal: Diamond 400 Bragg mirrors. Saturation in 10passes, ~30 meV BW.



[Z. Huang & R. Ruth, PRL **96**, 144801 (2006).]

Bragg mirrors

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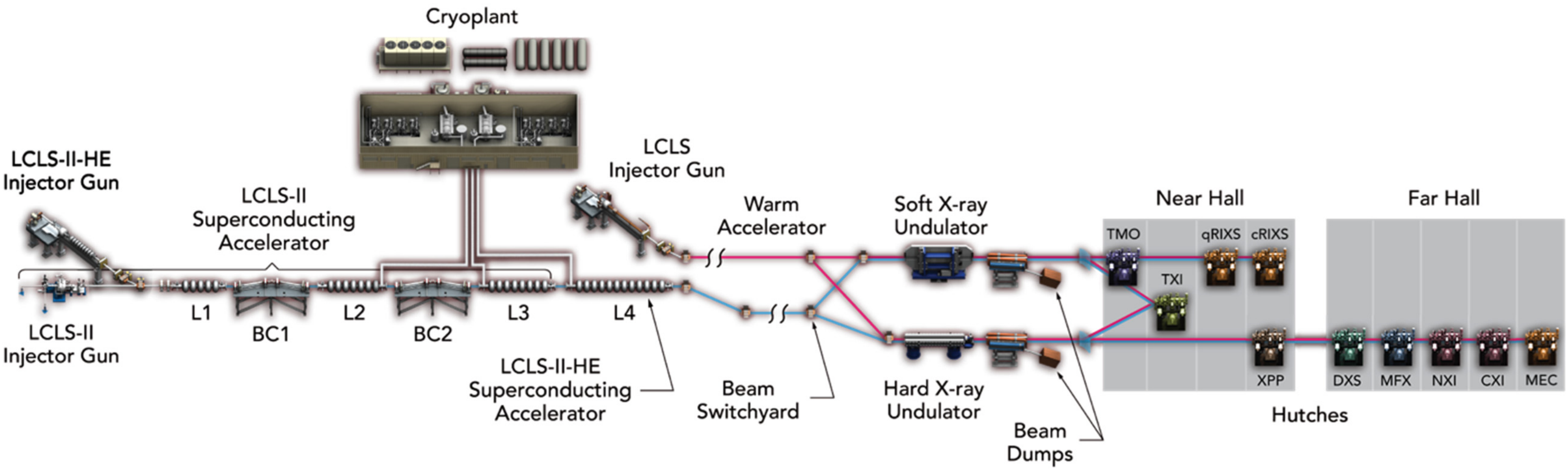
High rep-rate facilities are coming online

Key enabling technology for a CBXFEL



Commissioning has begun

LCLS-II and LCLS-II-HE

From 120 pulses/s to 1M pulses/s

CW superconducting RF accelerator

4 GeV LCLS-II first light early 2023

8 GeV LCLS-II-HE upgrade before the end of the decade

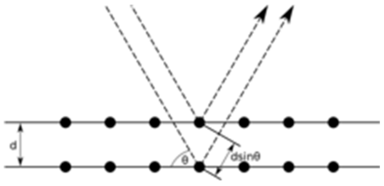
X-ray cavity footprints become more reasonable

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

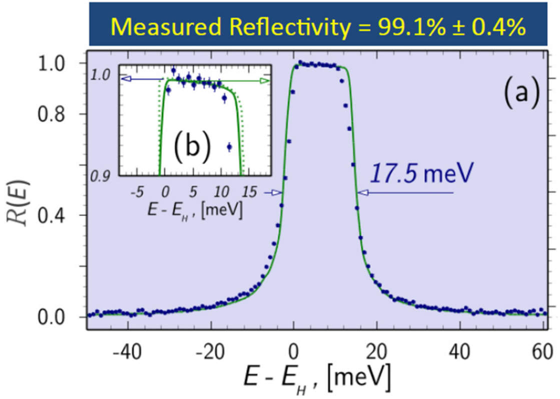
Bragg Reflection



Sample 4-bounce reflections

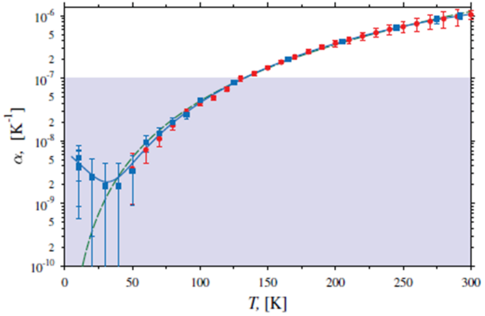
HKL	Energy 45° (eV)	4 Bounce FWHM (eV)
220	6952.3	0.139
400	**9831.9**	**0.079**
440	13904.4	0.048

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)

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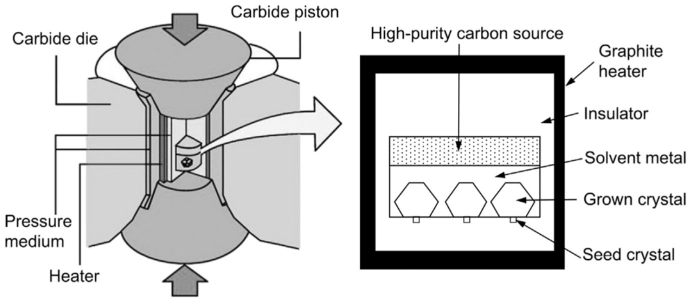
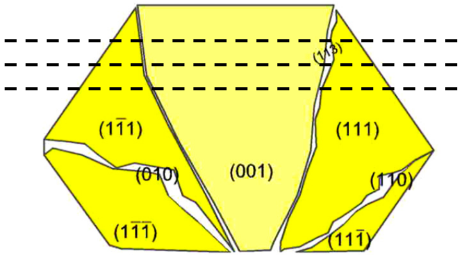
Diamond growth and preparation process

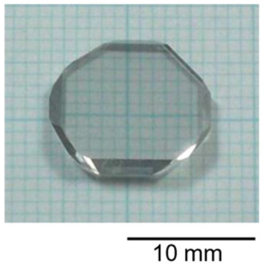
D. Zhu



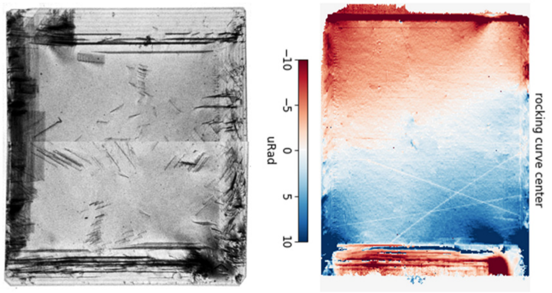
Step 1: HPHT growth

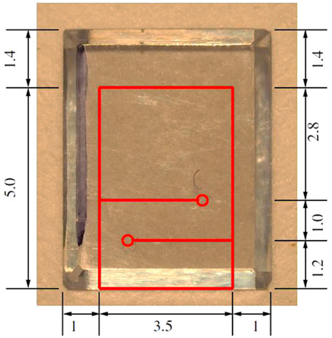


Step 2: Laser cutting



Step 3: surface polishing





Step 4: x-ray characterization

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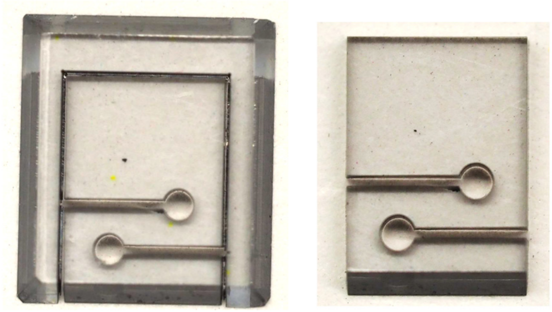
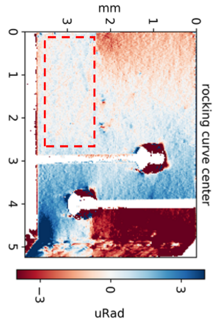


Step 5: laser machining

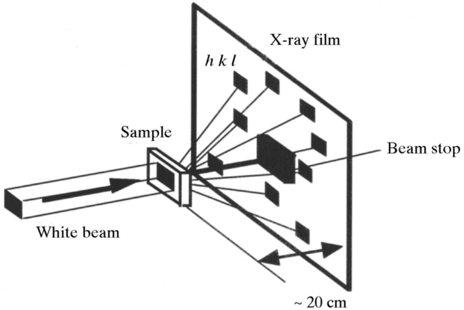


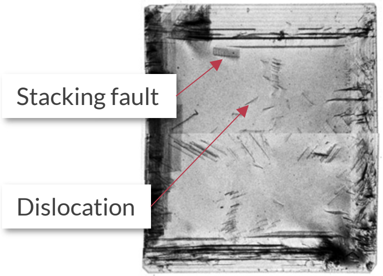
Step 6: post machining characterization

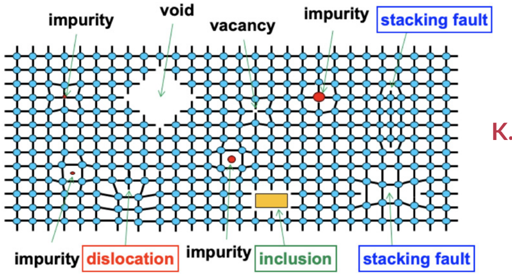
R. Burns, et al. "HPHT growth and x-ray characterization of high-quality type Iia diamond" (2009)H. Sumiya, "*HPHT Synthesis of Large, High-Quality, Single Crystal Diamonds*" (2012)

Diamond characterization

White beam topography and rocking curve imaging



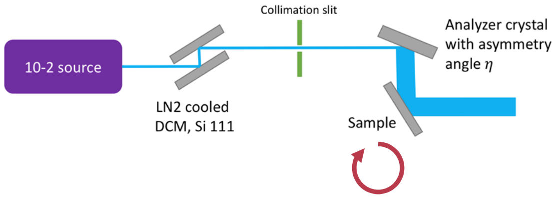


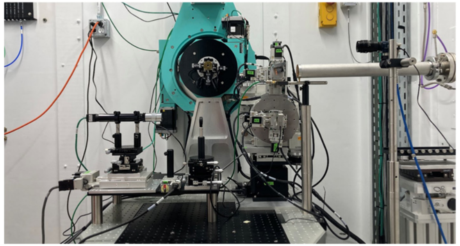


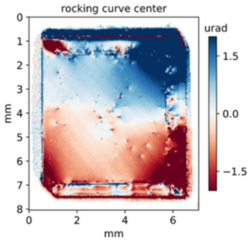
K. Tamasaku

Topography: identify and locate crystal defects such as inclusion, dislocation, stacking faults, etc. Identify potential high optical quality 'working area'.

Tuomi, T. et al., (1974) Use of synchrotron radiation in x-ray diffraction topography, Phys. Stat. Solidi (a) 25, 93.





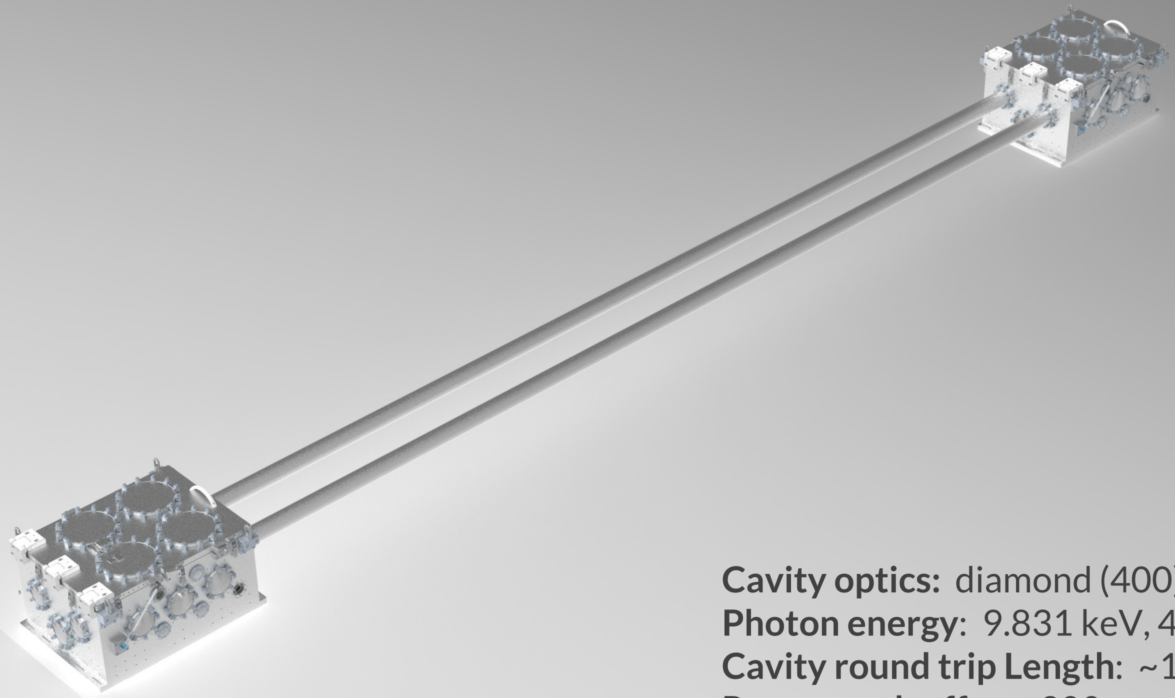


Rocking curve imaging: spatially resolved measurement of the reflectivity, rocking curve width, and most importantly, the 'flatness' of the diffraction Bragg planes.

J. MacArthur, D. Zhu, A. Halavanau

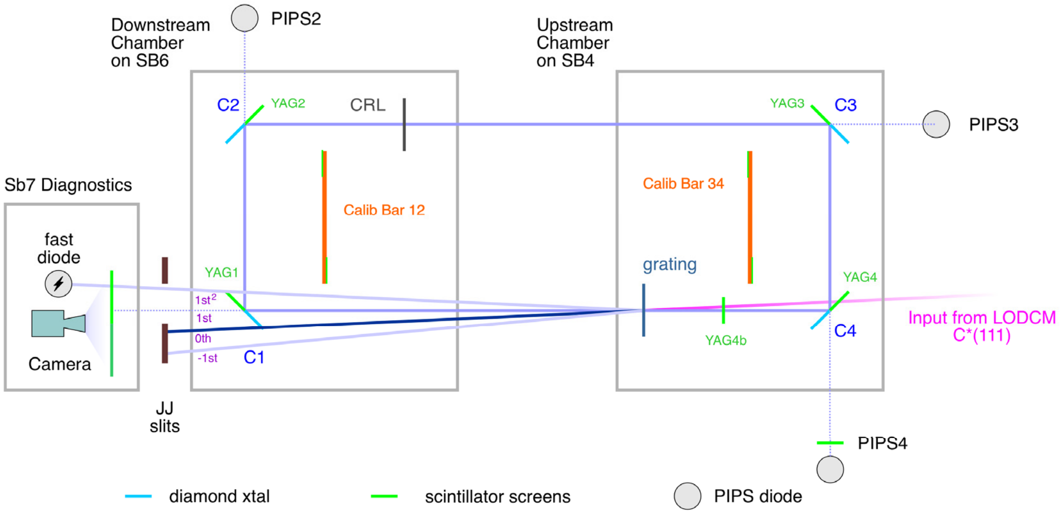
Lübbert et al., (2000). NIM B, 160, 521–527.

Cold cavity experiment at XPP (LDRD)



Cavity optics: diamond (400) x4
Photon energy: 9.831 keV, 45 degree Bragg
Cavity round trip Length: ~14.16 m
Return path offset: 300 mm
Cavity round trip time: ~47.25 ns
All in vacuum

Cavity schematic



Diagnostics

4 PIPS diodes for rocking curve scans, integrating

4 Fast Si diodes + digitizer, Acquiris 8-bit at 2 Gsps

1 Andor iStar camera + YAP:Ce provides ns time resolution of x-verse profile, 1 second exposures

1 Andor Zyla camera + Yag:Ce, integrating higher spatial resolution

8 GigE cameras monitoring diamonds, grating, scintillators, etc.

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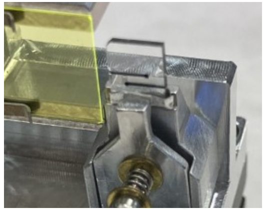
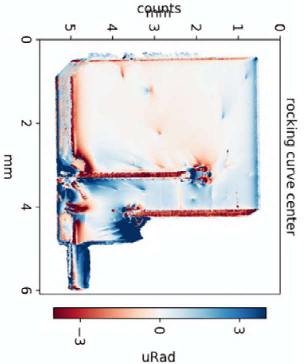
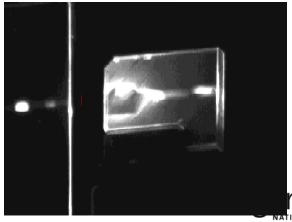
Diamond mirrors

C1/Sumi 43

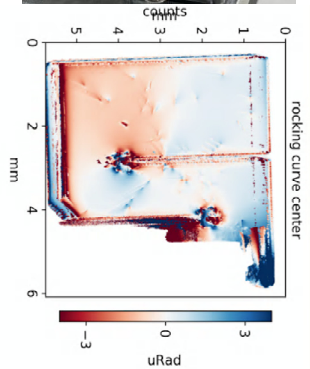


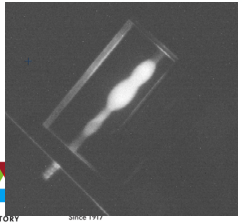




Miscut: .48°

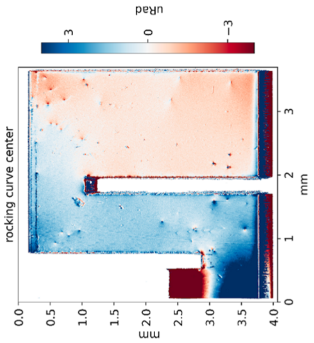
C2/Sumi 65

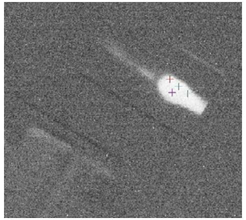




.23°

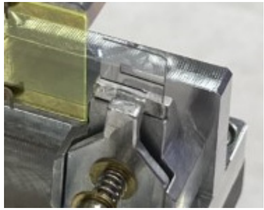
C3/Sumi 66 Small

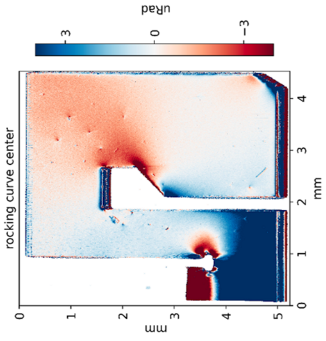


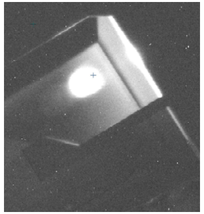


.12°

C4/Sumi 66 Large

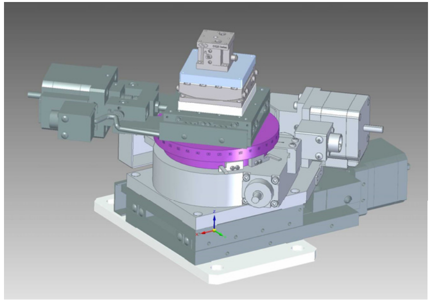




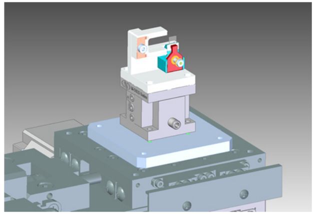


.45°

Motion Stack



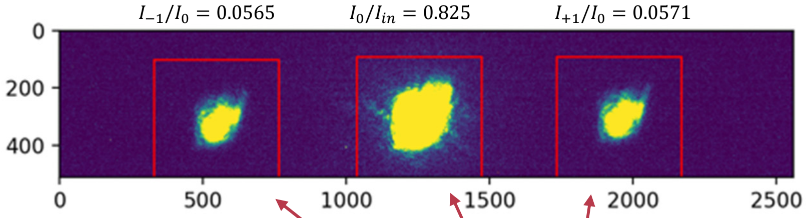
Clamped Diamond

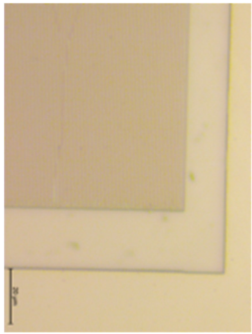


Transmission grating

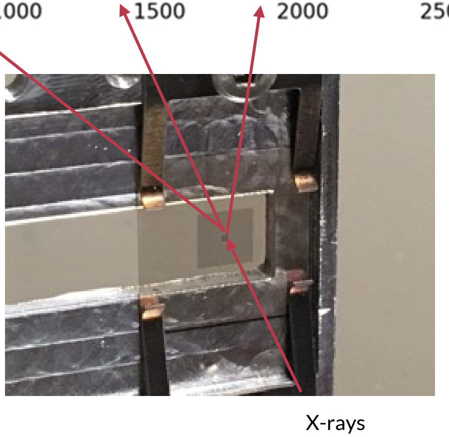
For both *in*-coupling and *out*-coupling radiation to and from the cavity

Diffraction pattern, -1, 0, +1 orders





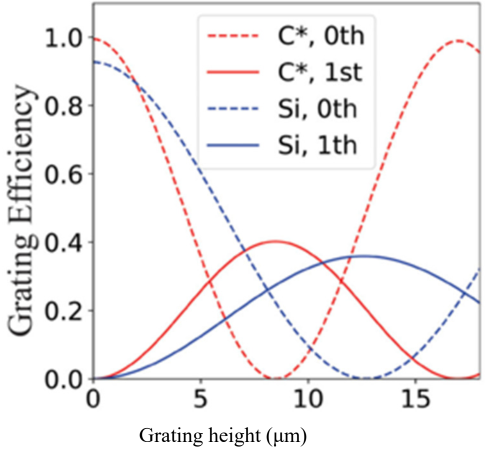
Optical Image



Mounted Grating

Transmission grating details

- Nanofabrication of diamond diffractive optics looks sufficiently mature in distributing x-ray beam power between different diffraction orders.



- CVD diamond grating was used for in/outcoupling
- From Stanford nanofab, K. Li, A. Sakdinawat, Y. Liu

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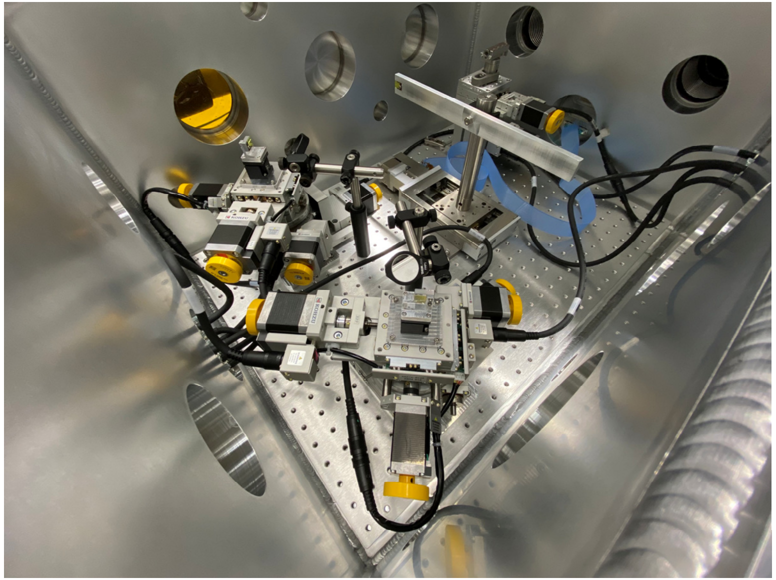
J. MacArthur

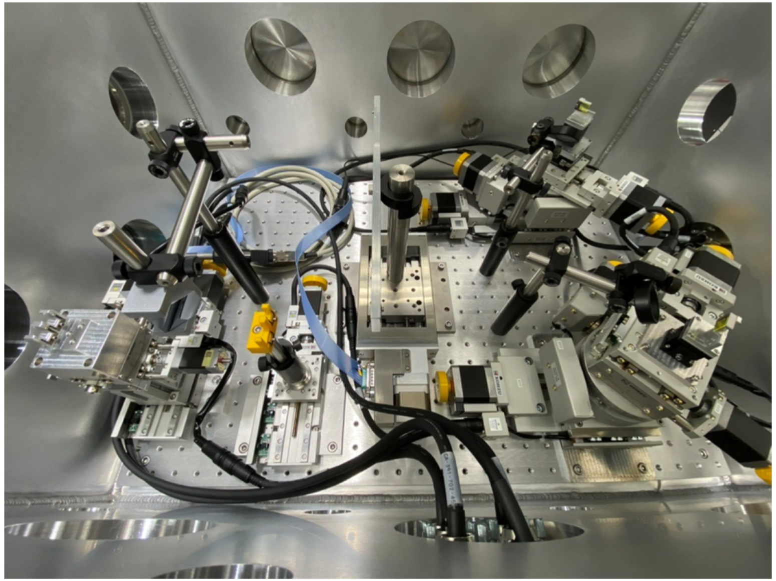
Chambers

Optics assemblies in the chambers

Downstream chamber



Upstream chamber



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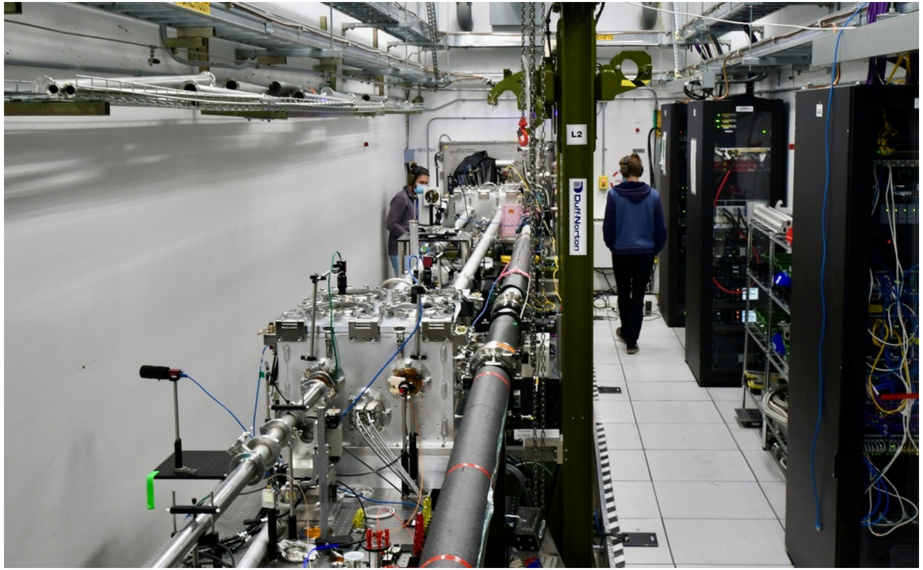
More cavity

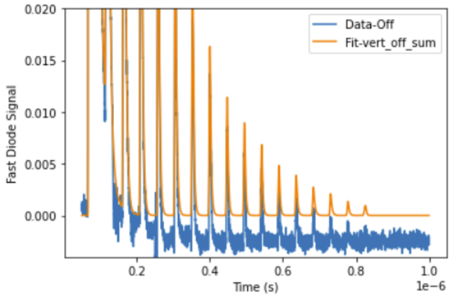
Gabe and River

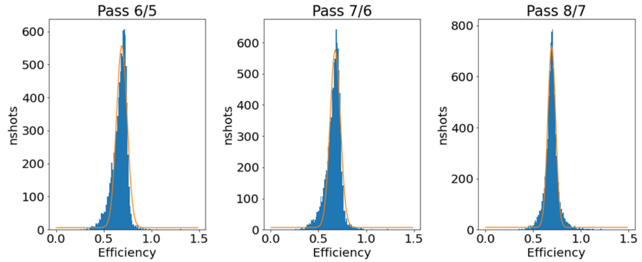


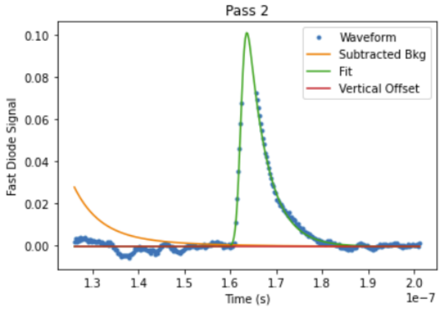
Rachel and River

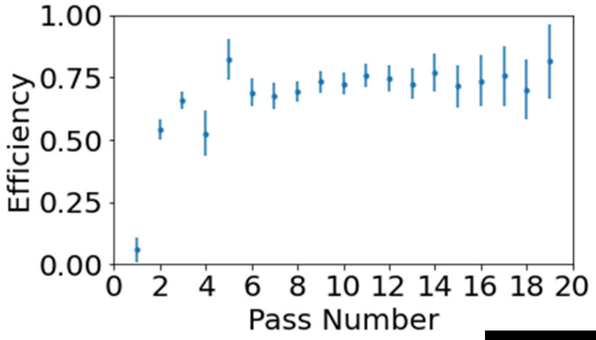
Cavity ringdown

5% grating in higher orders, down collimated, intracavity focusing f ~ 100 m









Large area and fast silicon diode is used to record the pulse intensity evolution – **Ring down.**

Round trip efficiency was measured to be typically ~70% in early passes and approaches ~75% in later passes.

Transmission grating 0th order efficiency measured to be ~ 81% for this grating.

Leads to estimates of ~86 - 92% single round trip efficiency. Error bar should be less than ~2%.

Other tests include thinner grating substrates, with/without down collimation, multiple intracavity focal lengths, no intracavity focusing, intentional misalignment, steering to bad parts of diamond, varying incoming pulse intensity, etc…

Incoming beam subject to **FEL jitter**

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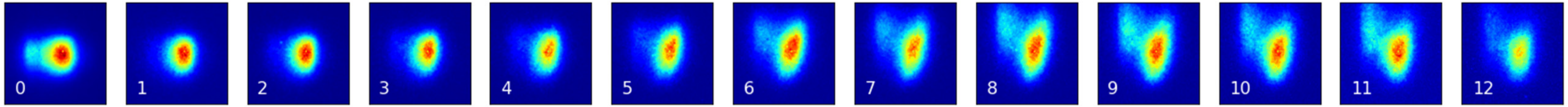
R. Margraf, R. Robles

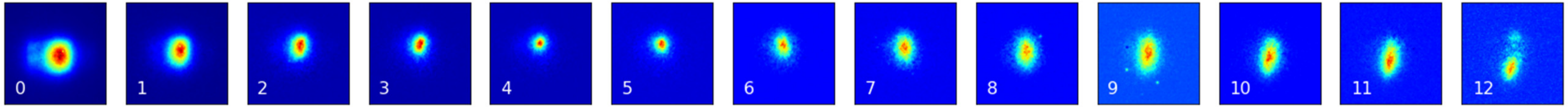
Transverse cavity dynamics with iStar – beam profile evolution over multiple round trips

Processed Andor iStar measurements of the out-coupled beam profile as a function of round trip.
***10ns** gate time, 100 pulses per exposure, 10-50 exposure average per image shown below.*

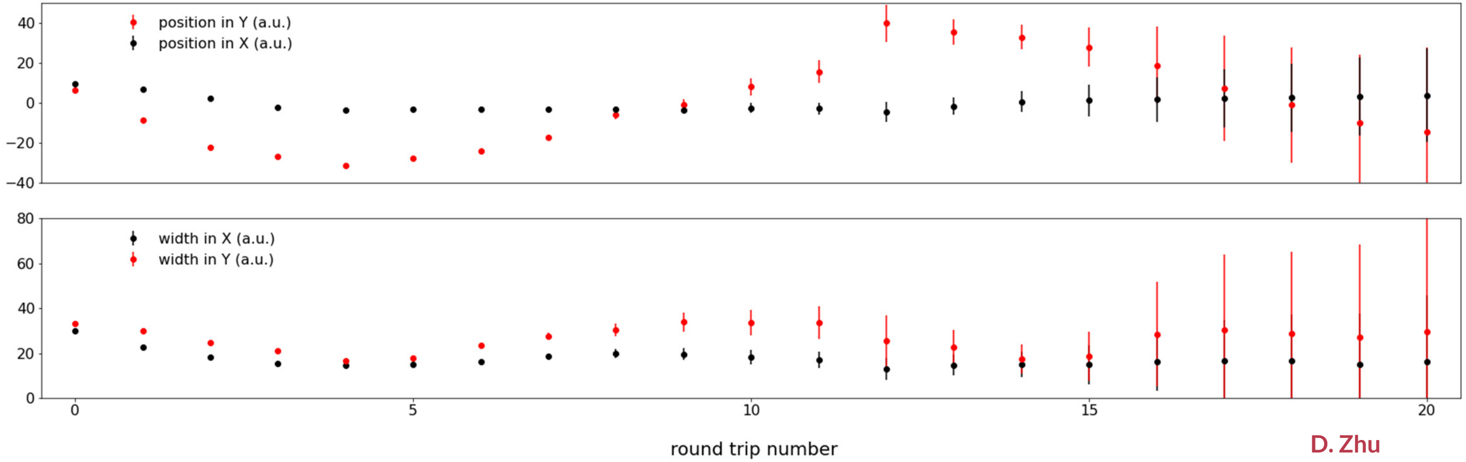
Without intra-cavity focusing



With intra-cavity focusing, f = 100m



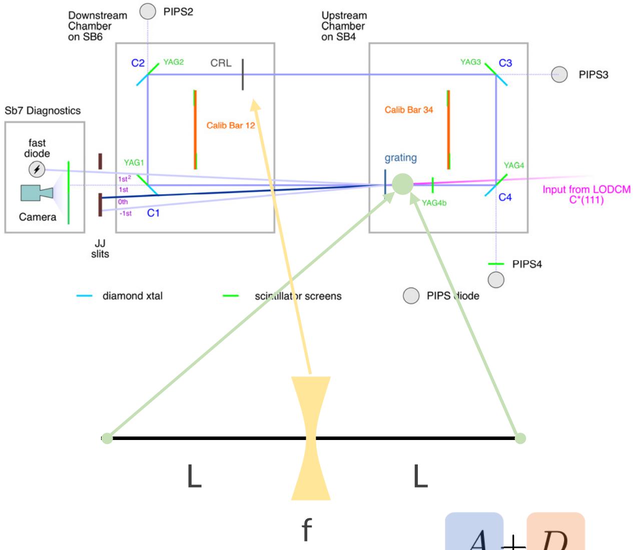
Beam position and size as a function of round trip (with intra cavity focusing lens)



D. Zhu

Stable cavity oscillations

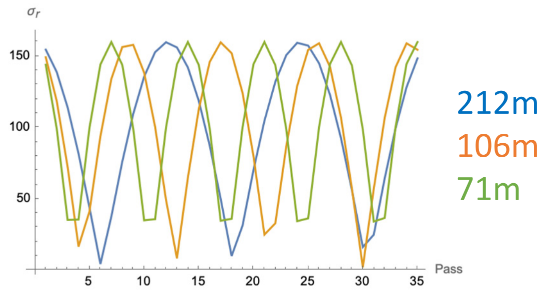
Analytical and numerical investigation – cavity stability theory



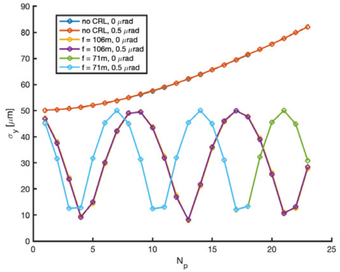
$$M = \begin{pmatrix} 1-\frac{L}{f} & L\left(2-\frac{L}{f}\right) \\ -\frac{1}{f} & 1-\frac{L}{f} \end{pmatrix}$$

$$m = \frac{A + D}{2}$$

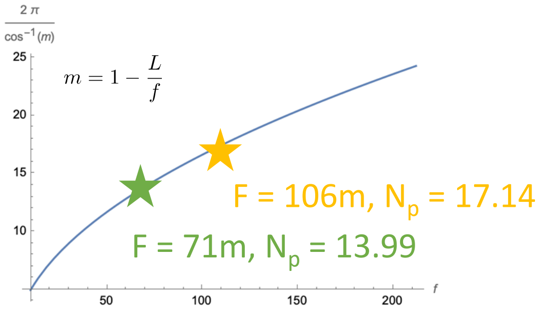
$$\theta = \cos^{-1}(m)$$

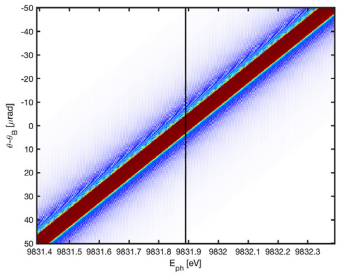


Analytical treatment, using Gaussian optics $q_{out} = \frac{Aq_{in} + B}{Cq_{in} + D}$



Numerical propagation using Fourier optics and dynamical theory of x-ray diffraction for diamonds





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CBXFEL project – ‘warm’ cavity

DOE funded SLAC/ANL/Spring-8 collaboration to conduct targeted R&D

Construct a rectangular X-ray cavity that encloses the first 7 LCLS-II HXR undulator modules.

Investigate crucial aspects related to CBXFEL physics using a pair of electron bunches from the SLAC copper RF linac.

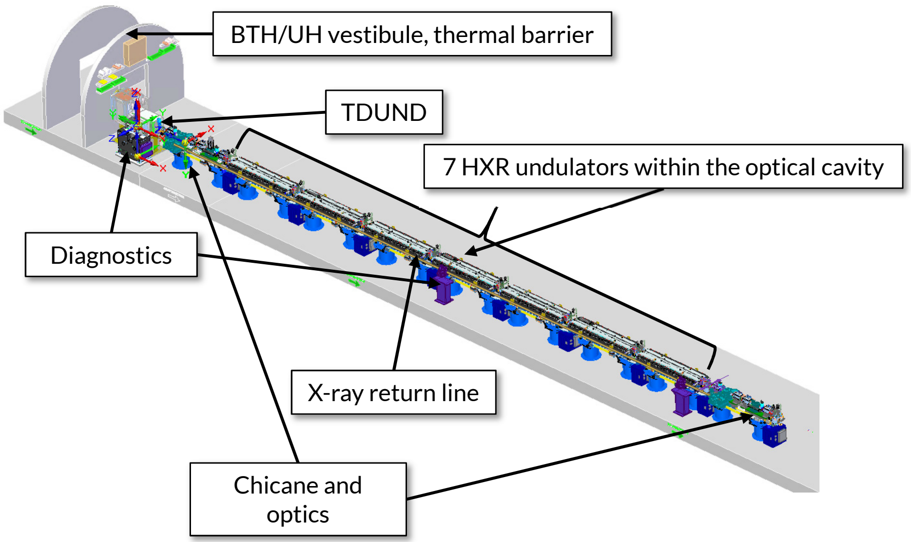
- Both XRAFEL and XFELO

Perform 2-pass gain measurements and cavity ring-down measurements for low and high gain schemes.

Demonstrate cavity tolerance and stability requirements necessary for both schemes.

R&D project from FY20 through FY24.

- Timed well to coincide with high rep-rate operation with LCLS-II.



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CBXFEL project overview

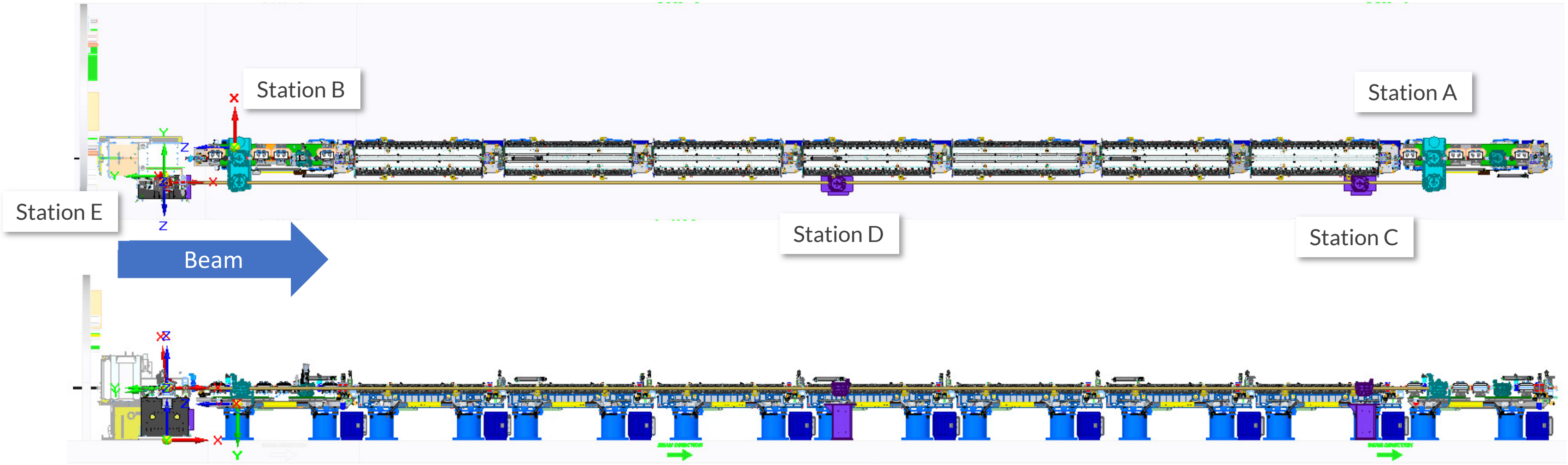
Station A/B: Chambers that house 4 diamond mirrors, 2 Beryllium CRLs, basic alignment diagnostics, beam overlap diagnostics

Station C: Chamber that houses alignment diagnostics + beam sampling diamond transmission grating

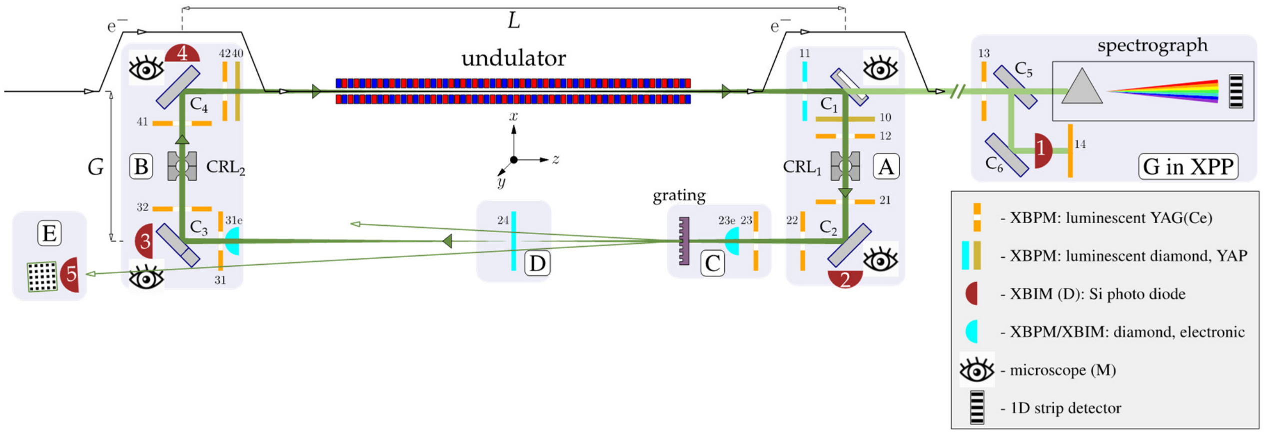
Station D: Middle of return line spatial diagnostics

Station E: Diagnostic station outside the cavity, for measurements using diffracted beam sample from station C grating

Station G (not shown): Additional temporal, intensity, spectral diagnostics far downstream in XPP experimental hutch in the near experimental hall



Schematic of CBXFEL cavity and diagnostics



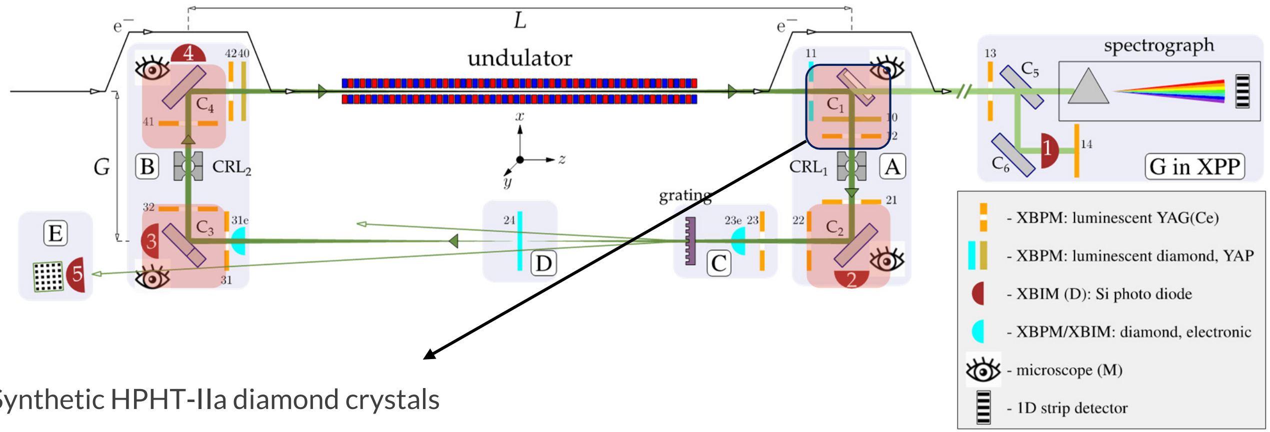
Y. Shvyd'ko

Undulator hall provides requisite temperature stability for sensitive opto-mechanical hardware

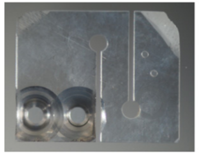
Cavity wraps 7 undulator sections

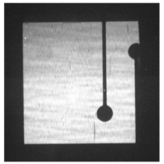
Total cavity length ~ 66 m (~ 220 ns, 624 linac RF buckets)

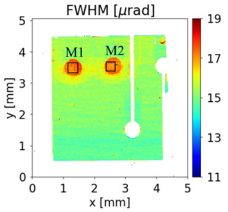
Schematic of CBXFEL cavity and diagnostics

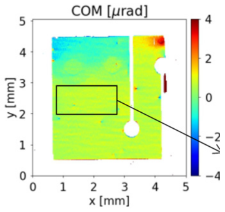


Synthetic HPHT-IIa diamond crystals







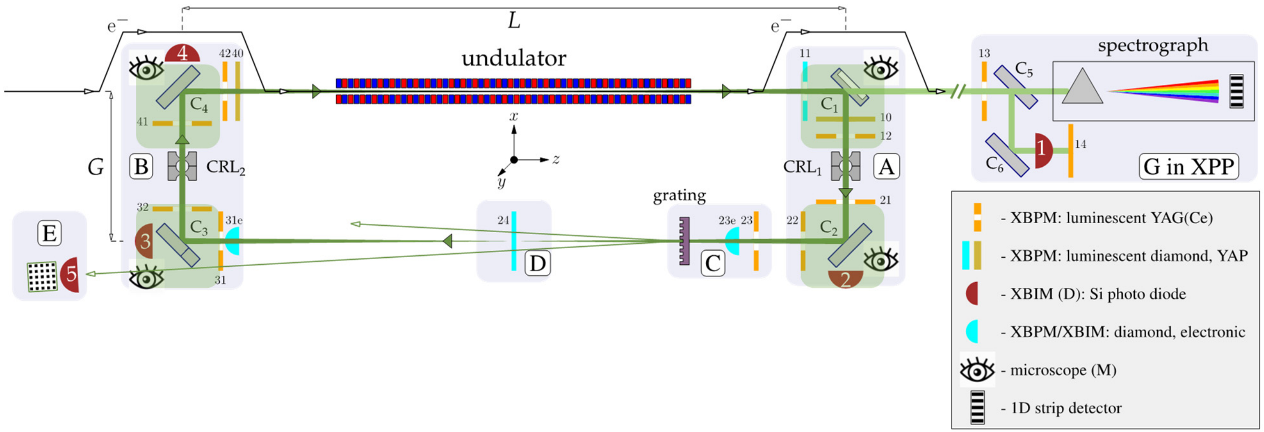


“Drum head” diamond (~ 20 μm thickness) to increase output coupling

Parameter	Value	Unit
Crystal material	C*(400)	-
Bragg angle	45	degree
Photon energy	9.83	keV
Wavelength	1.26	Angstrom
Bragg width (energy)	79	meV
Bragg width (angle)	8	μrad

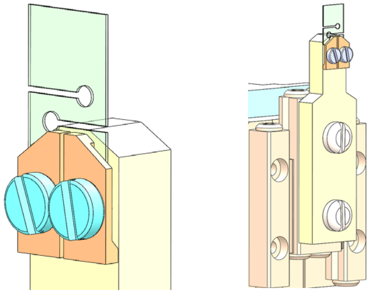
Shvyd’ko, Pradhan, Antipov, Liu, et al.

Schematic of CBXFEL cavity and diagnostics



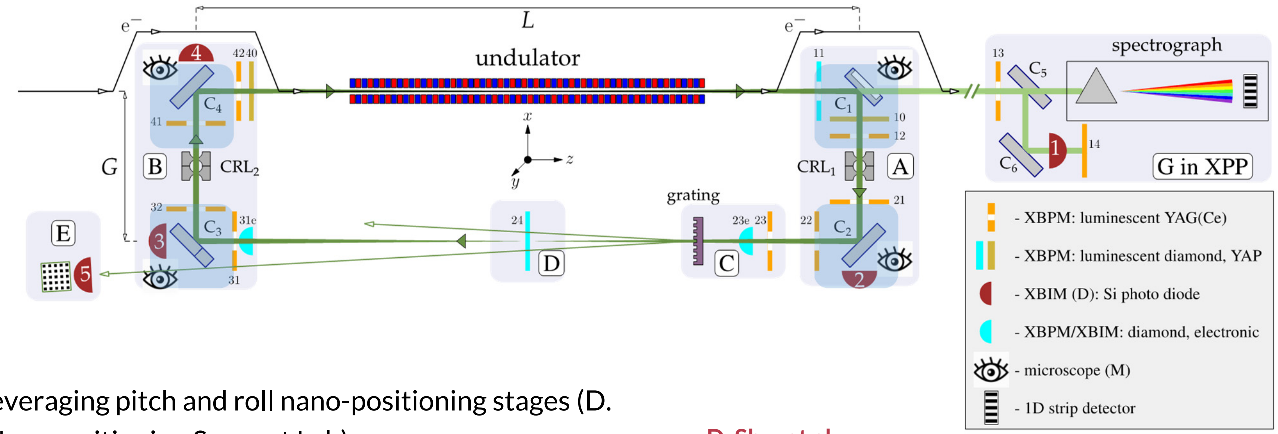
Strain free diamond mounting

Similar to crystal holder designed for EuXFEL self-seeding mono. and cold cavity



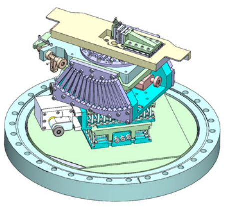
L. Samoylova, *et al*., Proceedings of SRI-2018, June 2018, Taipei, Taiwan.

Schematic of CBXFEL cavity and diagnostics

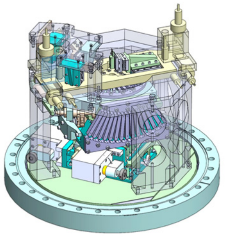


- Motion stacks leveraging pitch and roll nano-positioning stages (D. Shu, *et al*., APS Nanopositioning Support Lab)
- Laminar weak-link structure with resolution and stability < 50 nrad
- UHV compatible
- Proof of principle pilot stage (full stack) at ANL demonstrates strictest requirements – correction of angular cross talk between linear and tip-tilt stages (don't steer x-rays while scanning delay)

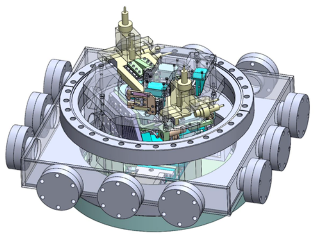
D. Shu, et al.



Motion stack



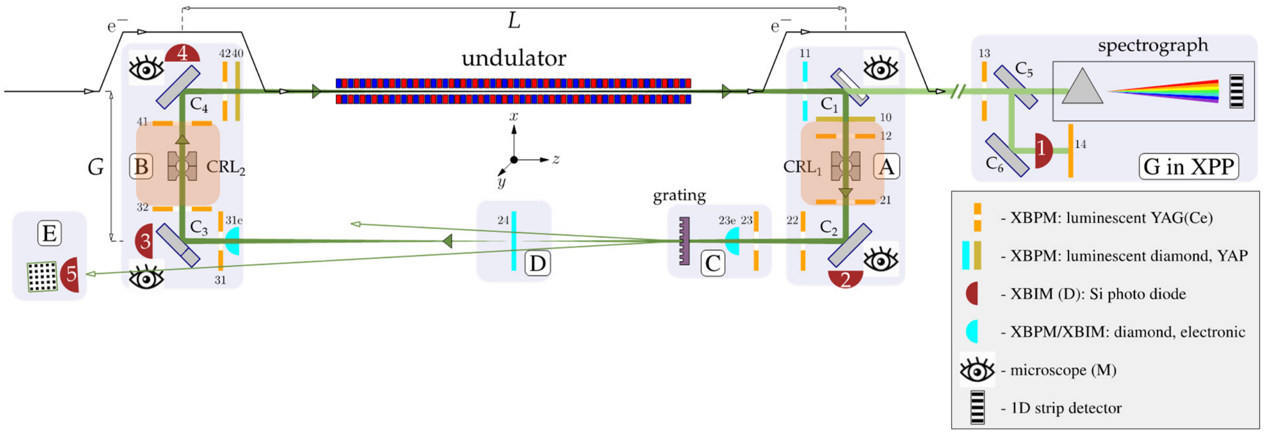
With BPMs and BODs



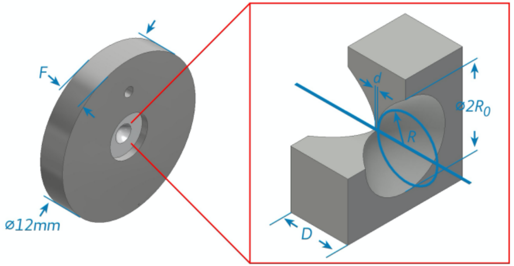
And cable management

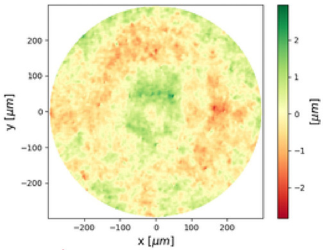
D. Shu *et al*, MEDSI2020.
D. Shu *et al*, SRI2021

Schematic of CBXFEL cavity and diagnostics



- High efficiency, low loss, wavefront preserving beryllium compound refractive lenses (CRL) provide focusing in the stable cavity
- CRLs have high transmission, excellent image quality, and are radiation hard

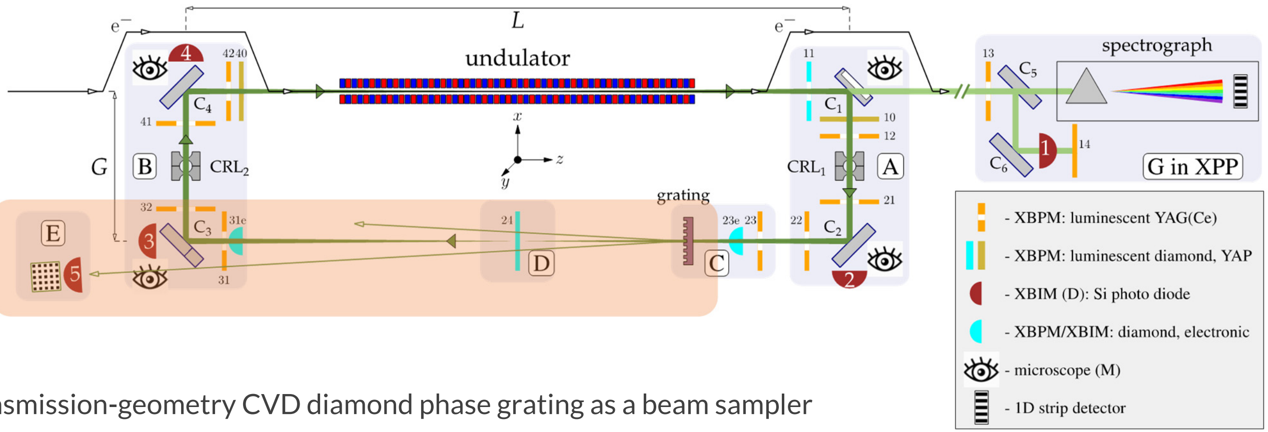




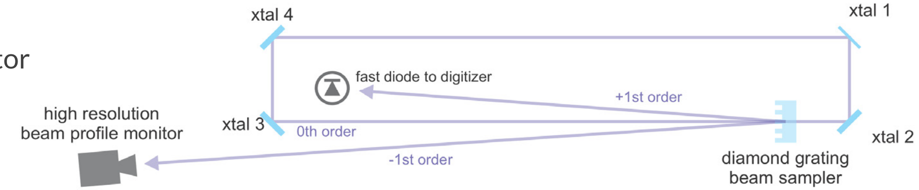
rms phase error ~ $\lambda/70$

Z. Qiao, *et al*., APL **119** (2021) 011105

Schematic of CBXFEL cavity and diagnostics



- A transmission-geometry CVD diamond phase grating as a beam sampler
- Measure the FEL amplification processes and cavity ring-down *in-situ*
- Silicon diode for cavity ring-down
- Scintillator based high-res beam profile monitor



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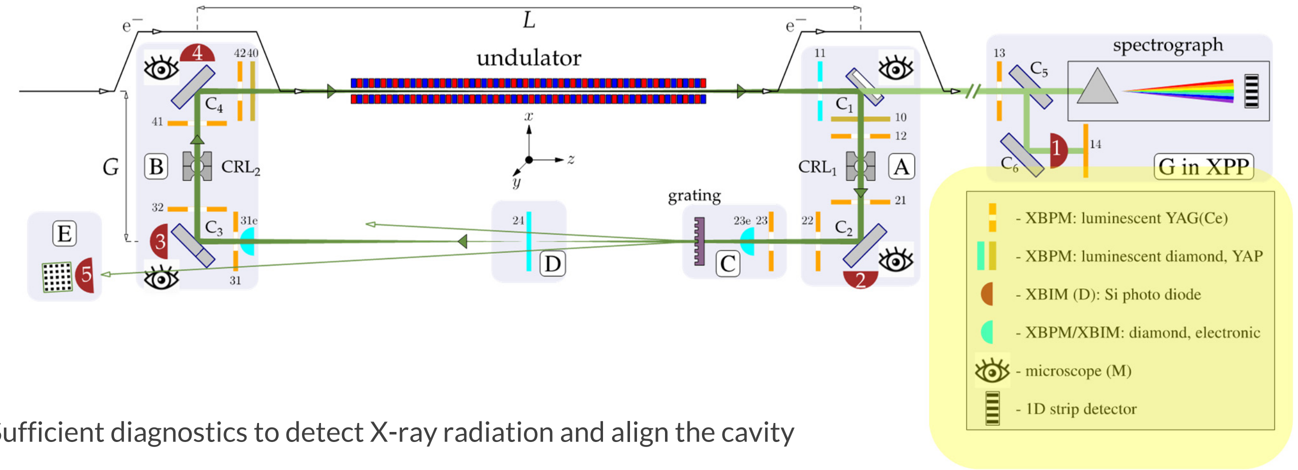
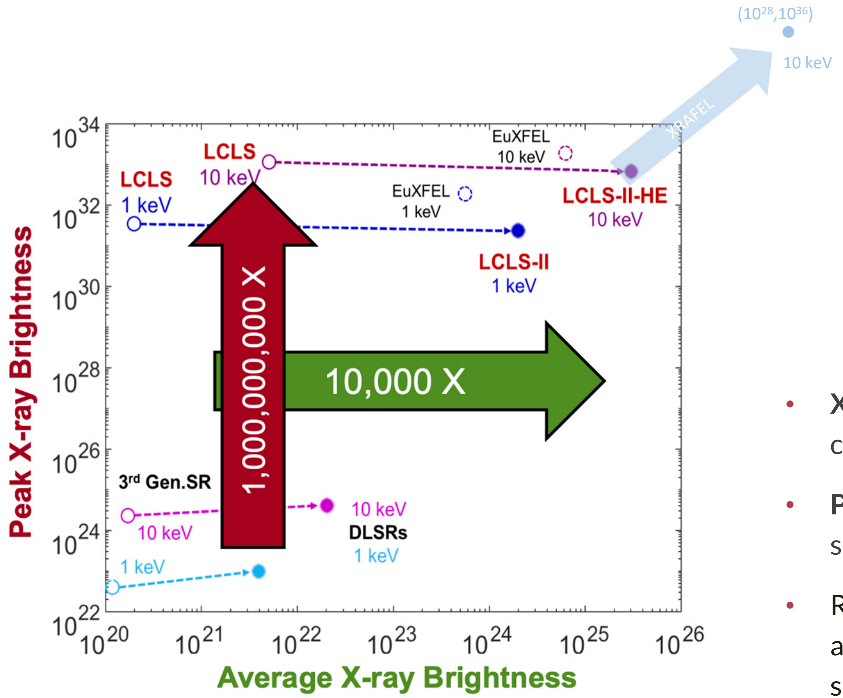
D. Zhu, et al.

Schematic of CBXFEL cavity and diagnostics

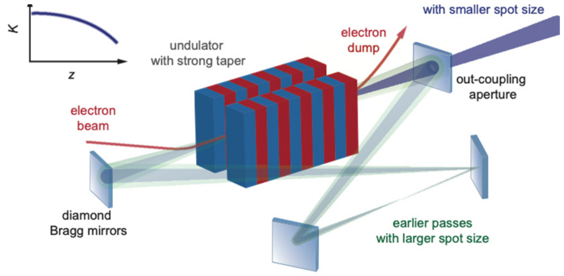


Sufficient diagnostics to detect X-ray radiation and align the cavity

CBXFEL concepts unlock true potential of a HXR laser



M. Dunne



- **XRAFEL** source assuming LCLS-II-HE parameters + 300 m RT length cavity produces coherent, stable, narrow bandwidth hard x-rays
- **Peak and average brightness** 2-3 orders of magnitude greater than single pass SASE amplifiers
- Realize the potential of a **true x-ray laser** to drive qualitative advances in many areas of science: x-ray photon correlation spectroscopy, coherent diffractive imaging, single-particle imaging, nonlinear x-ray optics, x-ray quantum optics, etc.

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

Ongoing CBXFEL studies

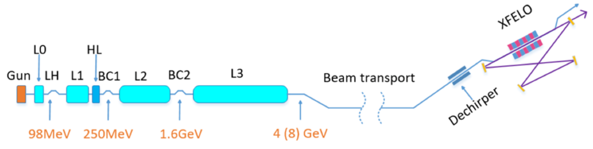
In March 2021, Eu-XFEL and DESY hosted a workshop

Opportunities & challenges of cavity-based X-ray free-electron lasers ***https://indico.desy.de/event/25361/***

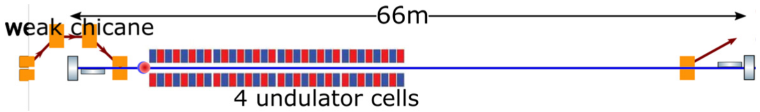
CBXFEL Design studies:

1. XFELO w/ 8 GeV linac (ANL)
   - 10^9-10^{10} ph/pulse
   - 2-6 meV bandwidth
   - 20-50 m undulator
2. XFELO/RAFEL w/ Eu-XFEL Pulse train (Hamburg)
   - 7×10^{11} ph/pulse
   - 76 meV bandwidth
   - 4 SASE1 undulator segments
3. XRAFEL w/ LCLS-II He (SLAC)
   - 10^{10}-10^{13} ph/pulse
   - 100 meV bandwidth
   - 108 m undulator

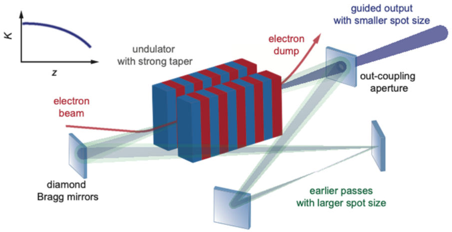
XFELO @ Petra IV storage ring from DESY also explored



R. Lindberg et al., PRSTAB 14, 010701 (2011)



P. Rauer et al., FEL2019, TUP009 (2019), also P. Rauer Dissertation



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

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Summary

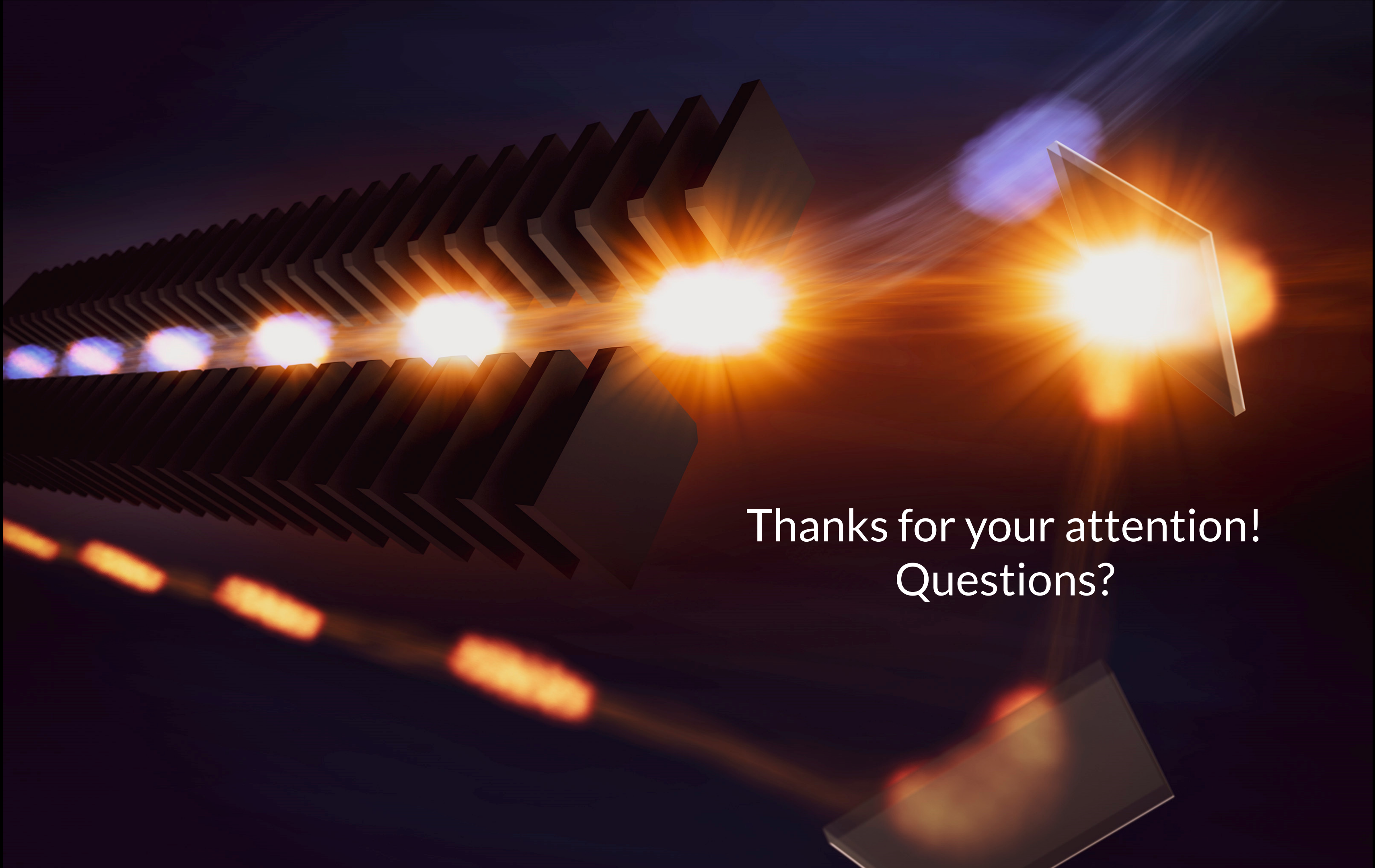
XFELs provide the medium by which high power x-rays can be generated.

SASE XFELs, while transversely coherent, have statistical properties that are characteristic of chaotic polarized sources – not a true laser.

High-brightness, high-repetition rate e^- beam delivery systems are (coming) online – a good time to develop mature x-ray cavity technologies.

CBXFELs can deliver fully coherent, stable, high average and peak brightness hard X-ray pulses and provide significant advances for many areas of science.

We hope to demonstrate CBXFEL technologies in the very near future!



Thanks for your attention!
Questions?