Cavity-based X-ray Free-Electron Laser Research and Development

A Joint Argonne National Laboratory and SLAC National Laboratory Collaboration

G. Marcus
On behalf of the ANL/SLAC CBXFEL team

39th International FEL Conference
Hamburg, Germany, 08/27/2019

Outline

- Motivation
- Cavity-based XFEL schemes
  - X-ray free-electron laser oscillator (XFELO)
  - X-ray regenerative amplifier free-electron laser (XRAFEL)
- ANL/SLAC R&D program
- Summary

Motivation - the need for longitudinal coherence

- SASE XFELs are capable of producing extremely bright, transversely coherent, ultra-short X-ray pulses that have opened the door to new regimes of photon science.
  - However, they suffer from poor longitudinal coherence due to the stochastic nature of the start-up process.

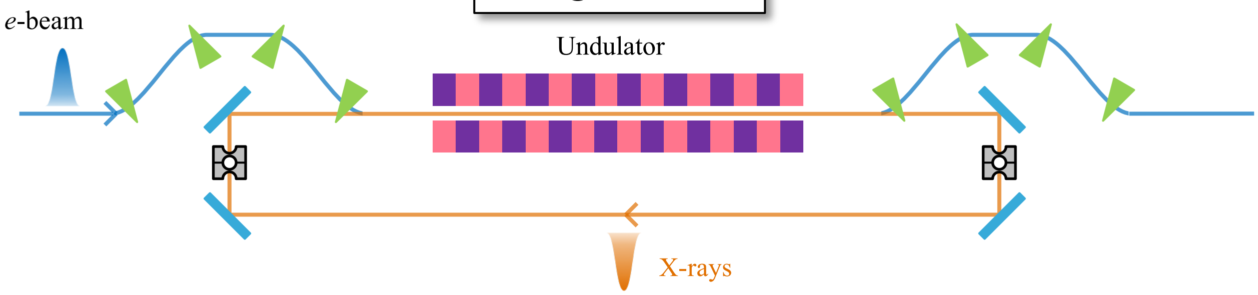
- Generating fully coherent X-ray beams at high repetition rate, and providing control of the longitudinal coherence (trade-off of BW vs. pulse length at the FT limit), will drive another qualitative advance for many areas of science.
  - Hard X-ray spectroscopy at the Fourier limit - RIXS and IXS
  - Two-pulse X-ray photon correlation spectroscopy (XPCS)
  - Nuclear resonance scattering
  - Quantitative investigation of nonlinear X-ray phenomena and applications
  - etc.

- Longitudinal coherence can be obtained by seeding an FEL amplifier with narrow bandwidth radiation well above the effective shot noise power in the electron beam

Cavity-based X-ray FELs

X-ray RAFEL: Z. Huang and R.D. Ruth, Phys. Rev. Lett. **96**, 144801 (2006).
X-ray Oscillator: K.-J. Kim, Y. Shvyd'ko, and Sven Reiche, Phys. Rev. Lett. **100**, 244802 (2008).

3 ingredients



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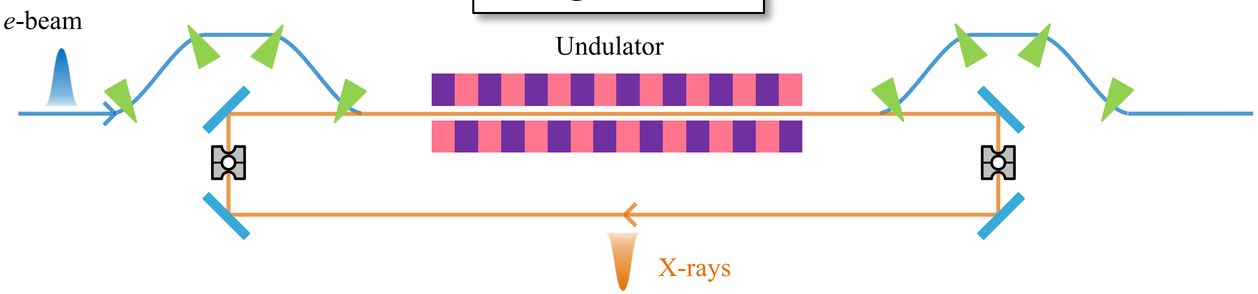
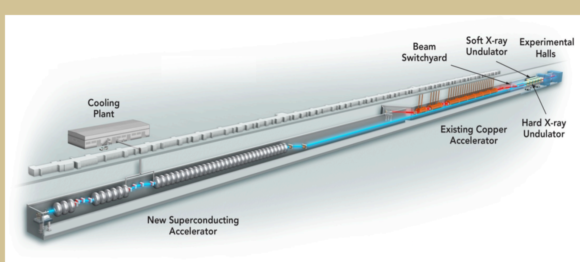


High-brightness and high repetition rate *e*-beam

- High repetition rate facilities are now coming online
  - EuXFEL, LCLS-II, SHINE
- LCLS-II will deliver CW high-brightness beams at ~ 1 MHz



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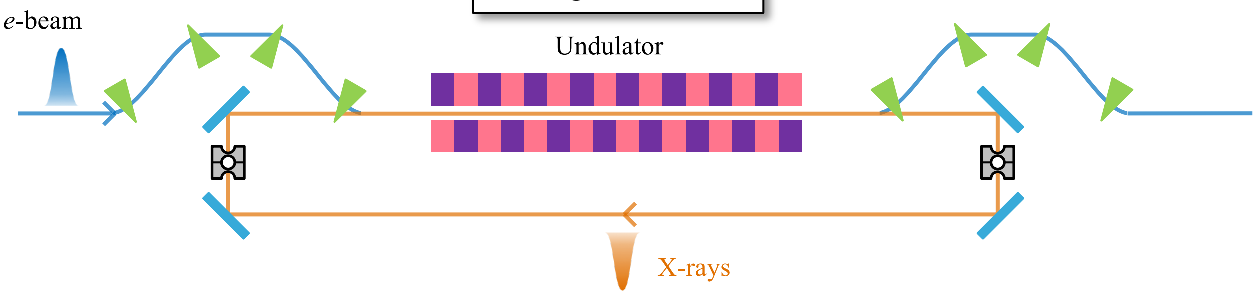

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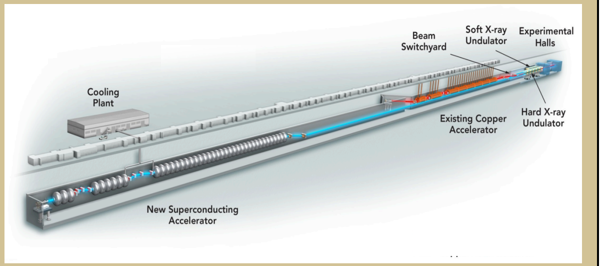
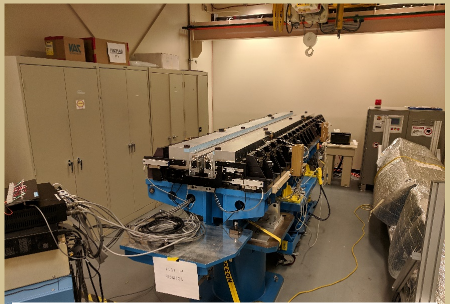


Undulator

HXU on CMM in B081



HXU in integration area in B081

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SLAC

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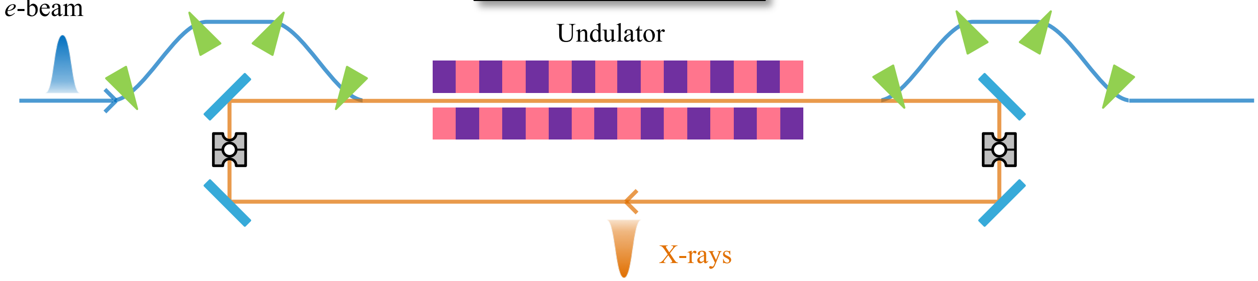

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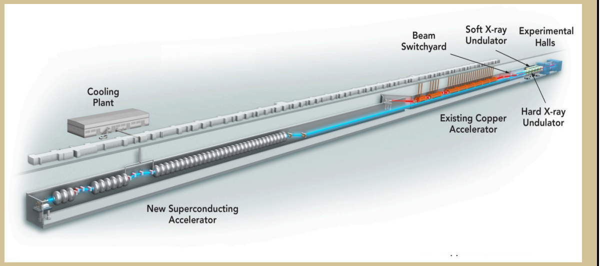

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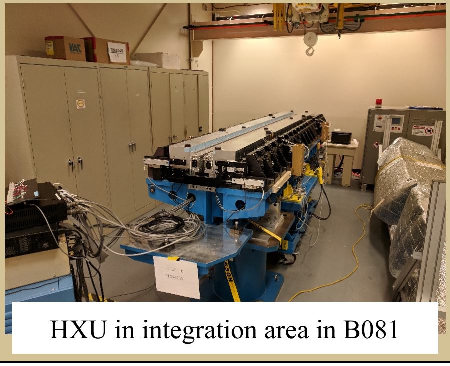
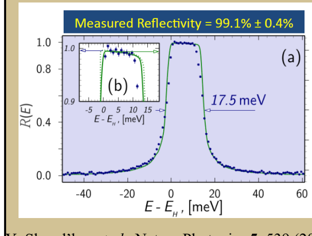


HXU in integration area in B081

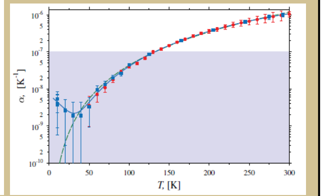
X-ray cavity

- Significant cavity component development done by ANL
- Diamond has ultra-high reflectivity and thermal diffusivity and ultra-low thermal expansion



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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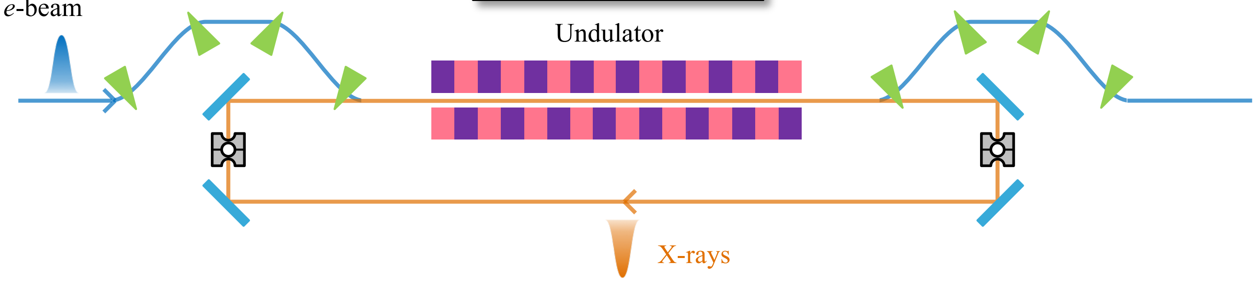

Cavity-based X-ray FELs store and recirculate the output of an amplifier in an X-ray cavity so that the X-ray pulse can interact with the following fresh electron bunches over many passes.

The development of full longitudinal coherence, and the commensurate increase in the spectral flux, would certainly benefit a great number of experiments

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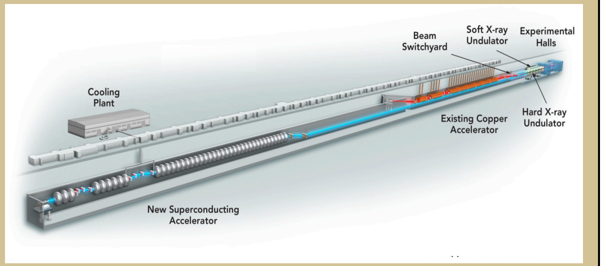
- Hi
  are
- LC
  brightness beams at ~ 1 MHz



HXU in integration area in B081

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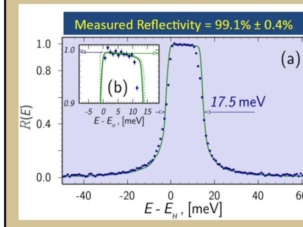

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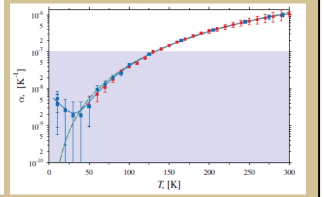
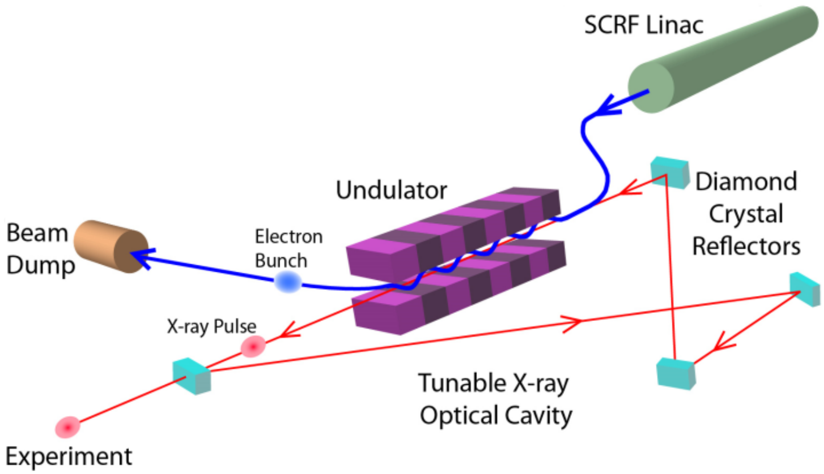


S. Stoupin, Y. Shvyd'ko, Phys. Rev. Lett. **104**, 085901 (2010)

XFELO

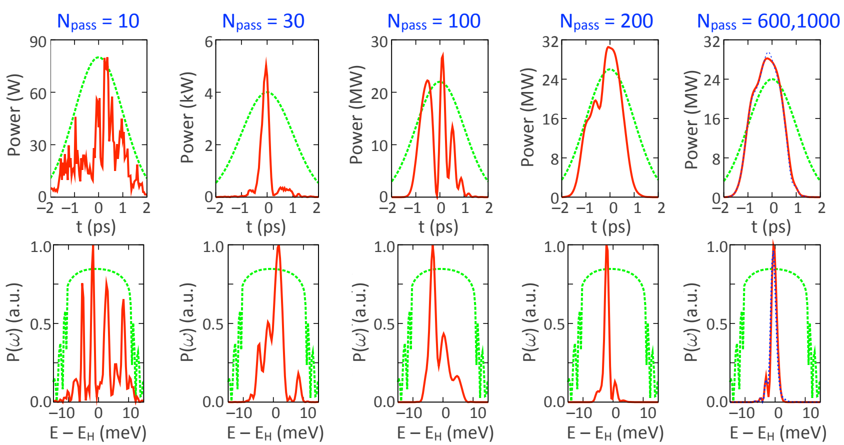
<u>Operational characteristics</u>

- XFELO relies on a low-loss cavity supporting a low-gain FEL for *ultra-narrow* bandwidth
- Typically relies on steady-state radiation output coupling
- CW operation after initial turn on – extremely stable



<u>Defining performance characteristics</u>

- Extremely *narrow* and *stable* spectral bandwidths as small as a few meV
- Average brightness ~3 order of magnitude greater than SASE (LCLS-II/-HE)
- *Ultrafine* spectral capabilities with high *spectral* photon density



Typical longitudinal pulse evolution in an XFELO

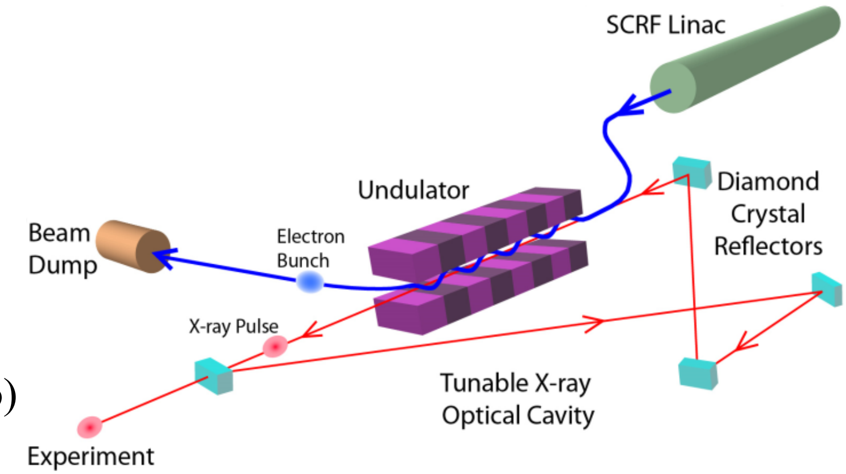
XRAFEL

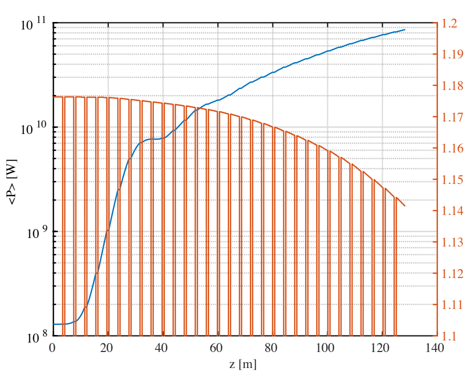
XRAFEL, G. Marcus, TUP032
Microbunch rotation, R. Margraf, THP036
Q-switching, J. Krzywinski, TUP033

SLAC

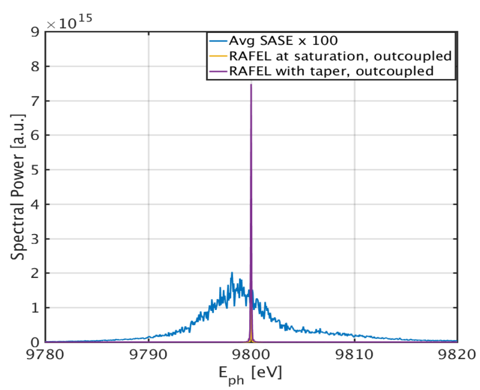
Operational characteristics

- XRAFEL is a high-gain FEL that can tolerate significant cavity losses and saturates in only few round trips
- *Active* radiation output coupling to dump significant cavity power (passive methods too)
- Gain-guiding relaxes cavity opto-mechanical alignment and stability tolerances





Strong tapering



Increase in peak spectral brightness

Defining performance characteristics

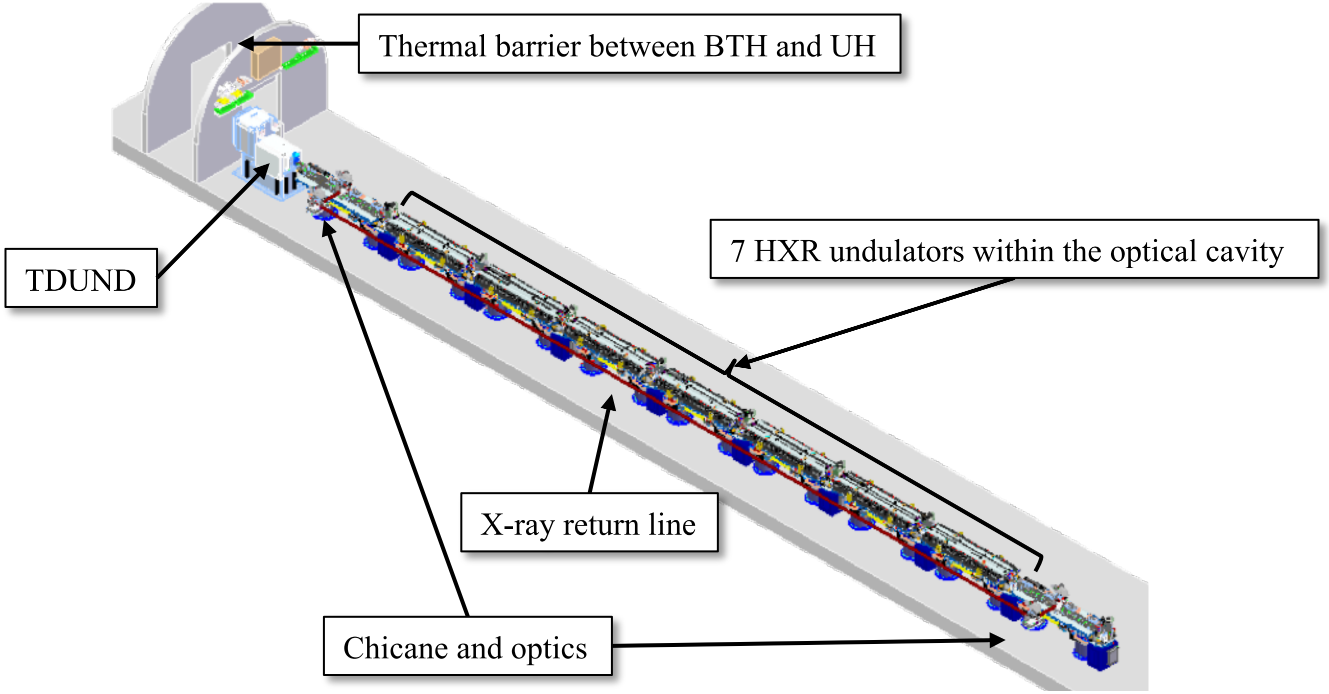
- Fully coherent but *shorter* pulses similar in length to SASE
- Can produce both high *average* (CW - passive) and high *peak* (active) power pulses
- Stable and high-power seed with fresh electrons enables strong undulator tapering

Complimentary characteristics of XFELO and XRAFEL for LCLS-II-HE

	XRAFEL	XFELO
Gain & output coupling	High	Low
Necessary cavity roundtrip efficiency	~ 1 %	~ 85%
Passes to saturation	~ 10's	~ 100's
Repetition rate	Q-switched (~10-50 kHz), CW (~ MHz)	CW (~ MHz)

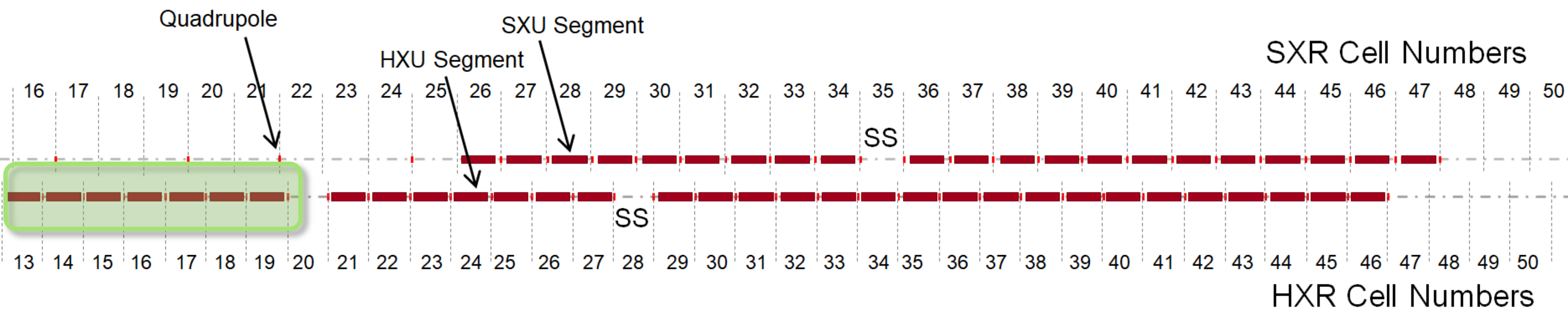
	SASE	XRAFEL	XFELO
Peak Power	~10 GW	~50 GW	~10 MW
Average power	~100 W (at ~1 MHz)	10 W (at 10 kHz)	20 W (at ~1 MHz)
Spectral bandwidth	~10 eV	~0.1 eV	~1 meV
Pulse length	~ 1 – 100 fs	~ 20 fs	~ 1 ps
Stability	Poor	Excellent	Excellent
Longitudinal coherence	Poor	Excellent	Excellent
Transverse mode	Defined by gain-guiding	Defined by gain-guiding	Defined by the optical cavity

ANL/SLAC collaboration to conduct targeted R&D

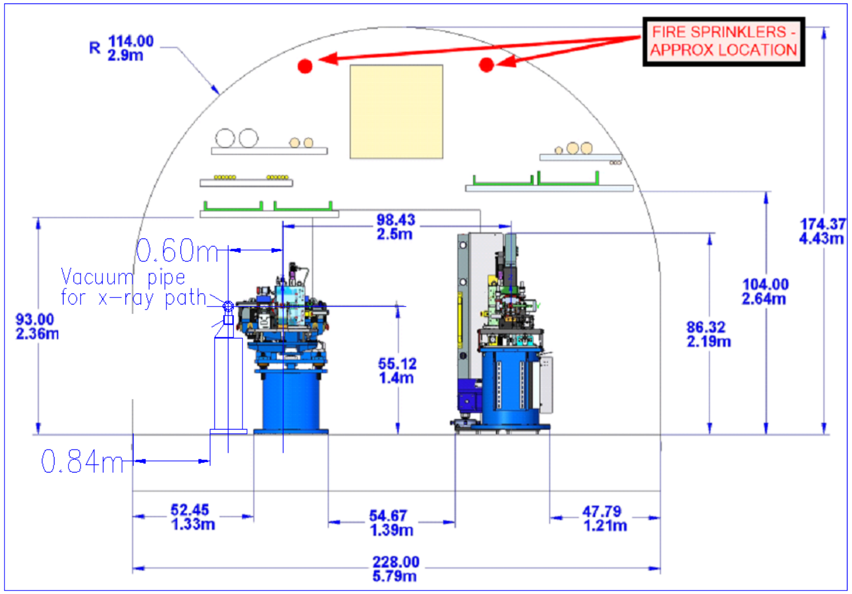


- Construct a rectangular X-ray cavity that encloses the first 7 LCLS-II HXR undulator modules.
- Investigate crucial aspects related to CBXFEL physics using a pair of electron bunches from the SLAC copper RF linac.
- Perform 2-pass gain measurements and cavity ring-down measurements for low and high gain schemes.
- Demonstrate cavity tolerance and stability requirements necessary for both schemes.

X-ray optical cavity in the undulator hall



- Undulator hall provides requisite temperature stability for sensitive opto-mechanical hardware
- Cavity wraps 7 undulator sections
- Total cavity length ~ 66 m (~ 220 ns)
- Lateral offset of return line < 1 m



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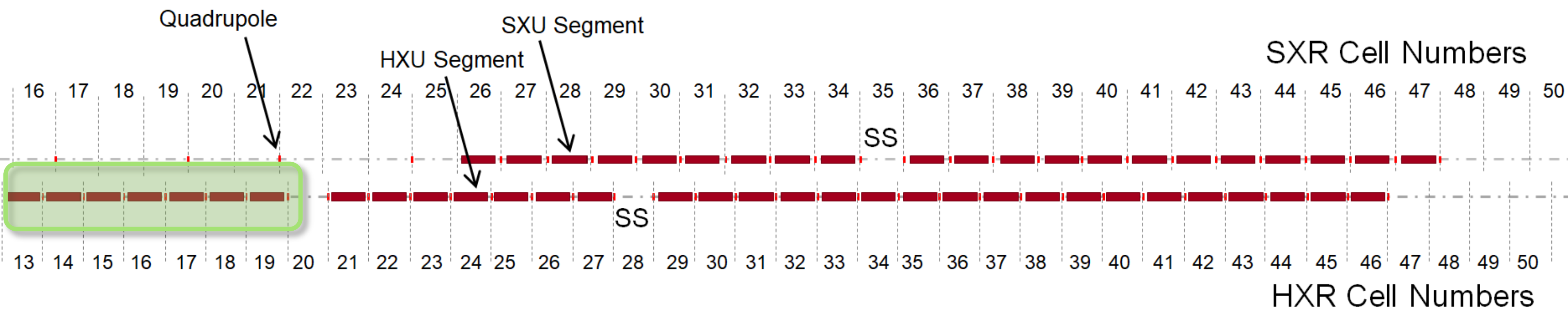
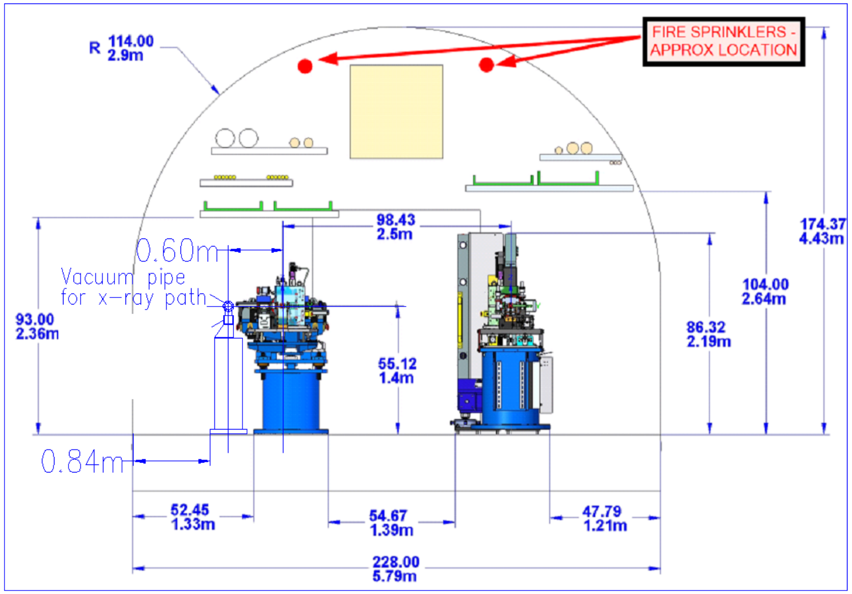
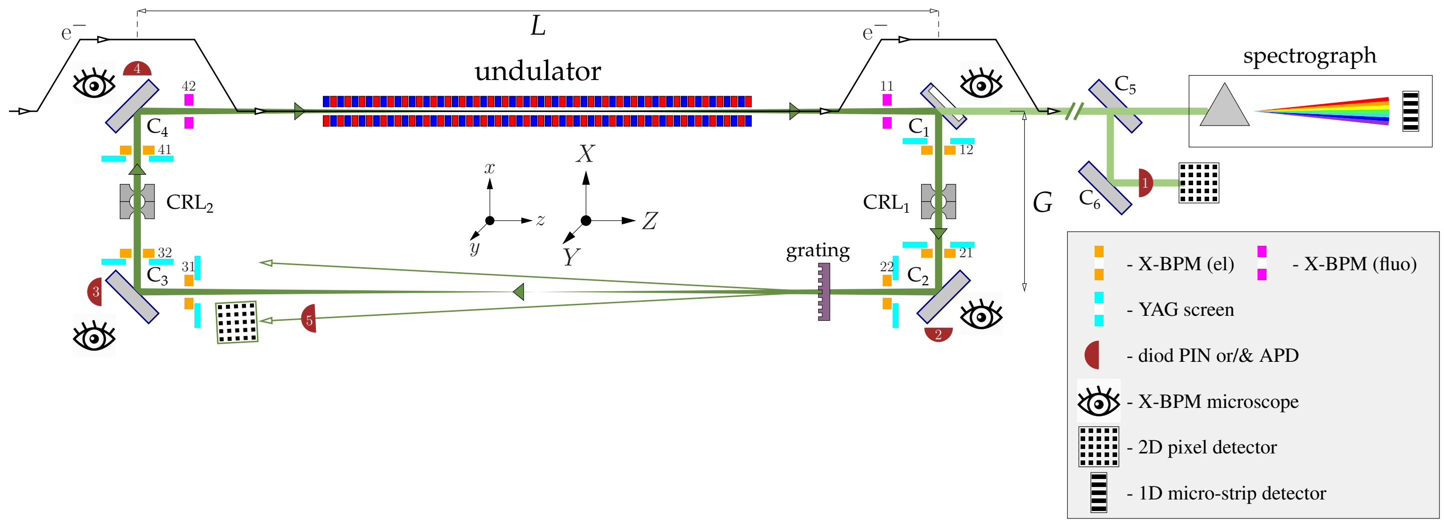


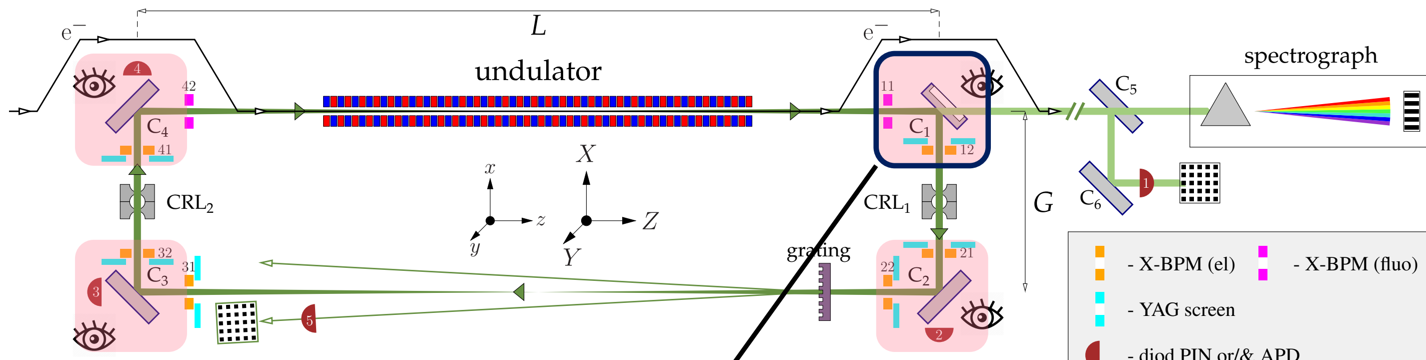


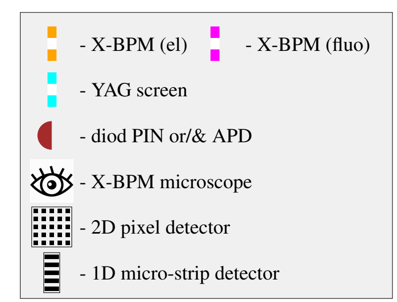
Cavity component development



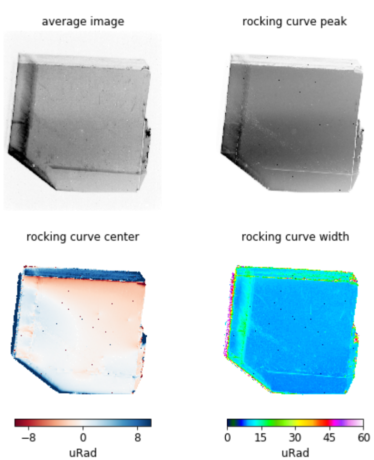
Cavity component development

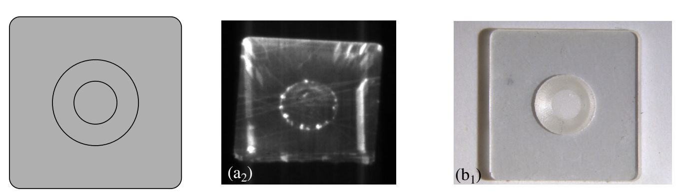
Output coupling, Y. Shvyd'ko, TUP029

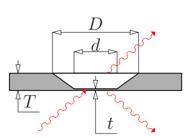




Synthetic HPHT-IIa diamond crystals



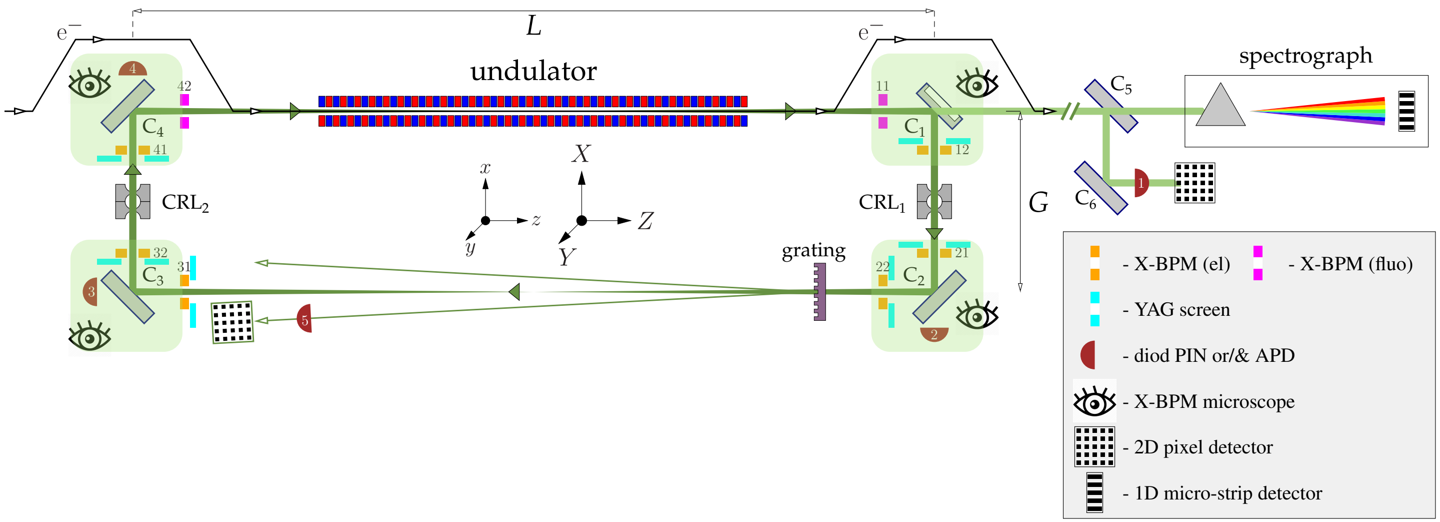




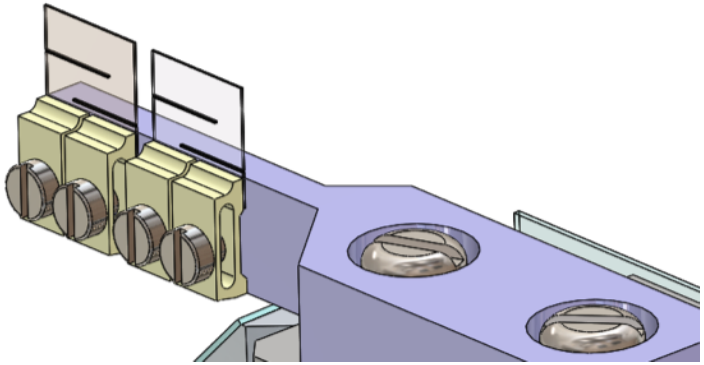
"Drum head" diamond ($\sim 20\ \mu m$ thickness) to increase output coupling

Parameter	Value	Unit
Crystal material	C*(400)	-
Bragg angle	45	degree
Photon energy	9.83	keV
Wavelength	1.26	Angstrom
Bragg width (energy)	75	meV
Bragg width (angle)	8	µrad

Cavity component development

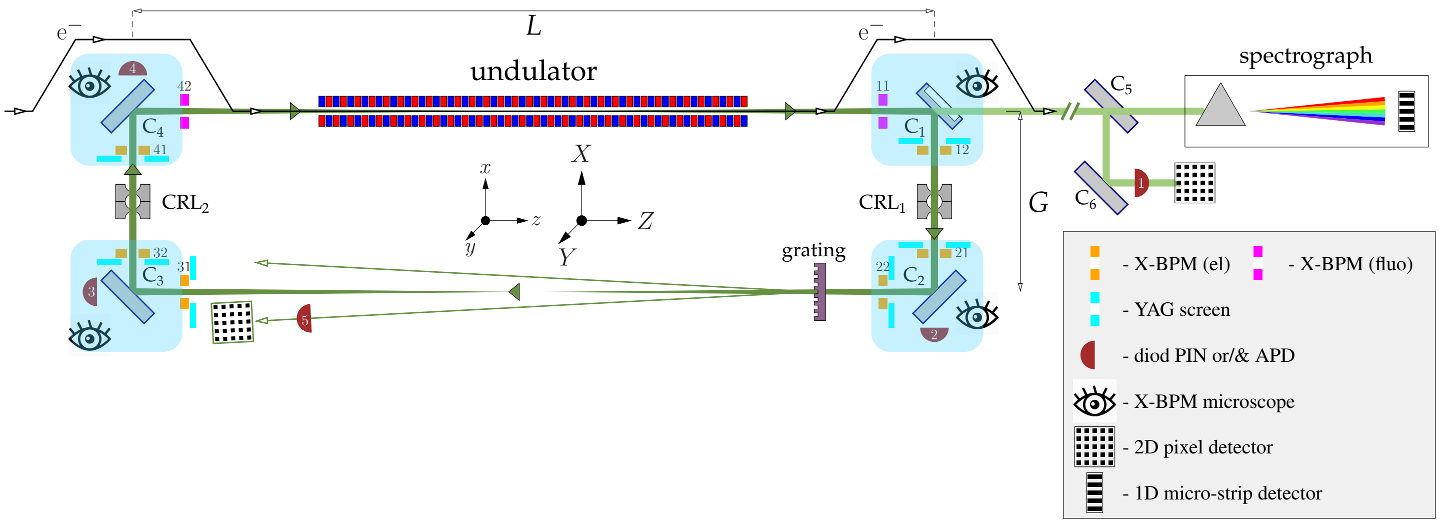


- Strain free diamond mounting
- Similar to crystal holder designed for EuXFEL self-seeding mono.

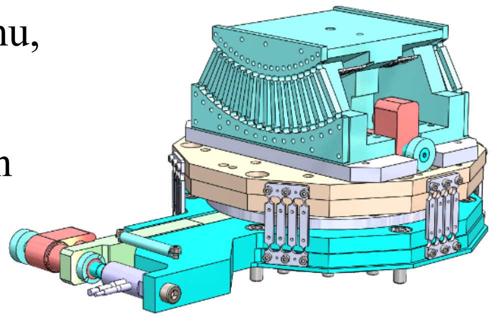


L. Samoylova, *et al.*, Proceedings of SRI-2018, June 2018, Taipei, Taiwan.

Cavity component development

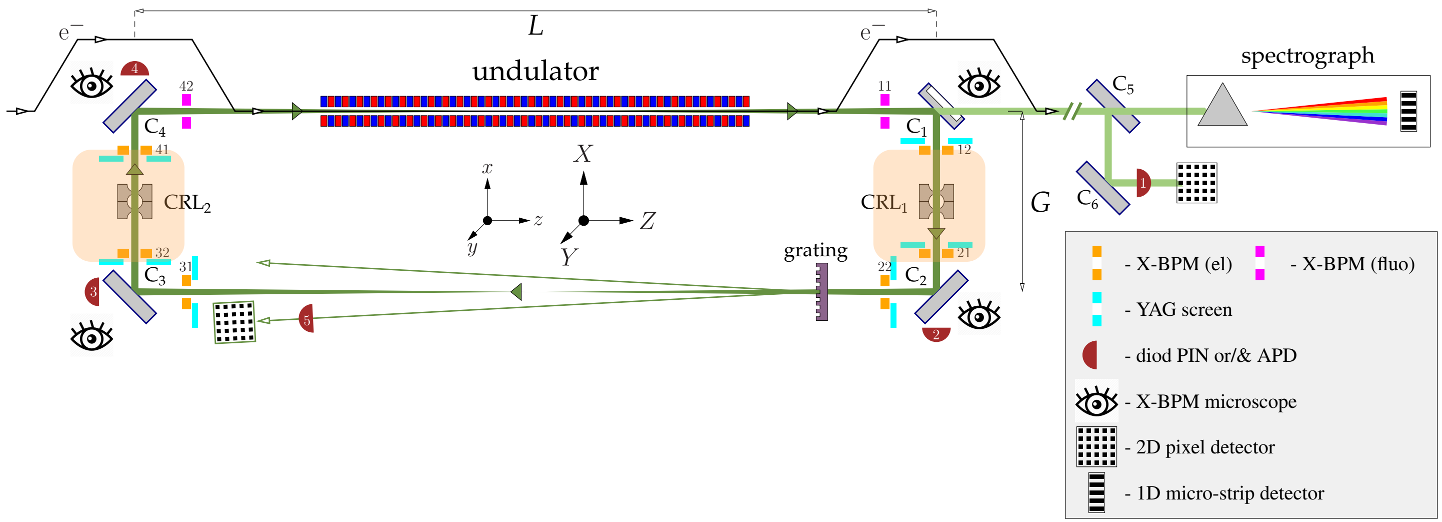


- Pitch and roll nano-positioning stage (D. Shu, *et al.*, APS Nanopositioning Support Lab)
- Laminar weak-link structure with resolution and stability < 50 nrad
- UHV compatible



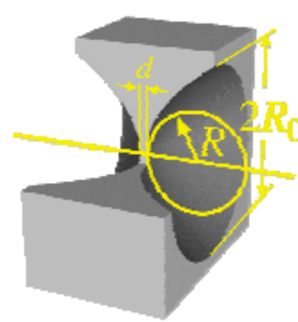
Cavity component development

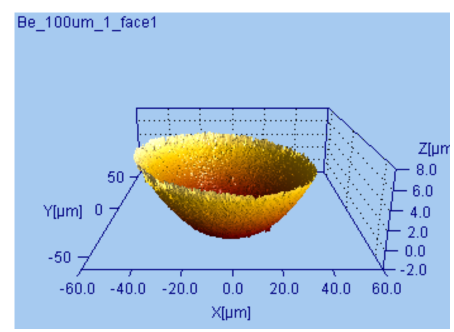
SLAC



- High efficiency, low loss beryllium compound refractive lenses (CRL) provide focusing in the stable cavity

- CRLs have high transmission, excellent image quality, and are radiation hard

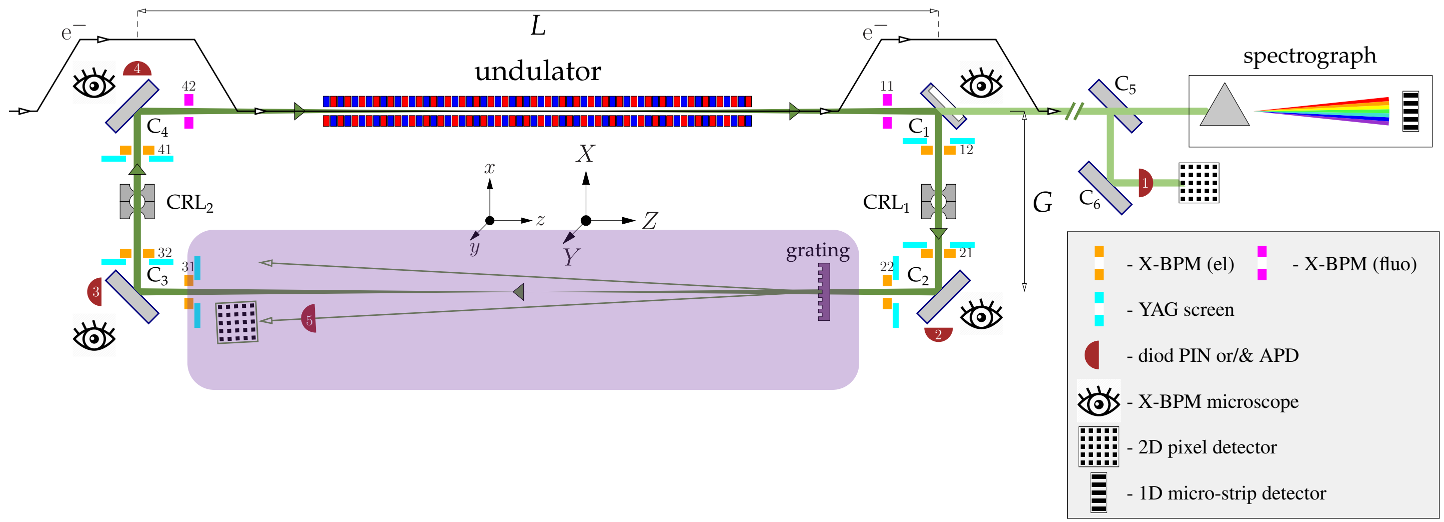




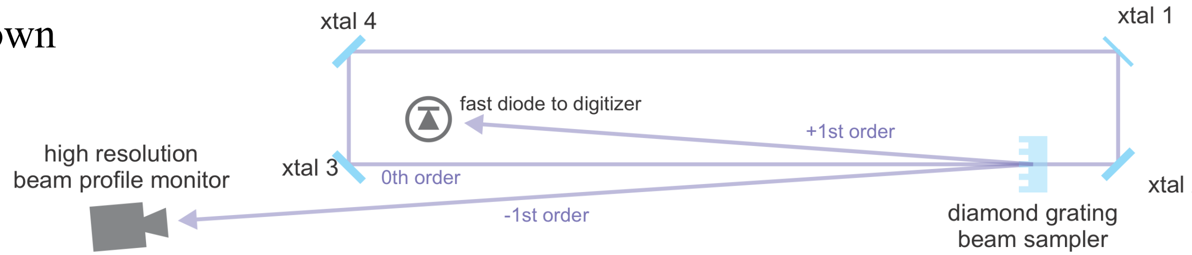
T. Kolodziej, S. Staupin, et al., JSR 25, 354 (2018)

Cavity component development

Wavefront sensor, Y. Liu, WEP106



- 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
- Optional upgrade: Wavefront sensor



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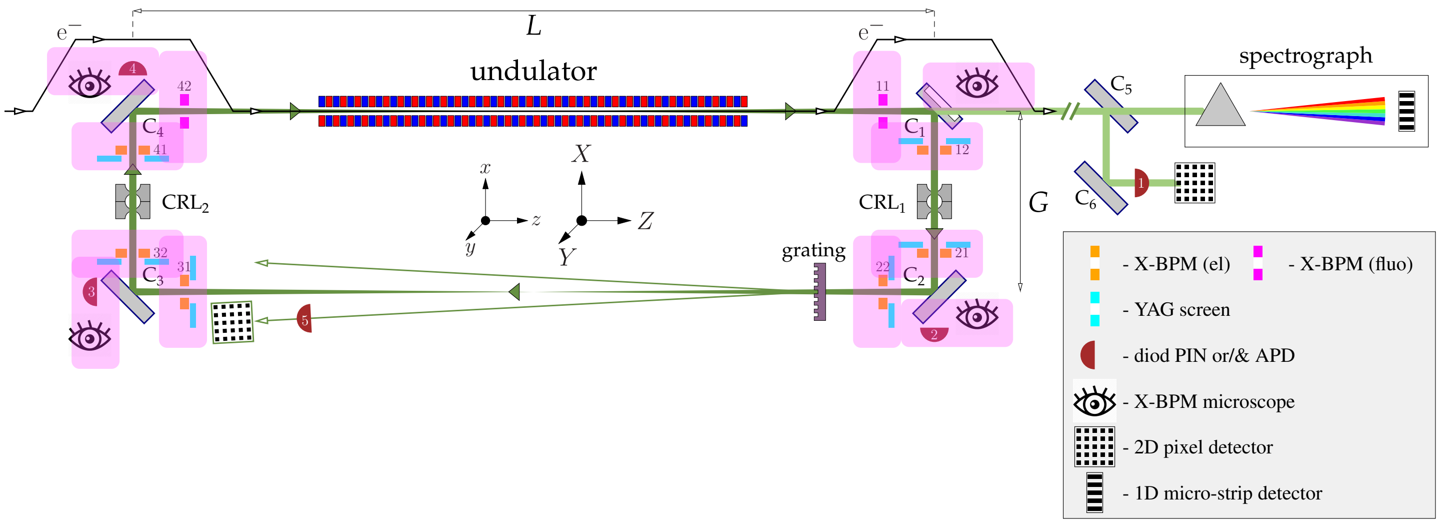
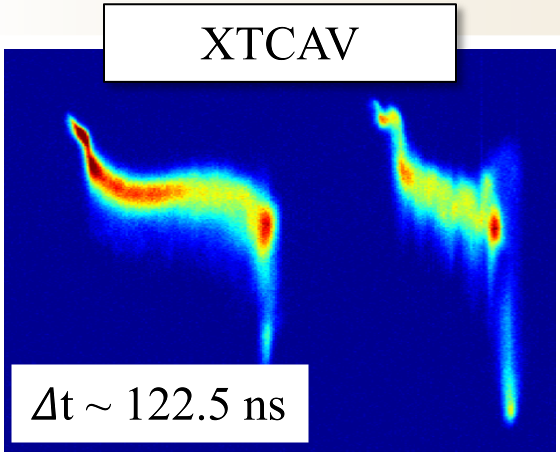


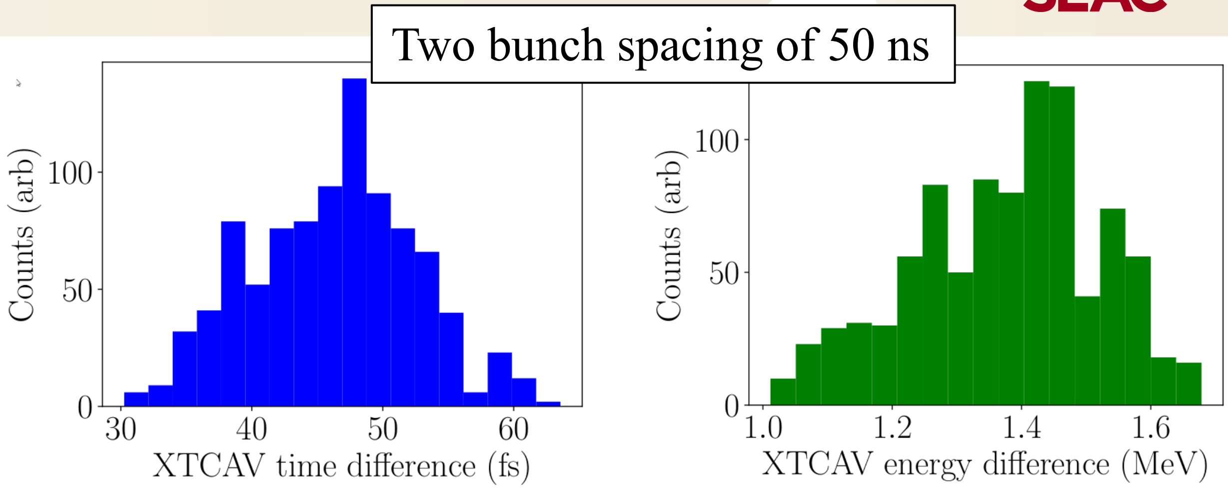
- Sufficient diagnostics to detect X-ray radiation and align the cavity

XFELO crystal misalignments, R. Lindberg, TUP027

Two-bunch experiments at SLAC

Double bunch FEL, A. Halavanau, THP071





- 2-bunch schemes have been explored in the past
  - ~10, 50, 122.5, 210 ns bunch separations (F.J. Decker, *et al.*)
- Achieved close to 2 x single bunch FEL performance
- Relative temporal (energy) jitter between the two bunches for the 50 ns separation case is ~ 6 fs (0.35 MeV) rms
- Relative energy jitter can be overlapped and controlled with some effort
- Implement fast kickers to control pointing and lateral offsets in the undulator

Estimates of two-pass gain

XRAFEL, G. Marcus, TUP032
Spon. Rad. 2-bunch, Y. Shen, TUP038

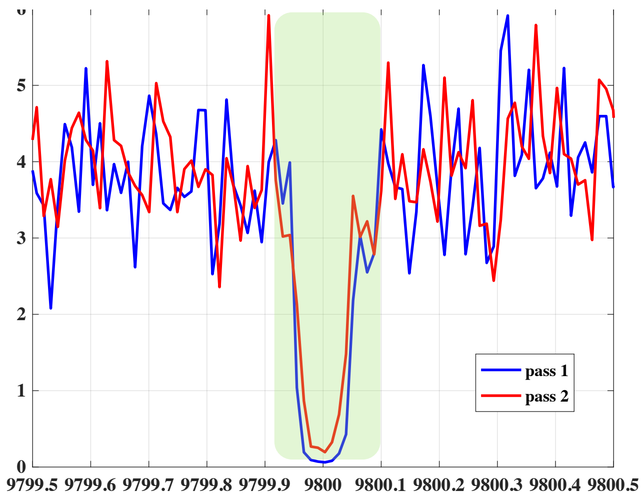
SLAC

Parameter	XFELO	XRAFEL	Unit
Energy	10.3		GeV
Charge	100	150	pC
FWHM length	300	50	fs
RMS beam size	22	24	µm
RMS angular divergence	1.1	1.2	µrad
RMS energy spread	0.5	1.5	MeV
Bunch spacing	~66 (620)		m (RF cycles)

I_{pk} = 300 A (flat-top)

I_{pk} = 3 kA (flat-top)

Low gain, 50 shot averaged transmitted spectra



Perform both 2-pass time-independent and time-dependent GENESIS simulations with Fourier optics propagation in an ideally aligned cavity

Gain of ~ 3 consistent with TI simulations at the optimal detuning, GINGER simulations, and analytic estimates

Gain of ~ 100 seen for high-gain case

Summary

- CBXFELs can deliver fully coherent, stable, high average and peak brightness hard X-ray pulses
  - Provides significant advances for many areas of science
- All the pieces are nearly in place to experimentally study CBXFEL concepts
- Joint ANL/SLAC collaboration plans to install an X-ray cavity around 7 LCLS-II HXR undulator modules
- Explore CBXFEL physics from low to high gain and demonstrate necessary performance tolerances needed for a full scale implementation

Acknowledgements

ANL

J. W. J. Anton
L. Assoufid
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D. Shu
Y. Shvyd'ko
J. P. Sullivan
M. White

SLAC

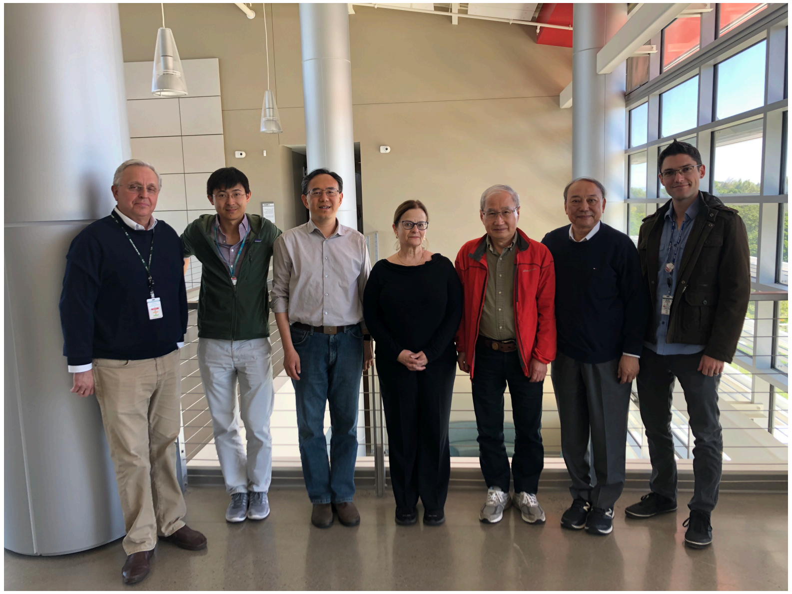
F.-J. Decker
G. L. Gassner
A. Halavanau
J. Hastings
Z. Huang
Y. Liu
J. MacArthur
R. Margraf
T. Raubenheimer
A Sakdinawat
T. Tan
D. Zhu

Stanford

B. Lantz

LANL

D. Nguyen



Thank you for your attention!

SLAC