Bringing Coherent X-Ray Science to the Lab: The ASU Compact XFEL

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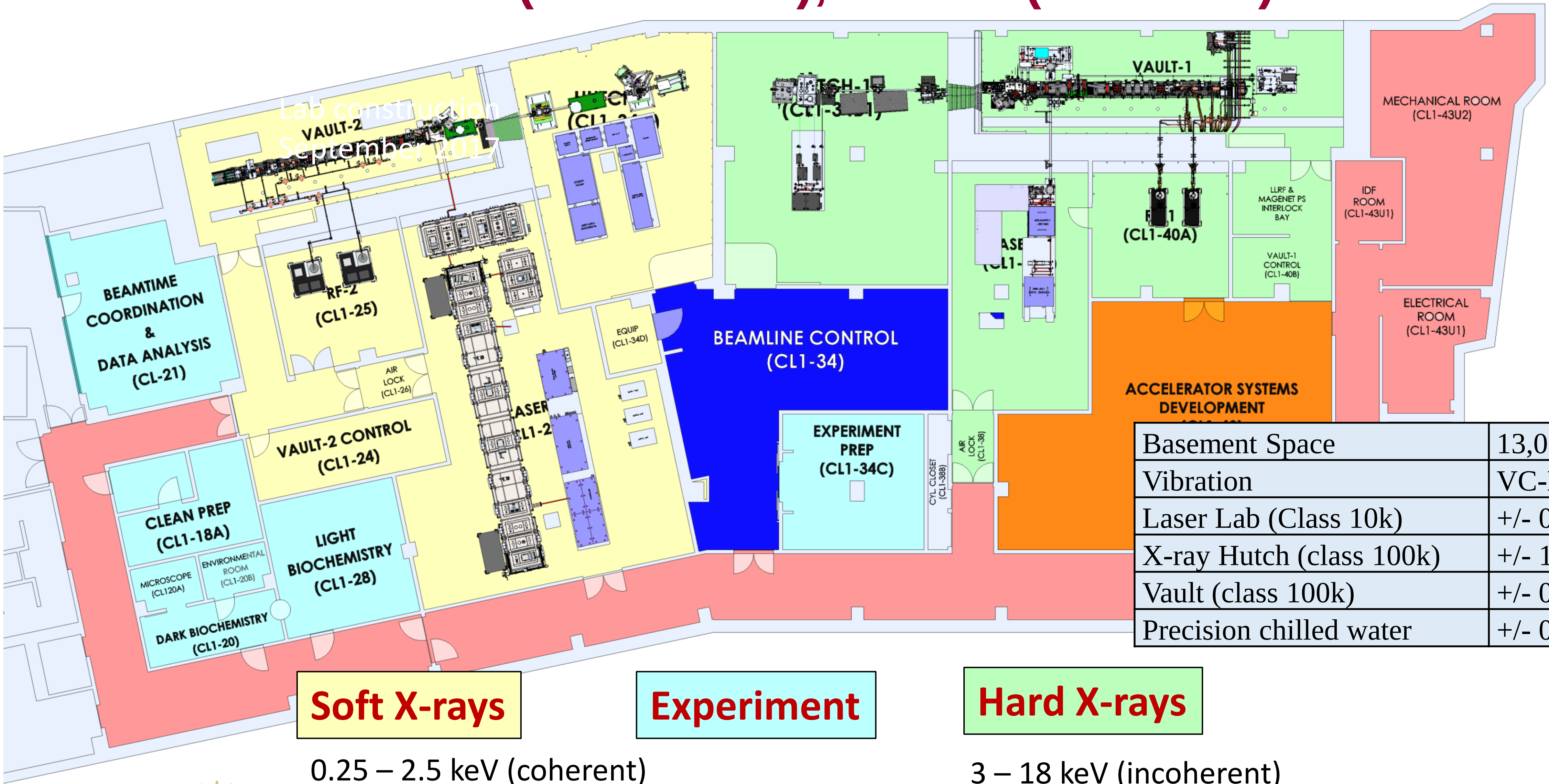
Arizona State University

This work supported by the
National Science Foundation grants 2153503, 1935994

ASU Labs for two ICS devices
CXLS (incoherent), CXFEL (coherent)



Basement Space	13,000 sq ft
Vibration	VC-E
Laser Lab (Class 10k)	+/- 0.25° C
X-ray Hutch (class 100k)	+/- 1° C
Vault (class 100k)	+/- 0.5° C
Precision chilled water	+/- 0.01° C

Soft X-rays

Experiment

Hard X-rays

0.25 – 2.5 keV (coherent)
Being constructed under NSF RI-2 program

3 – 18 keV (incoherent)
Commissioning

CXFEL Labs

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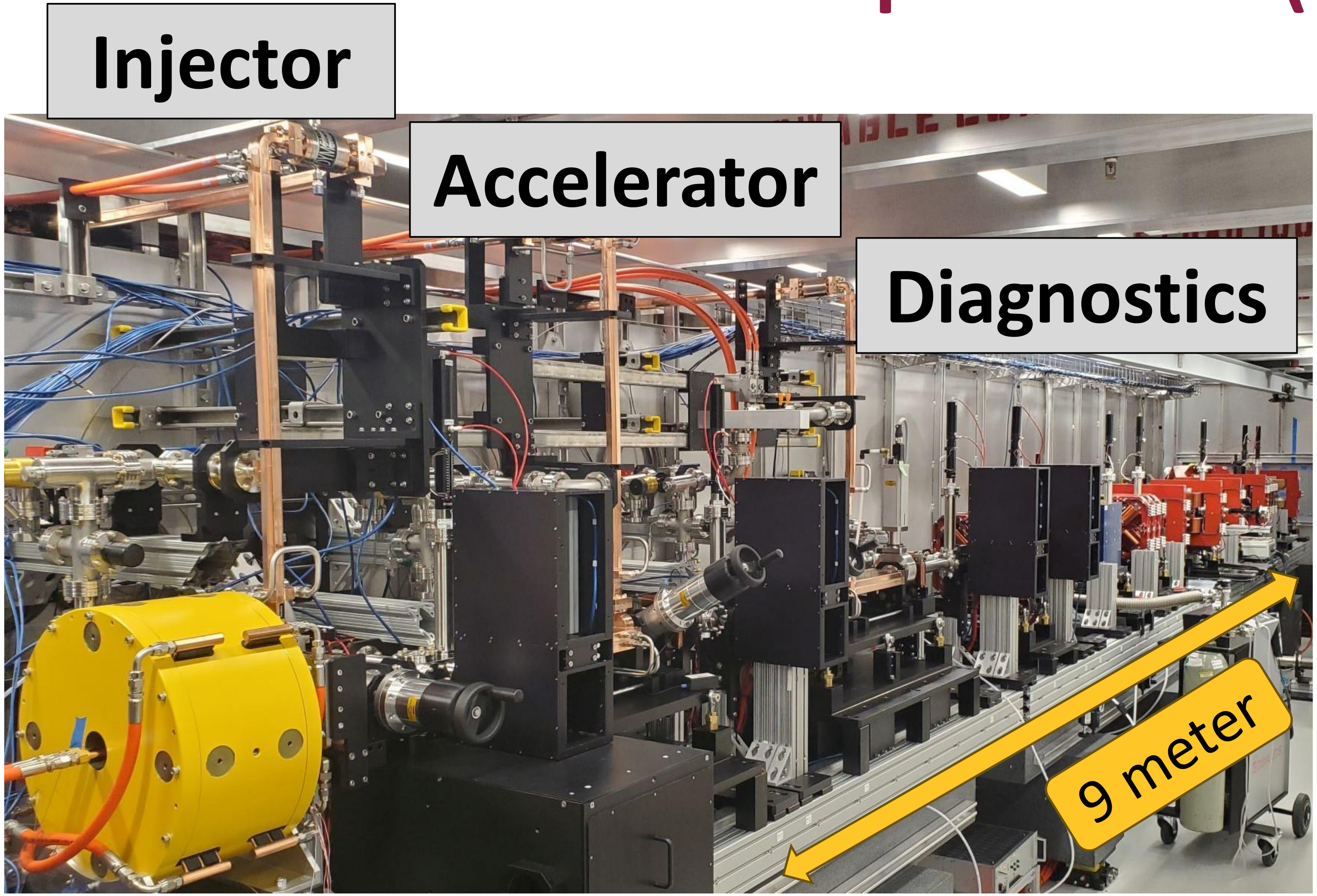
CXLS Operational (2025)



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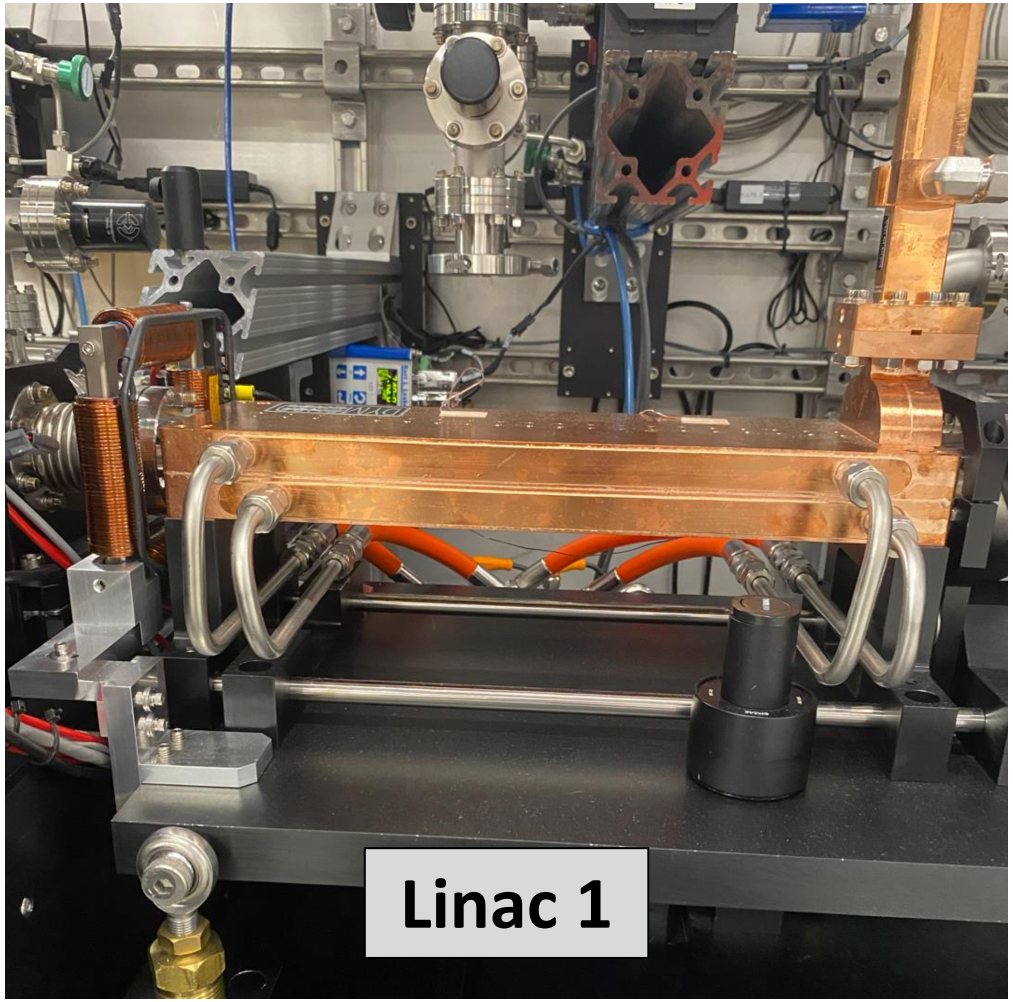
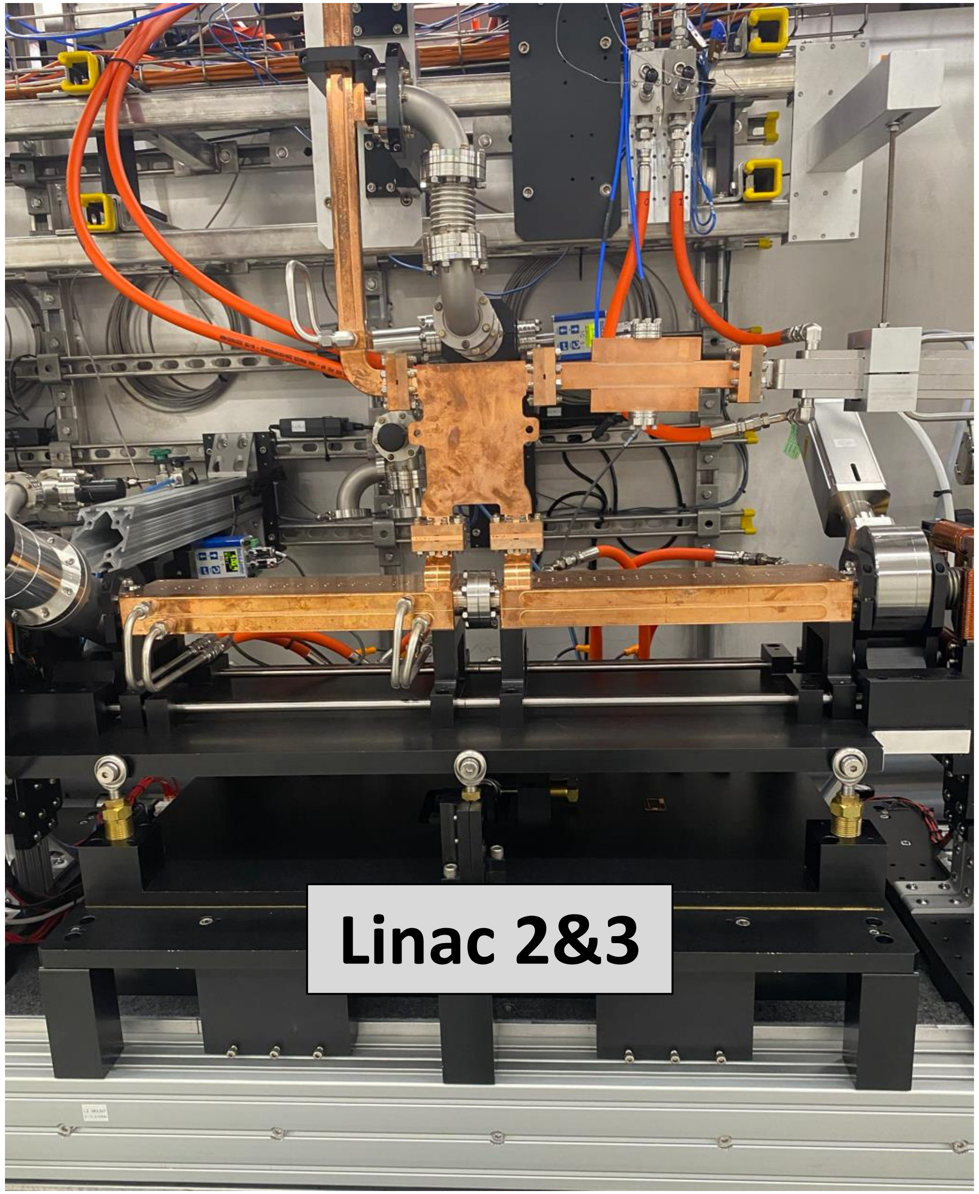
Distributed Coupling Linacs





Operating at 35 MV/m
with shunt impedance of 170 MΩ/m

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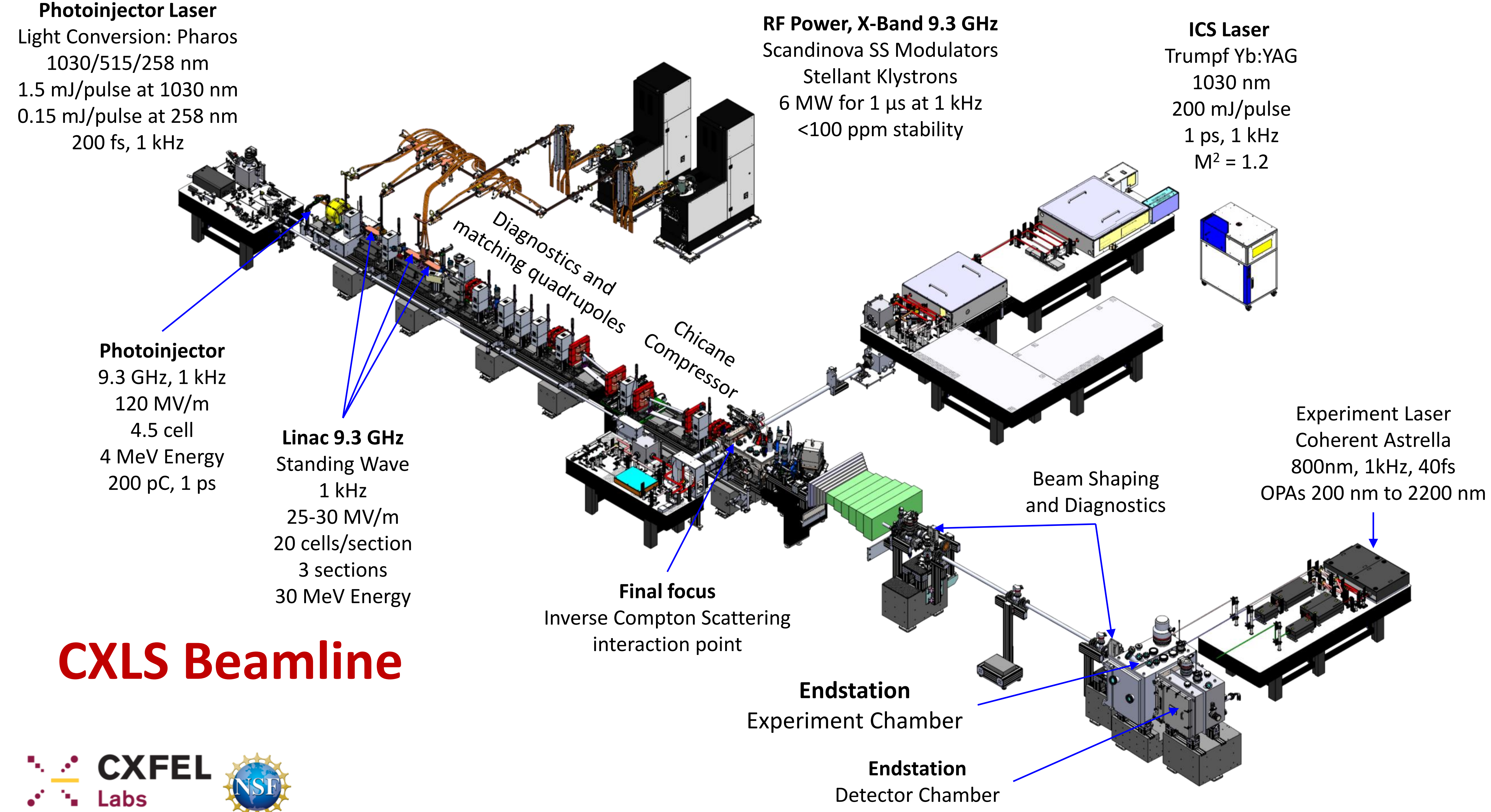

CXLS Beamline

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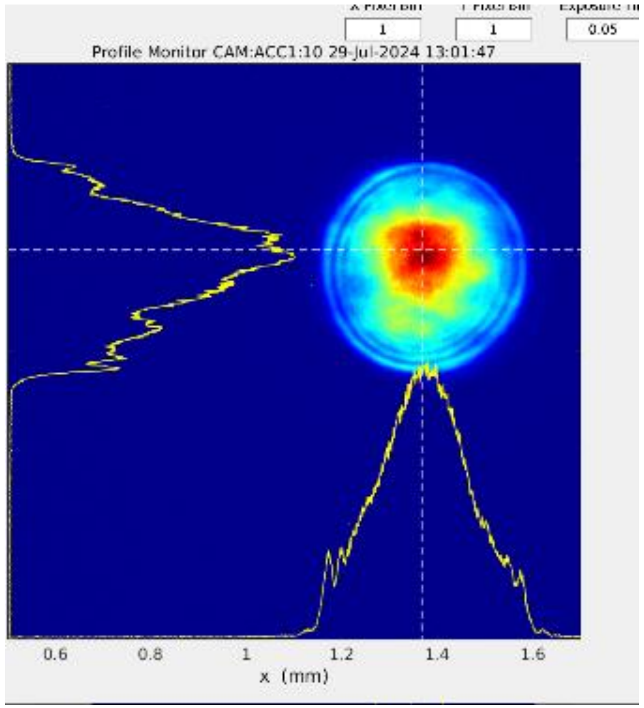
Photoinjector

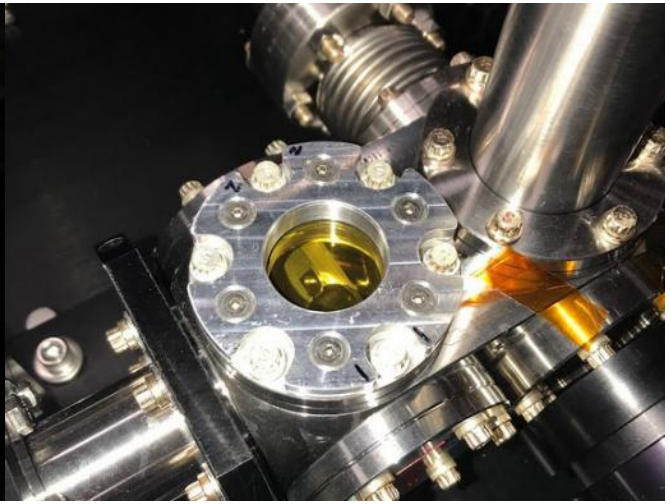
Femtosecond UV pulses at kHz rates pose challenges!

Poor beam mode from the 4th harmonic generators

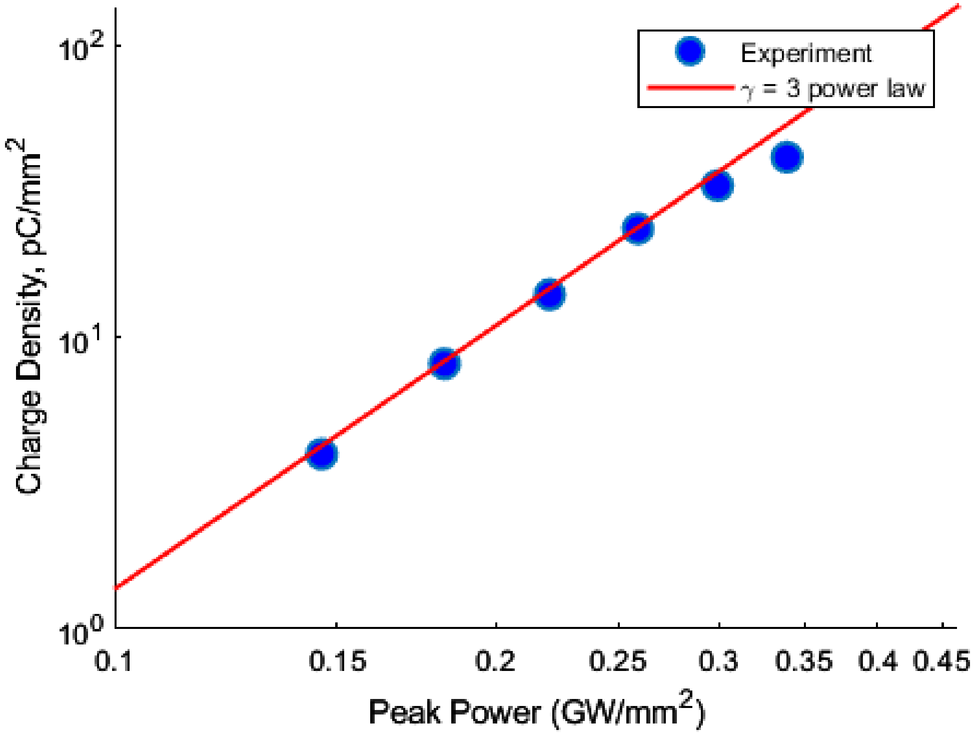
UV damage with femtosecond pulses

Yellowing of UV optics MgF_2, LiF Radiation-soft





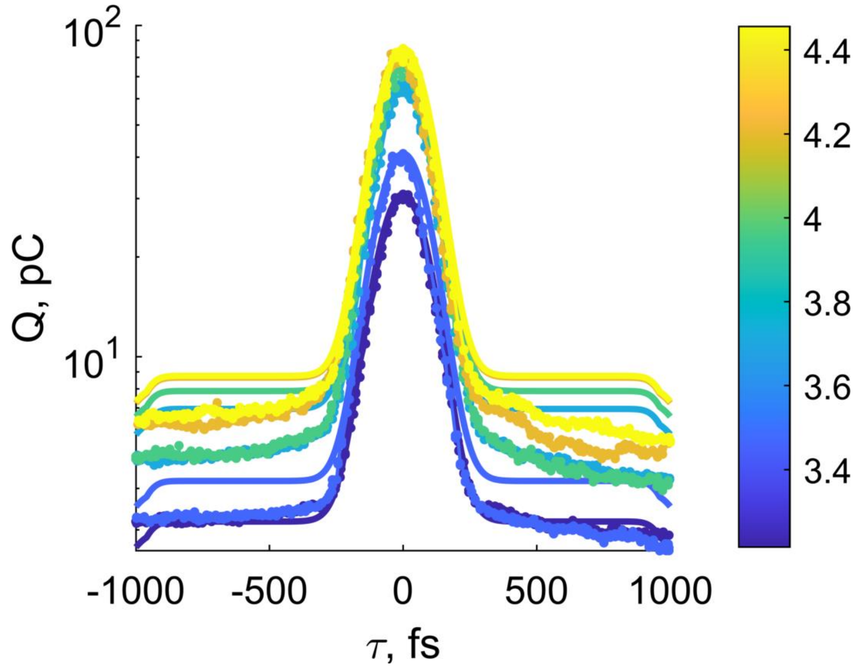
New Approach: Multiphoton Photoemission with 515 nm light



Nonlinear photoemission

Charge scales as laser power cubed

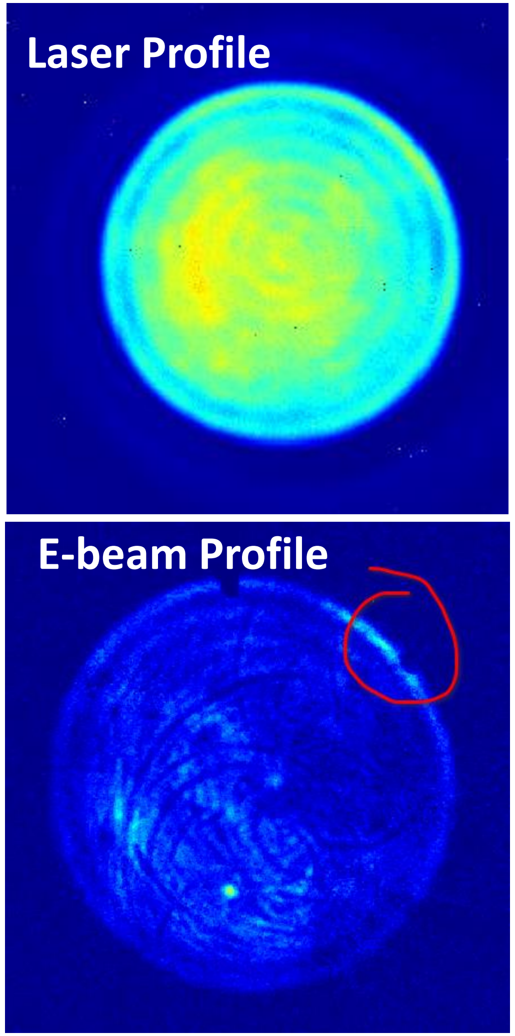
Demonstrated 165 pC, expect to increase

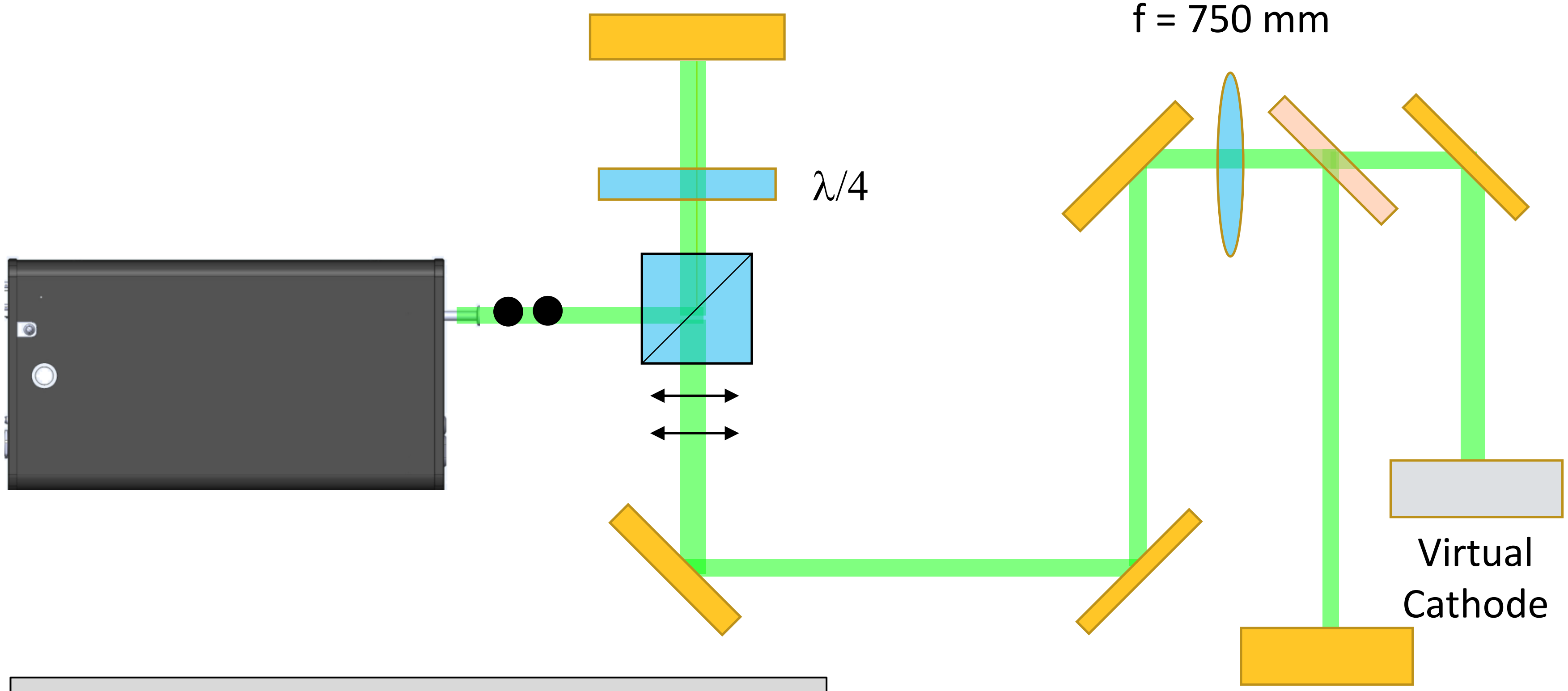


Charge autocorrelation indicates quasi-instantaneous response

Graves, Teitelbaum, Timms, et. al.

SLM-based adaptive photocathode beam shaping





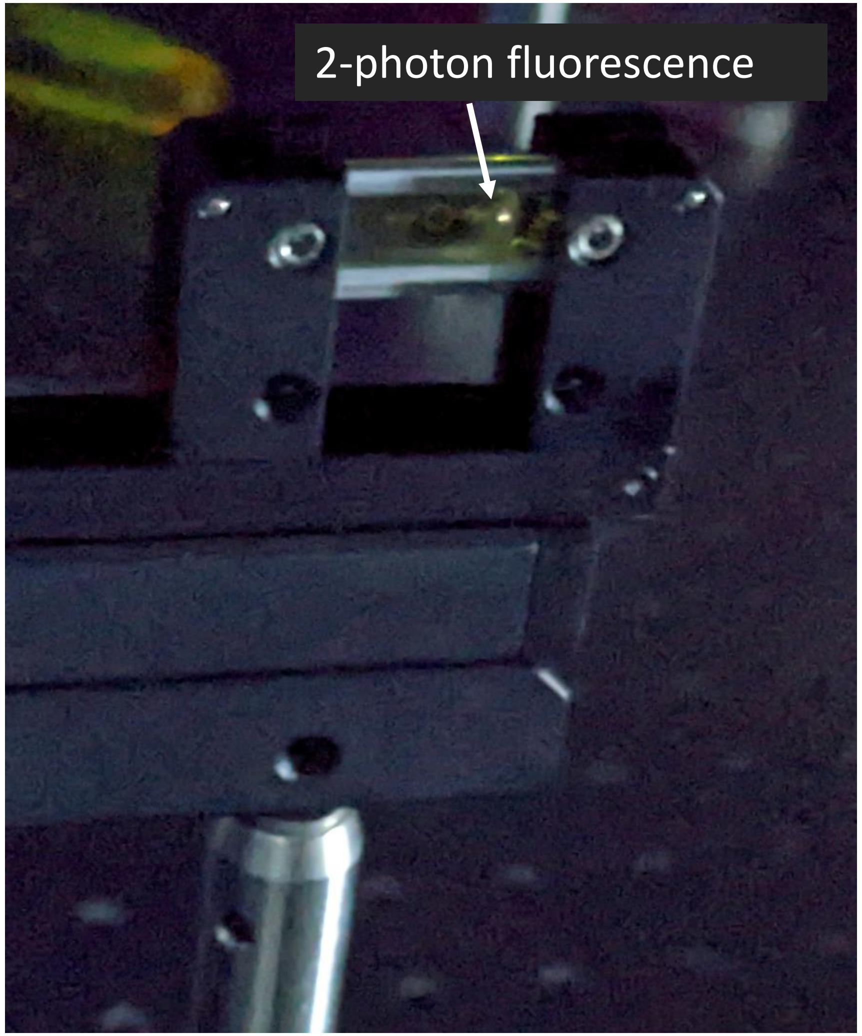
Secondary advantage of using nonlinear photoemission: more high-quality optics and commercially available beam shaping options available at 515 nm vs 257 nm

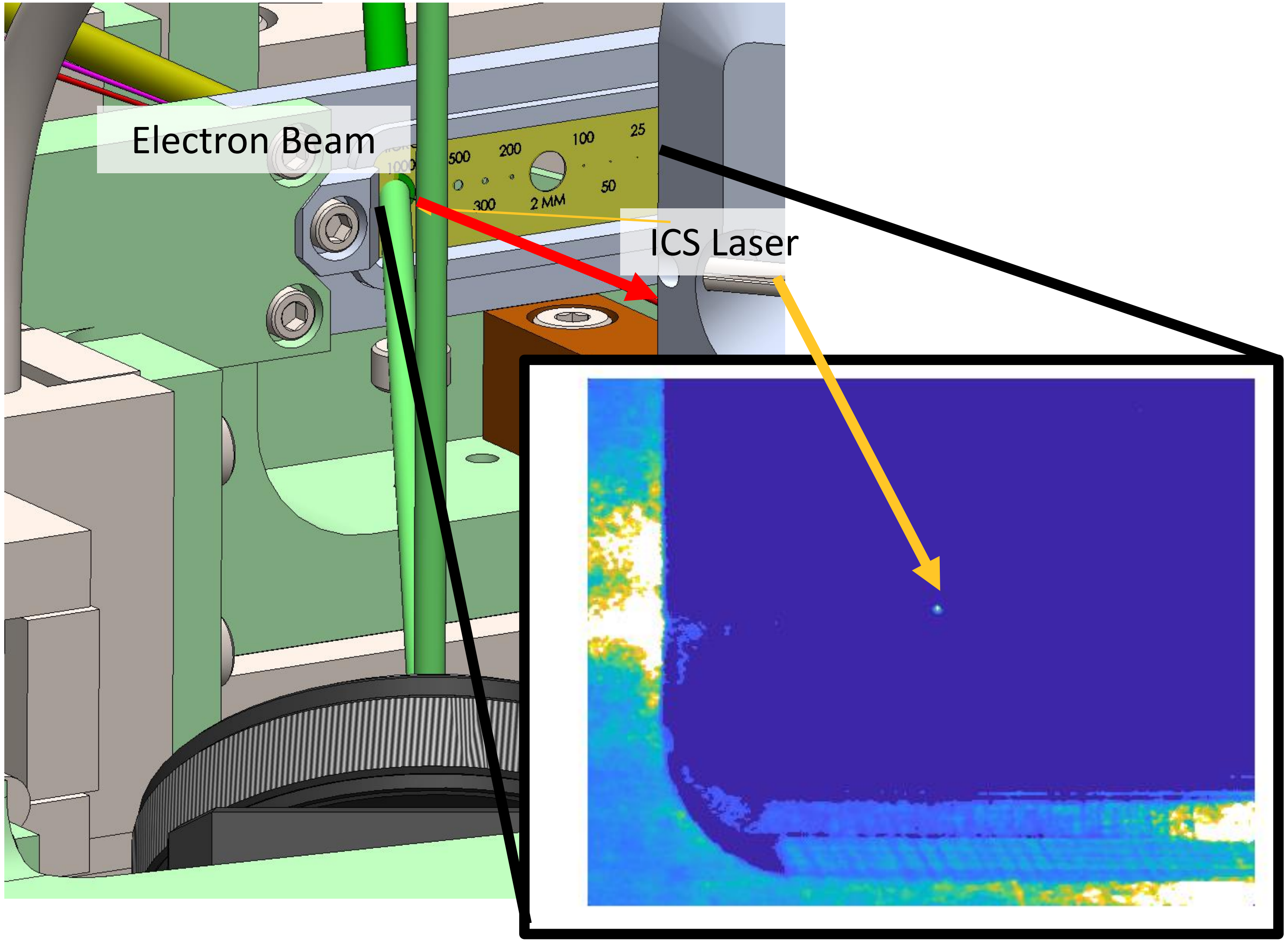
PRAB, 18, 023401 (2015)
Photonics 2024, 11, 1143 (2024)

CXFEL Labs NSF

Timms, Sandhu, et. al.

Spatial and Temporal Overlap: Two photon fluorescence





Teitelbaum, Graves, Holl, et. al.

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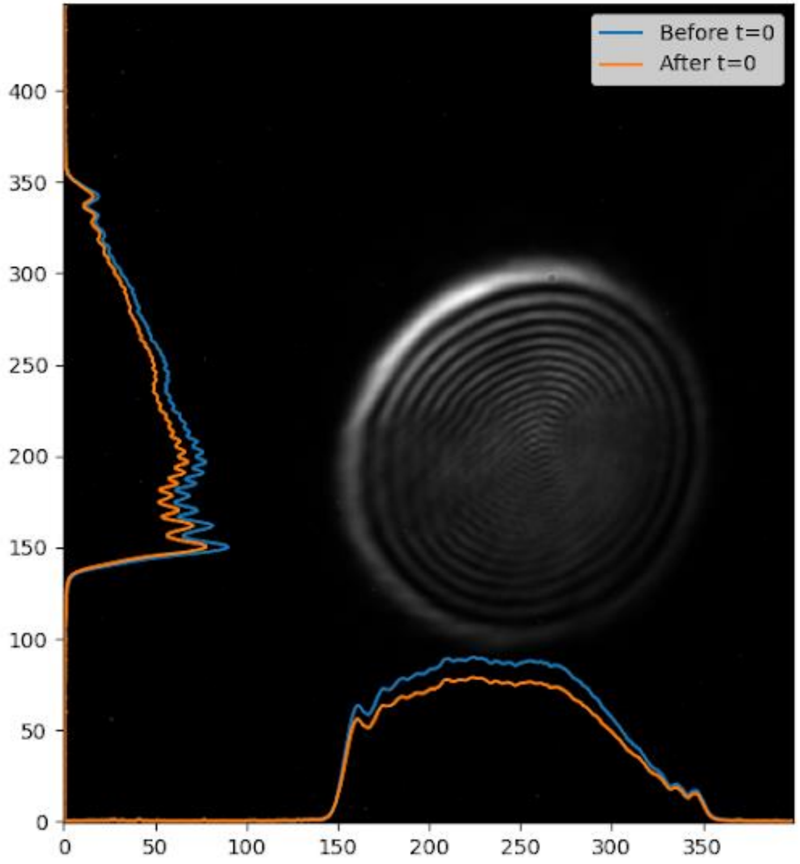
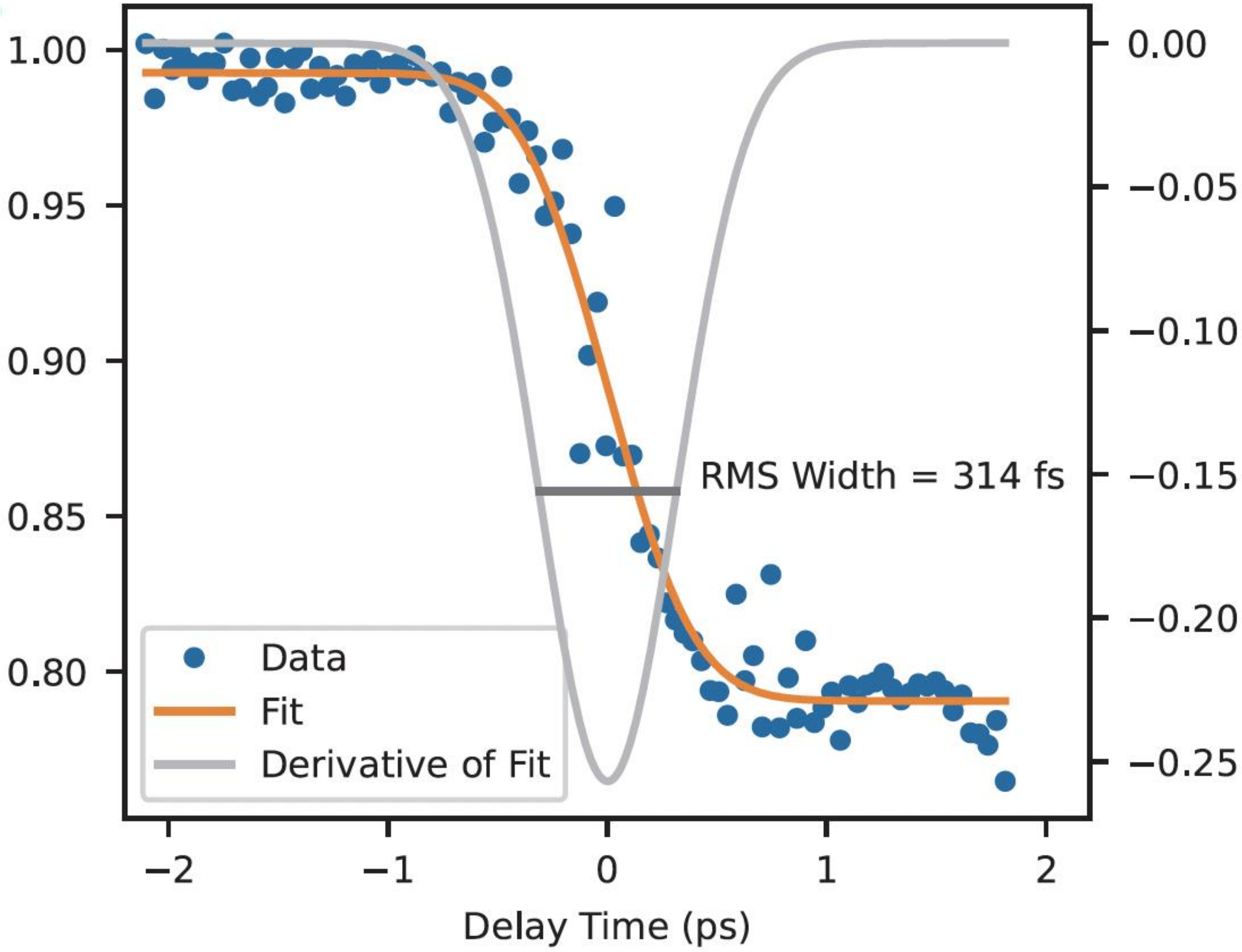
Spatial and Temporal Overlap: Transient YAG Transmission



Eckrosh et al
Rev. Sci. Instrum. 96, 123016 (2025)



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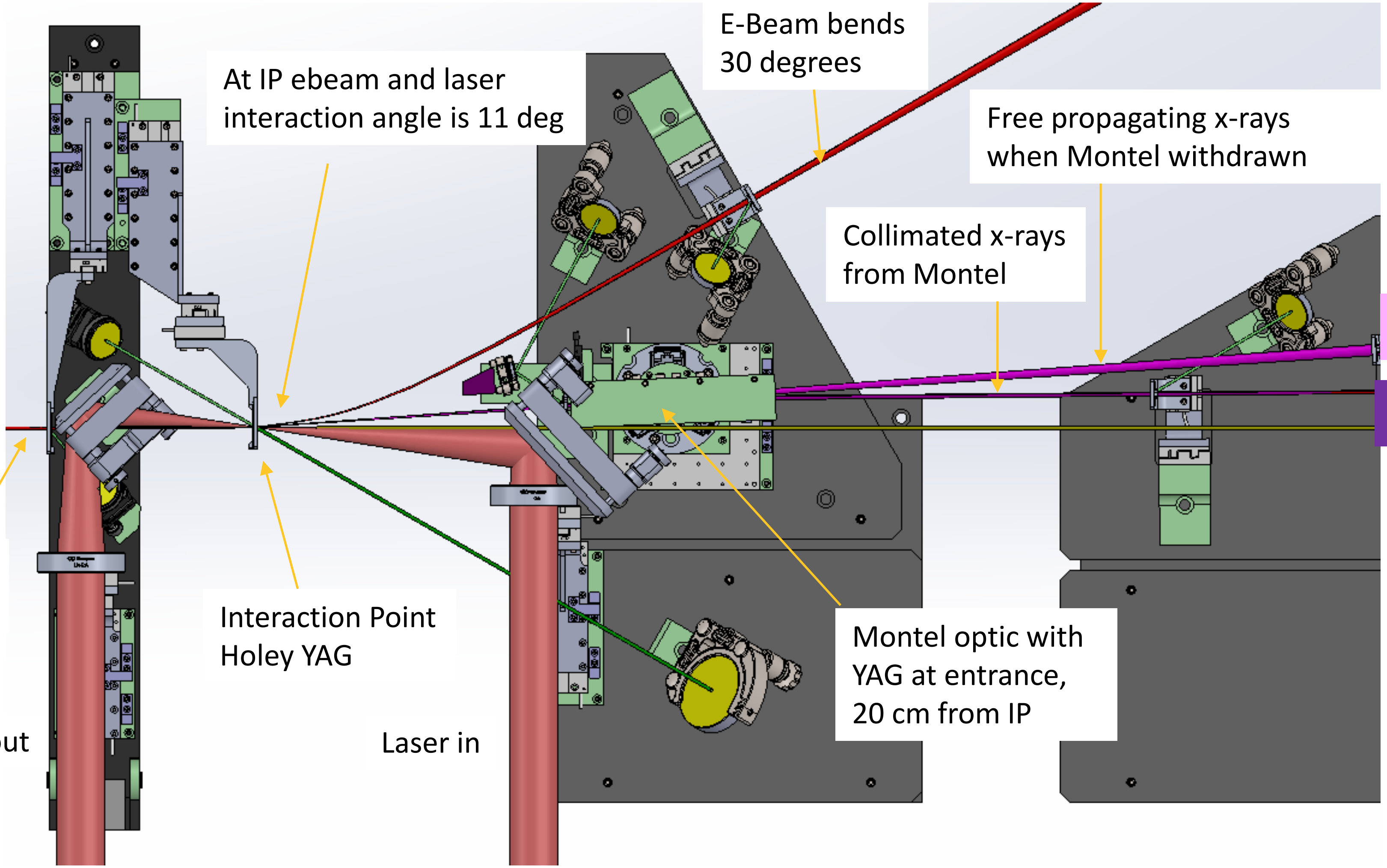
Interaction Chamber and X-ray Outputs

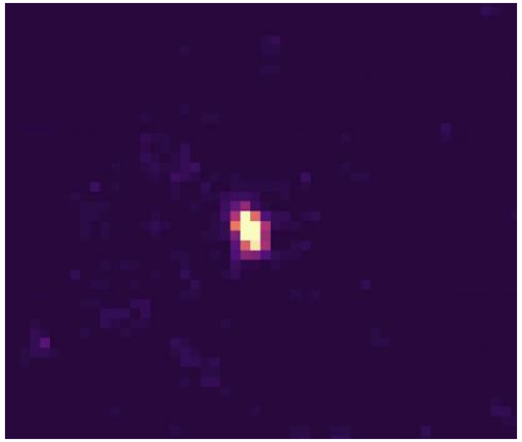


X-ray path (diverging)

X-ray path (collimated)

Current Commissioning Status

~5x10^{9} photons/sec



~5x10^{8} photons/sec

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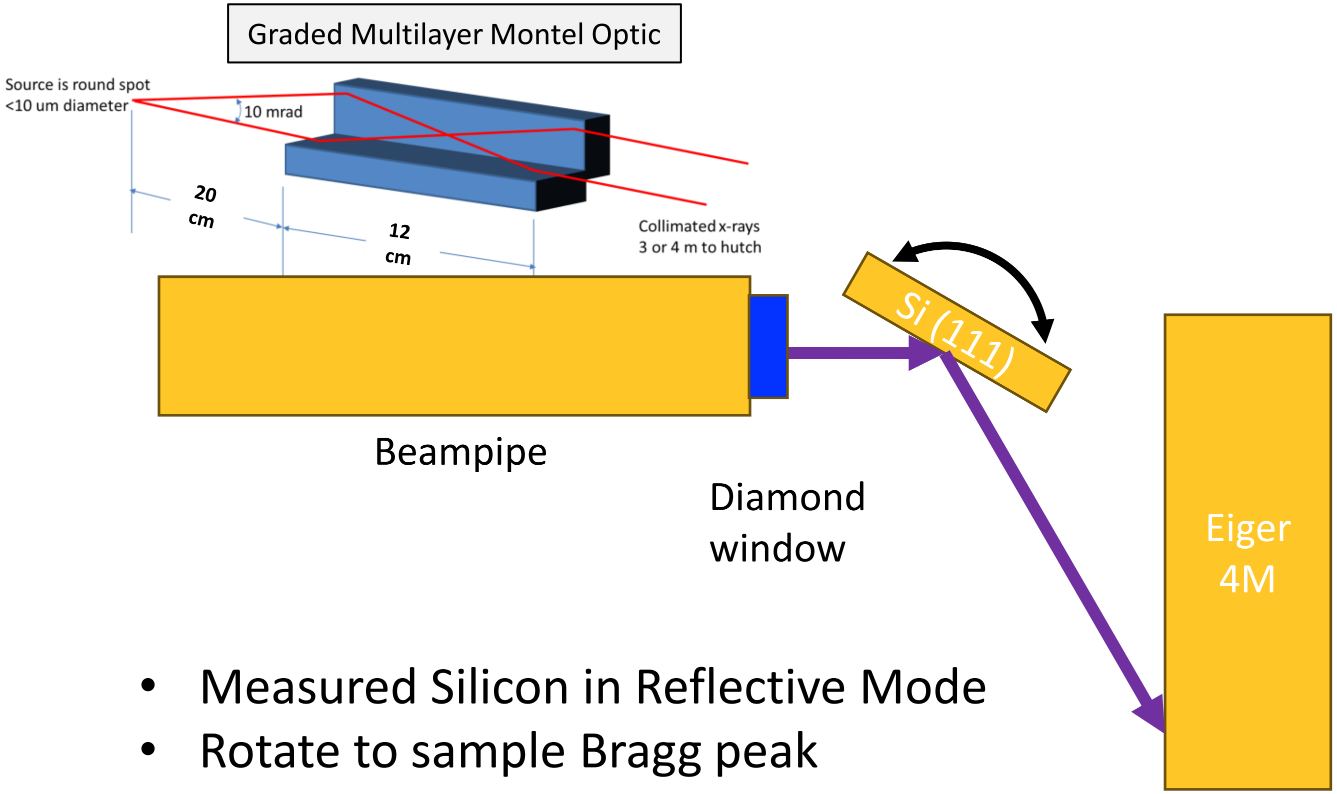
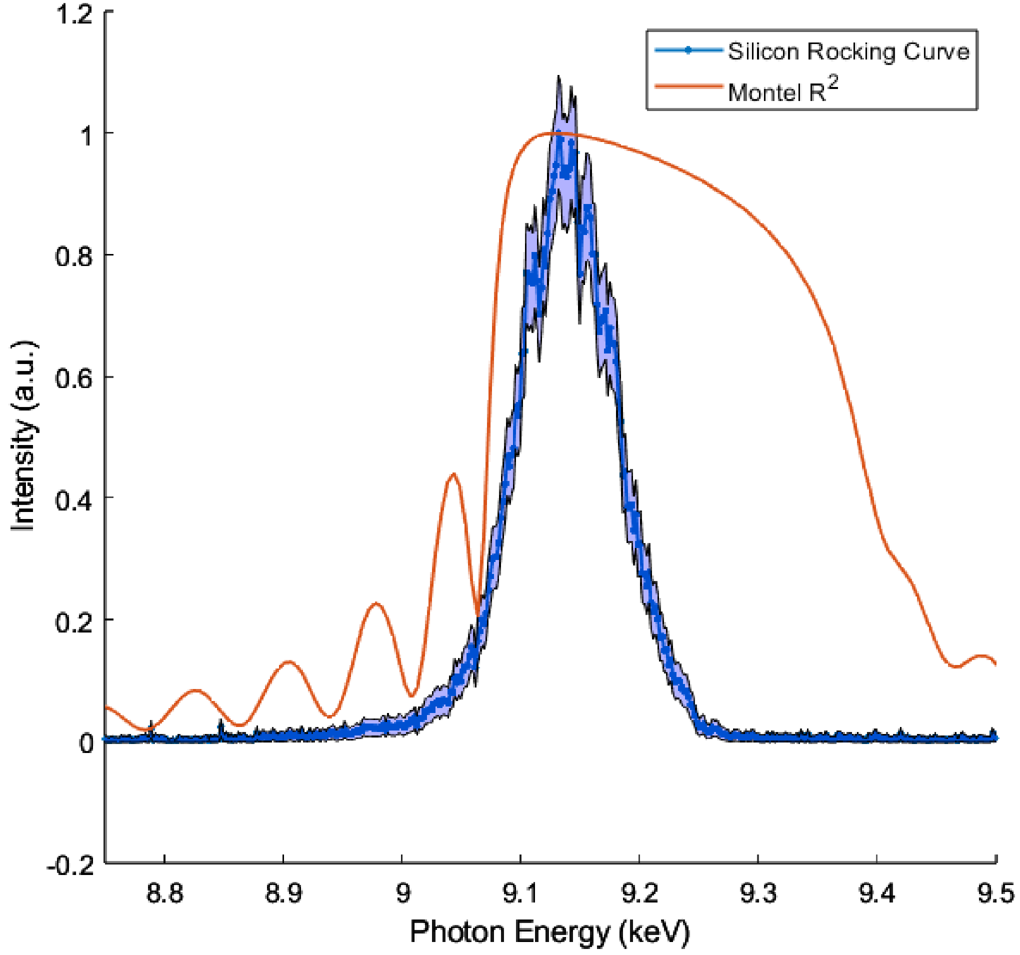
Bandwidth Measurement using Silicon Rocking Curve



- Measured Silicon in Reflective Mode
- Rotate to sample Bragg peak
- Estimate Energy Bandwidth



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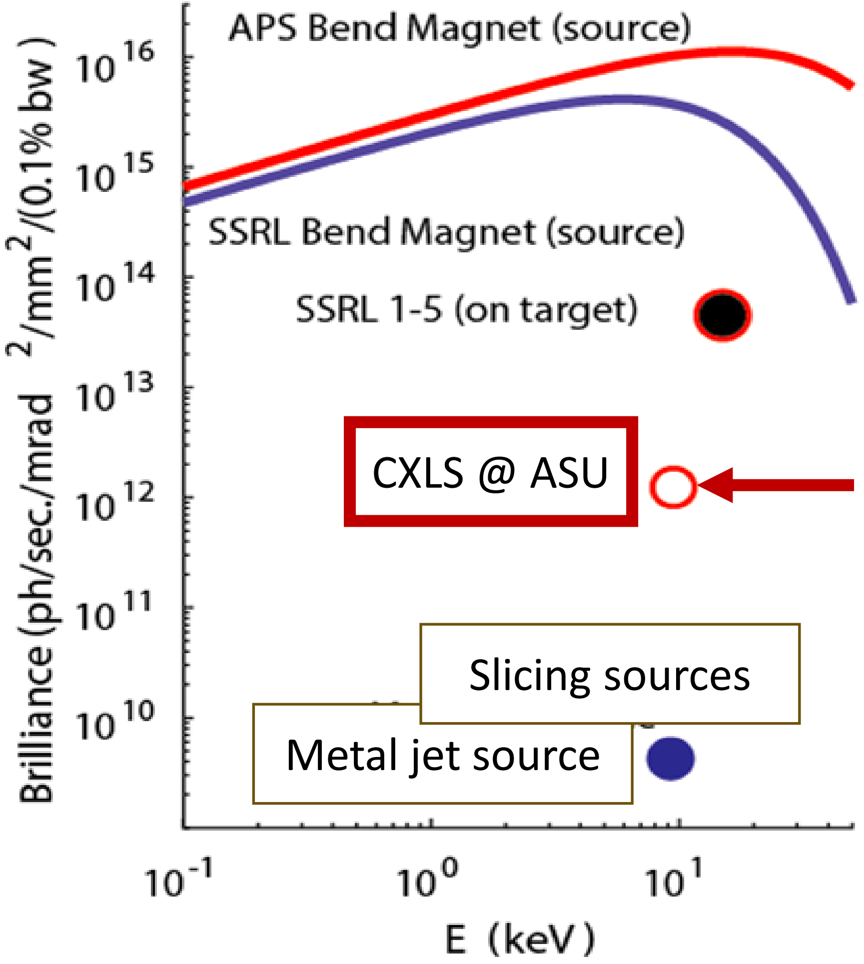
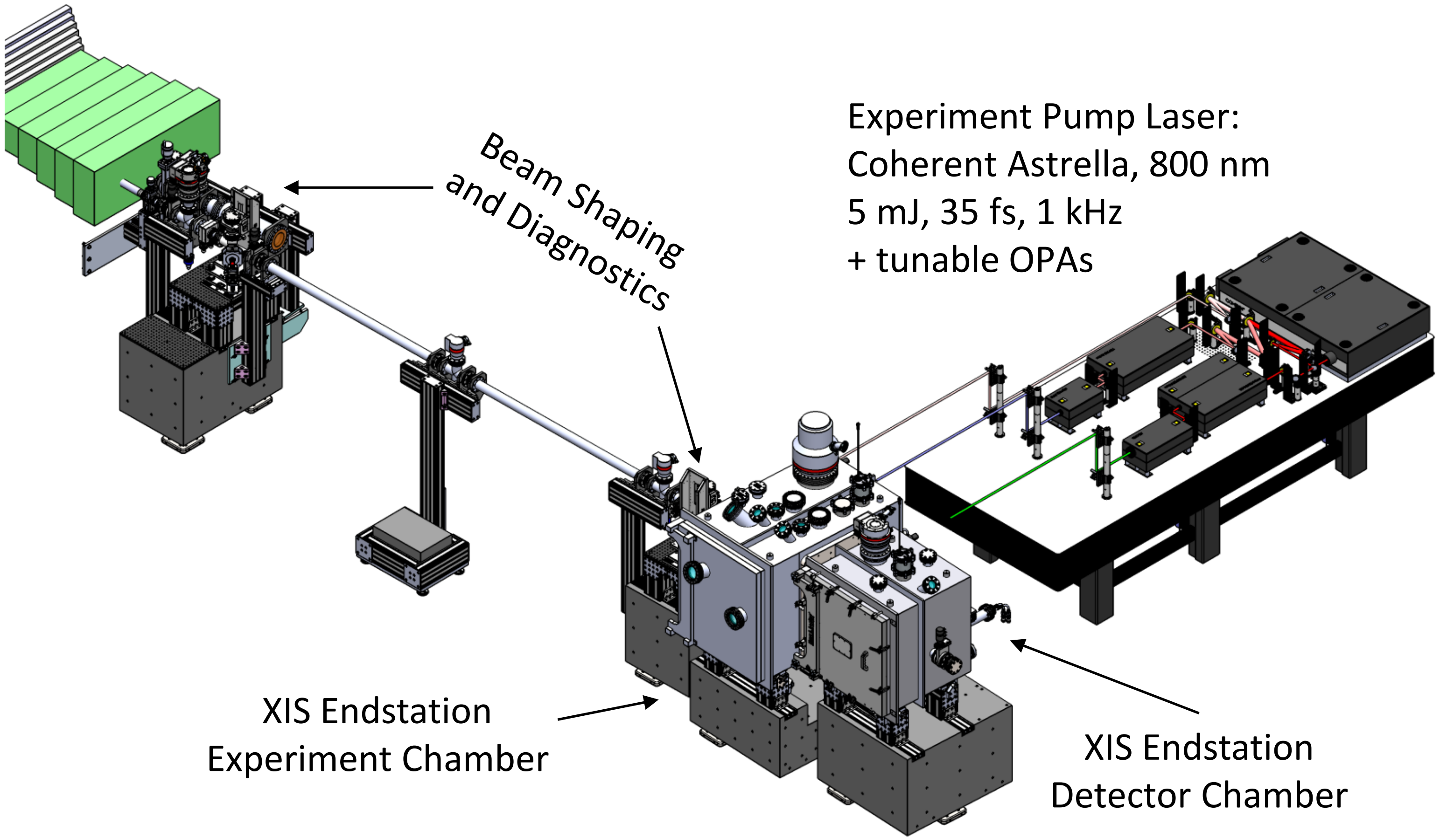
Compact Femtosecond Hard X-ray Source



- Easily tunable for applications
- Polarization variation on demand

Multimodal Experimental Endstation



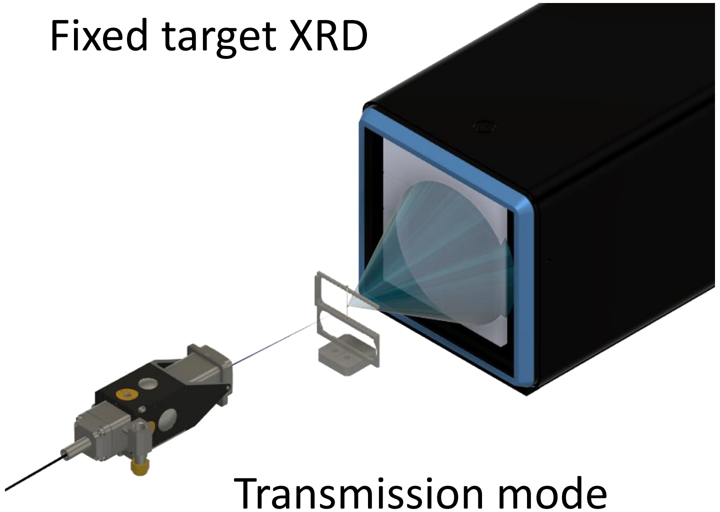
- Research Thrusts
  - Structural Biology (BIO)
  - Quantum Materials (QM)
  - Chemical Dynamics (AMO)
- Time-resolved capabilities
  - Pump-probe spectroscopy

Current Experiment Configurations

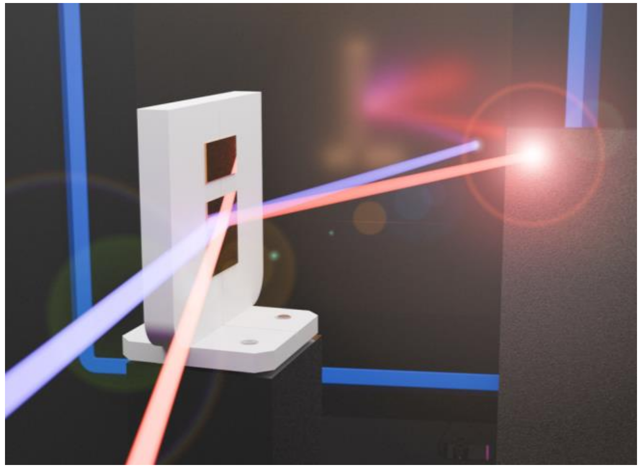
X-ray diffraction imaging and spectroscopy

- Fixed photon energy: 9.3 keV
- Time resolved capabilities
- Techniques
    - Crystallography (XRD)
    - Solution phase scattering (SAXS/WAXS)
    - X-ray emission spectroscopy (XES)
- Fixed target
    - Transmission/reflection mode
    - 1- and 2-axis goniometric stages
- Liquid jet injection (planned)
- In-air and in-vacuum capabilities

Fixed target XRD

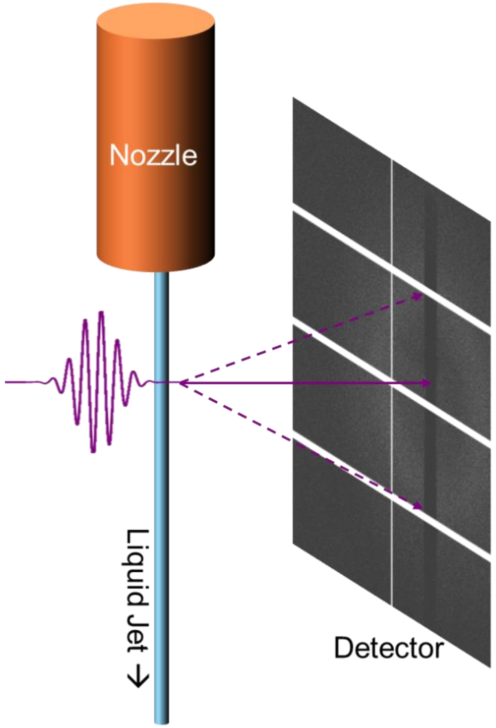


Transmission mode



Reflection mode

Jet injection XRD



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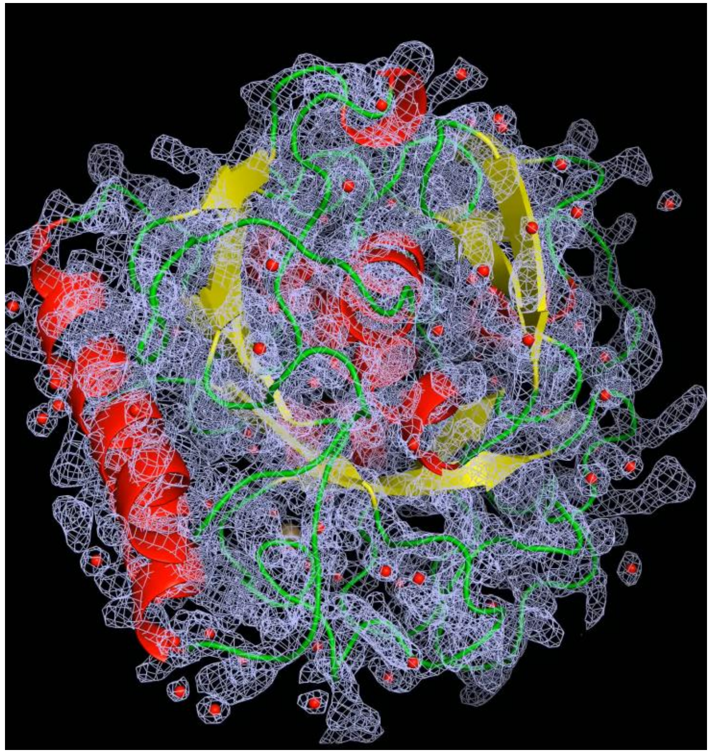
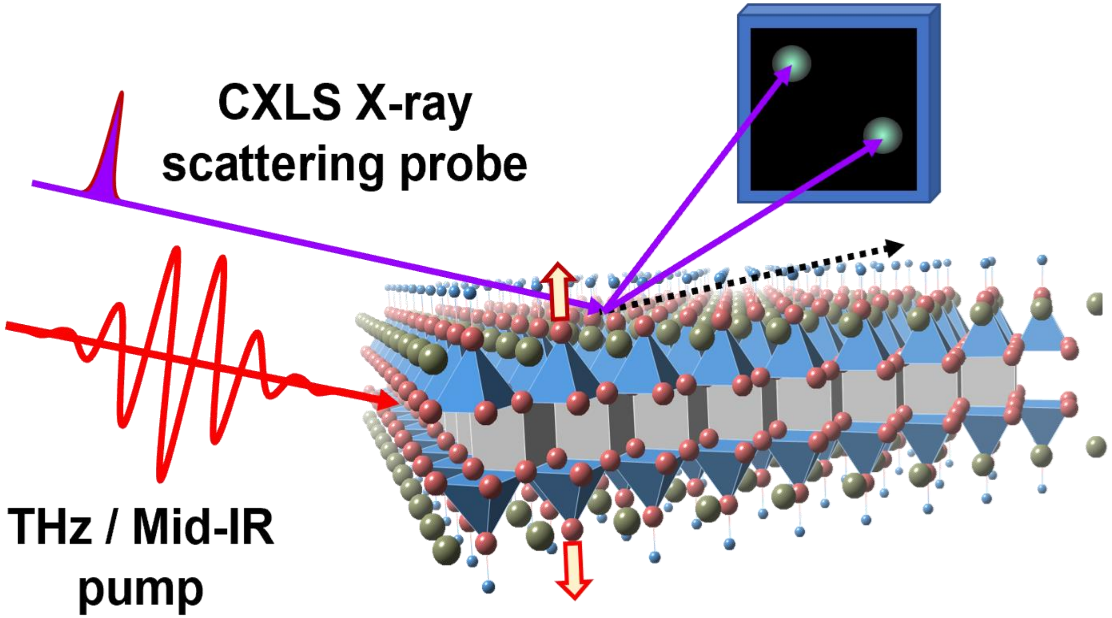
CXLS Applications

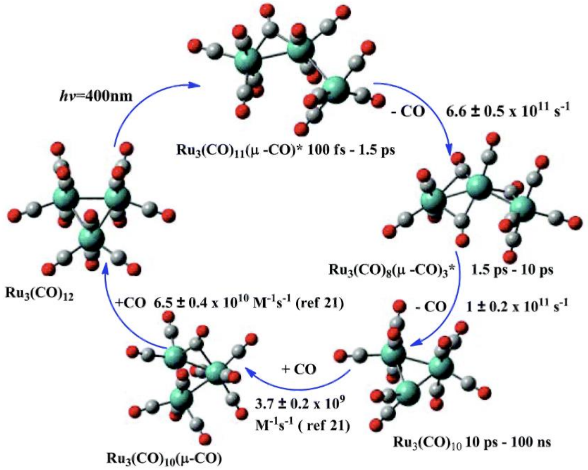
Bio: Protein Structure



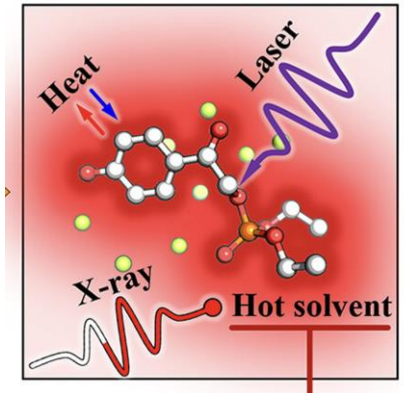
Materials: TR-XRD



Solution Scattering



Photochem. Photobiol. Sci. 18, 319 (2019)



J. Phys. Chem. Lett. 14, 3103 (2023)

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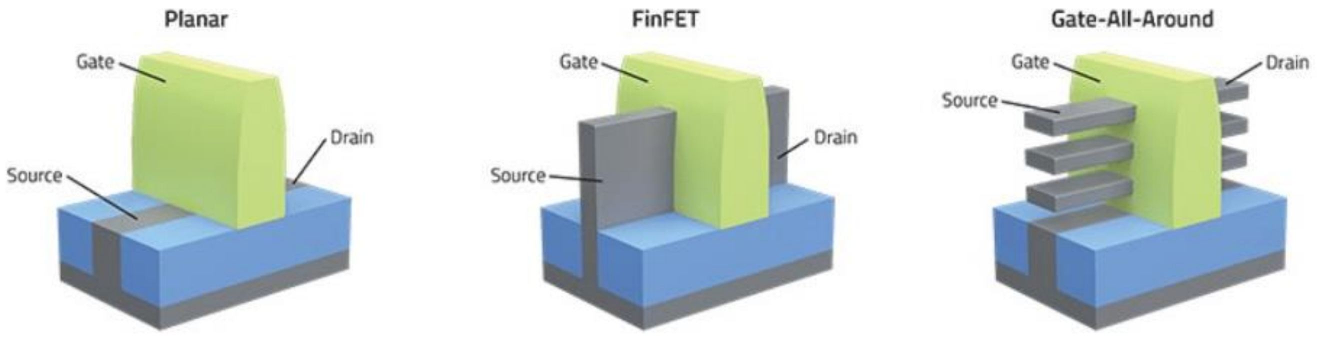
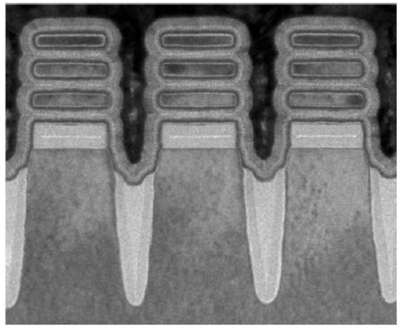
Semiconductor and Medical Applications

Chips Metrology

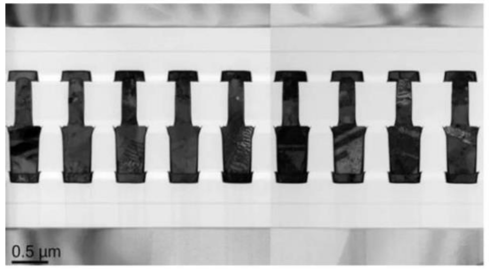


2 nm nanosheet gate-all-around



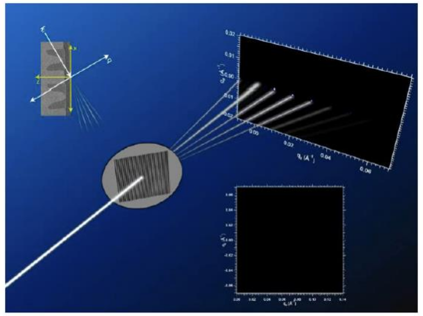
ibm.com

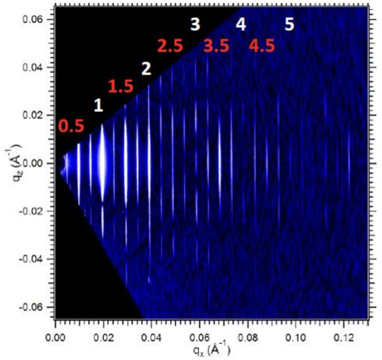
Advanced Packaging



imec

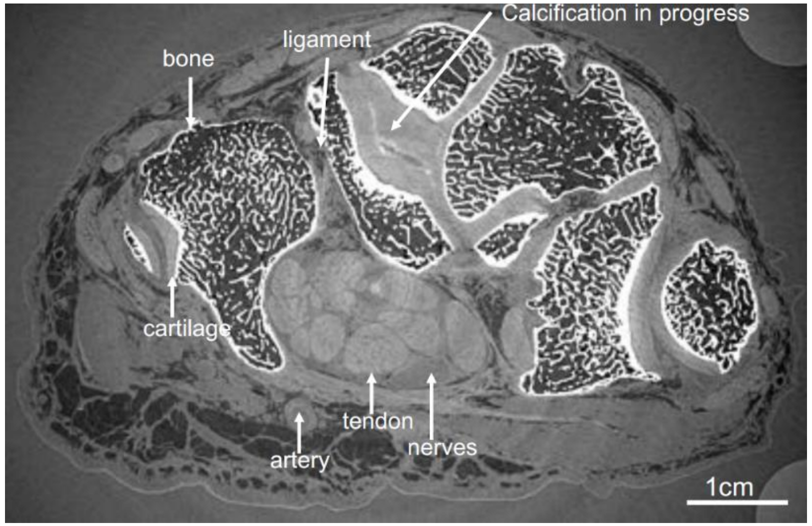
CDSAXS



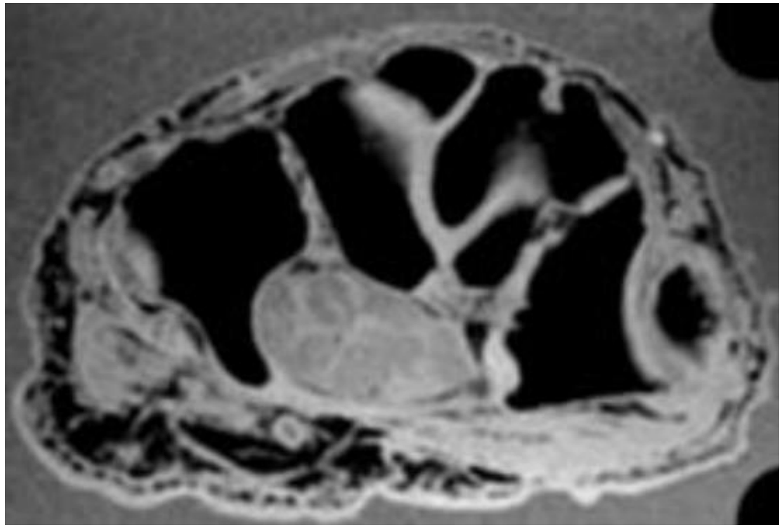


Courtesy: Joe Kline

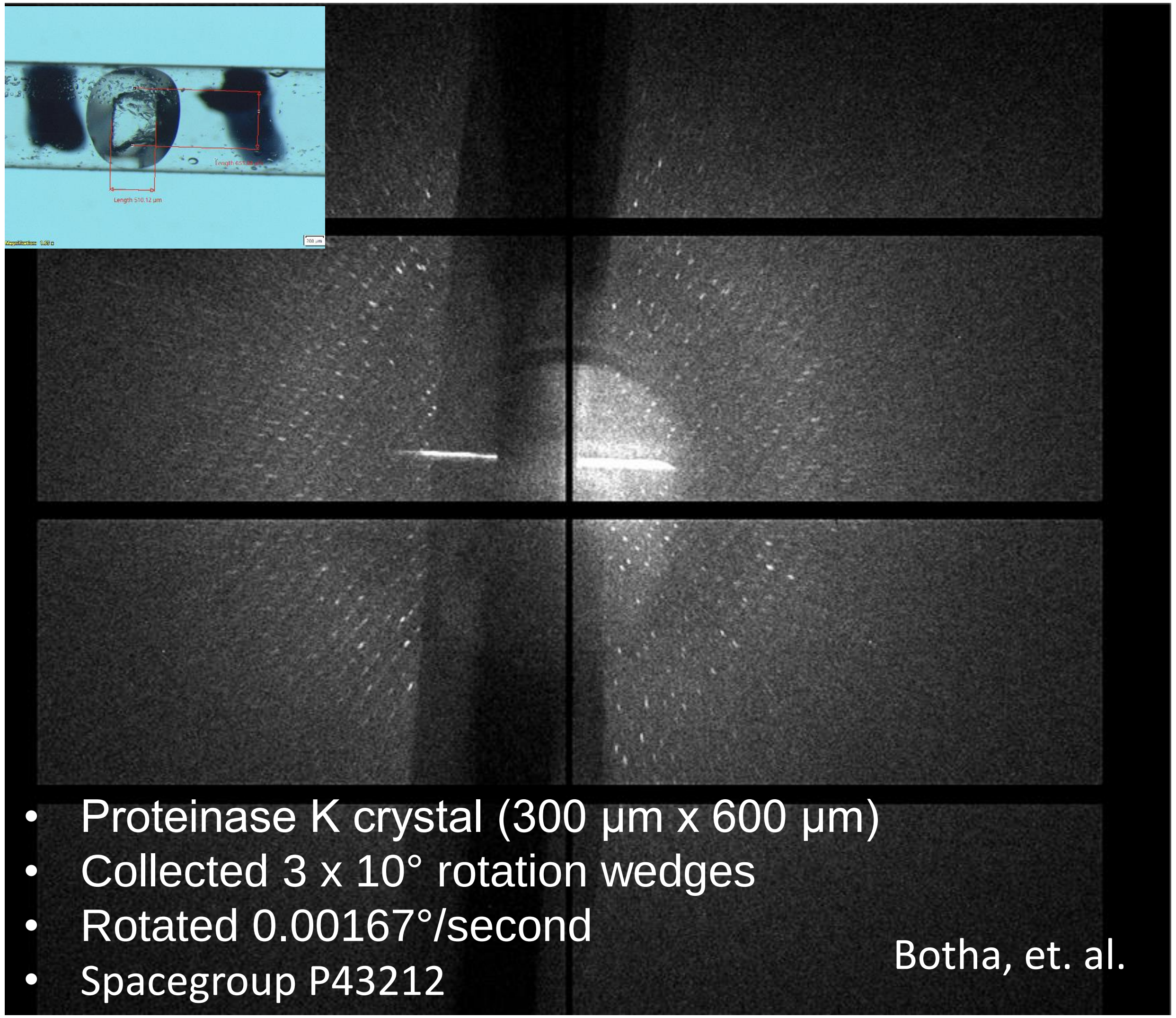
Phase Contrast X-ray Imaging



MRI



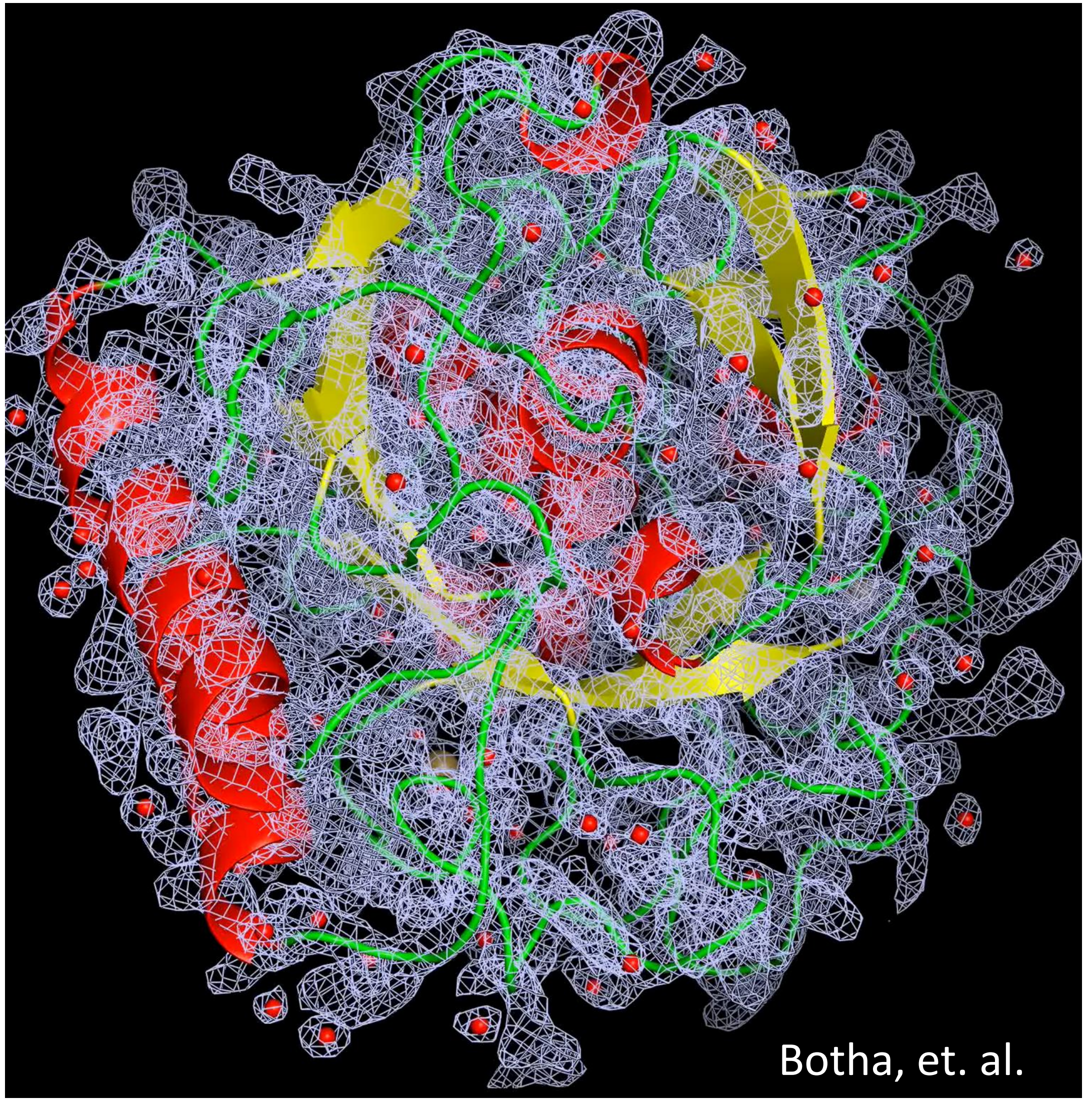
First experiment: Protein Structure Determination



- Proteinase K crystal (300 µm x 600 µm)
- Collected 3 x 10° rotation wedges
- Rotated 0.00167°/second
- Spacegroup P43212

Botha, et. al.

Proteinase K from *Tritirachium album Limber* 2Å resolution.
2Fo-Fc map contoured at 1.0σ, secondary structure.



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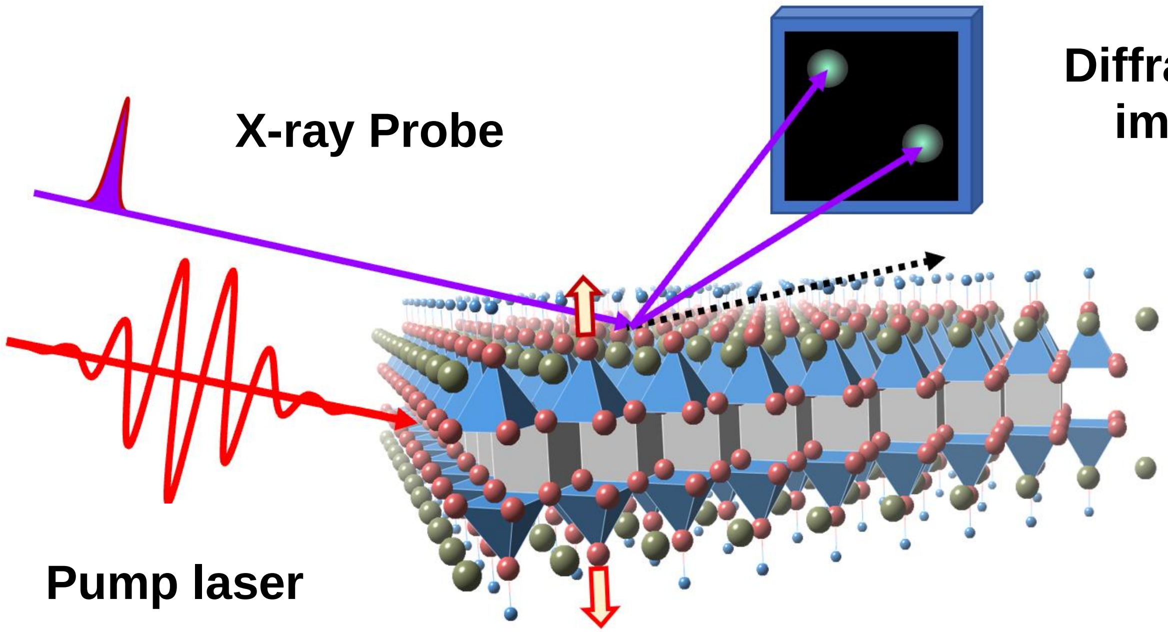
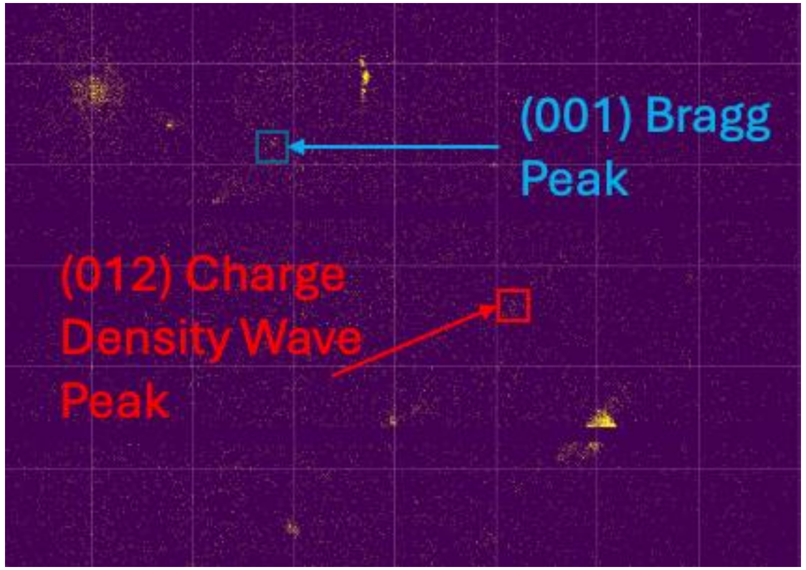
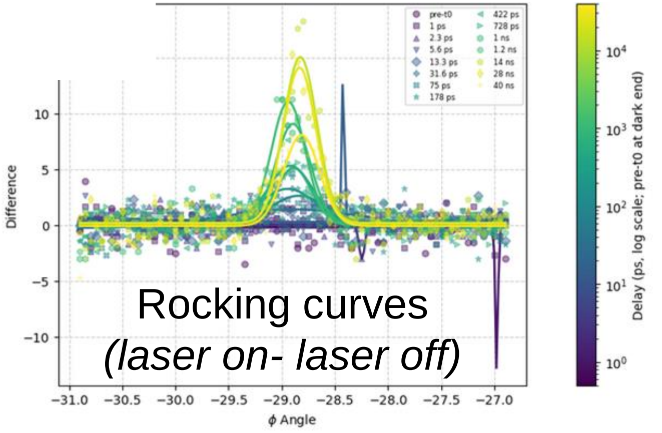
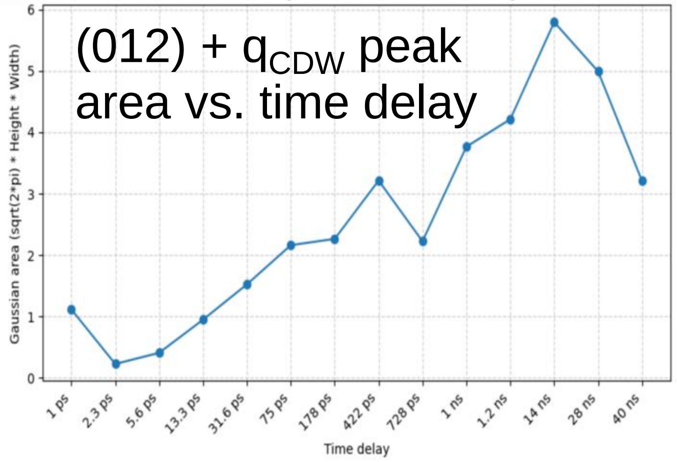
Time-resolved Experiment in a Quantum Materials

Light-induced phase transition of charge density wave









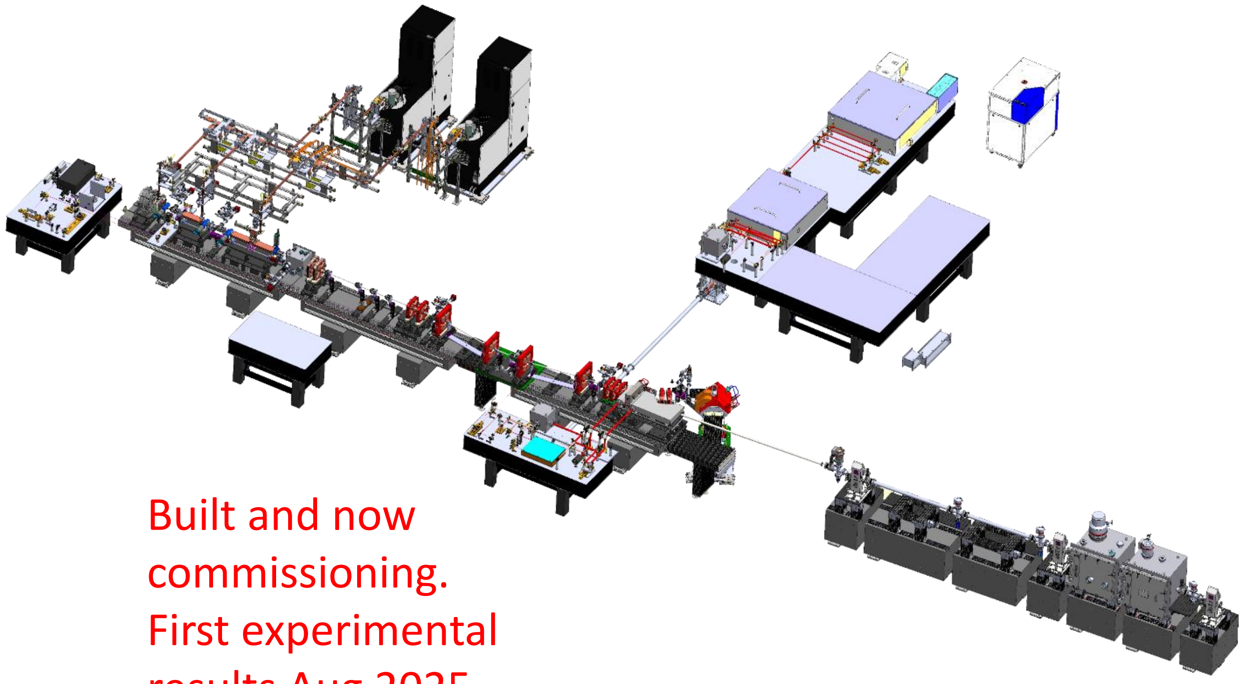
Teitelbaum, et. al.

NSF ASU Biodesign Institute Arizona State University CXFEL Labs

CXFEL: A two-phase project at ASU leading to a compact coherent x-ray laser

Compact X-ray Light Source (CXLS)

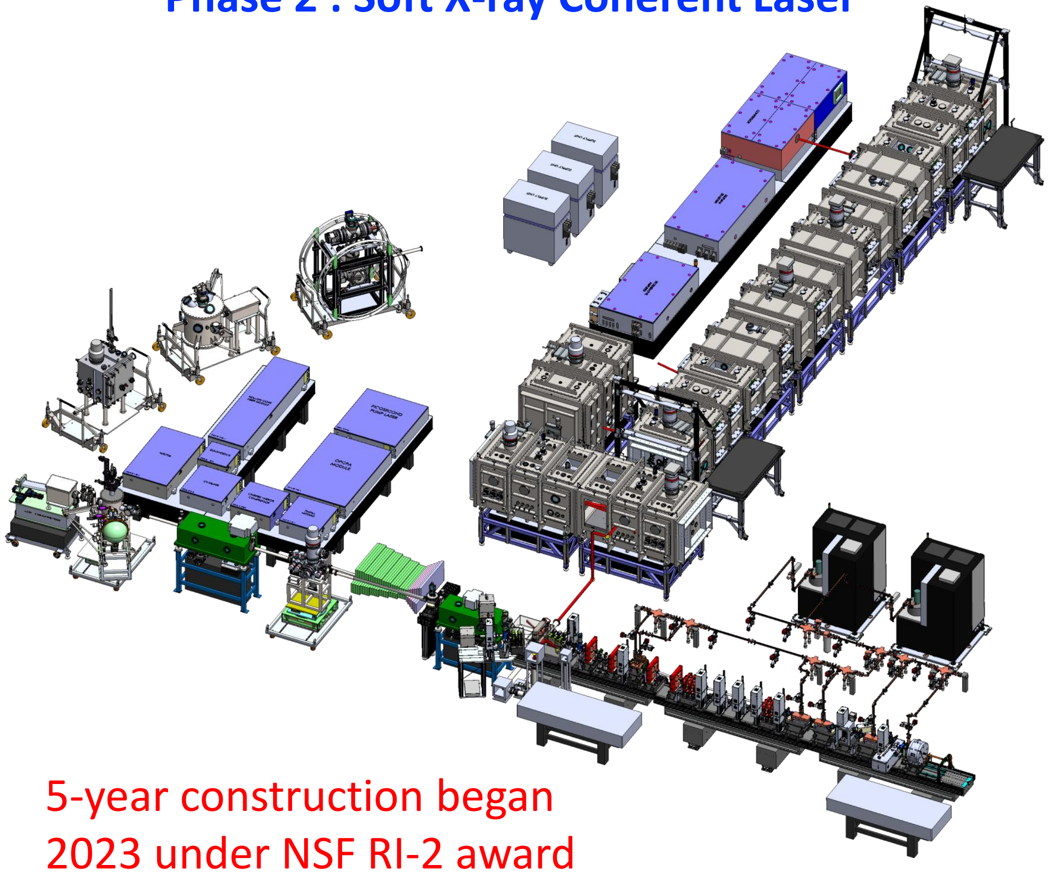
Phase 1 : Hard X-ray ICS Source



Built and now commissioning. First experimental results Aug 2025

Compact X-ray Free Electron Laser (CXFEL)

Phase 2 : Soft X-ray Coherent Laser



5-year construction began 2023 under NSF RI-2 award

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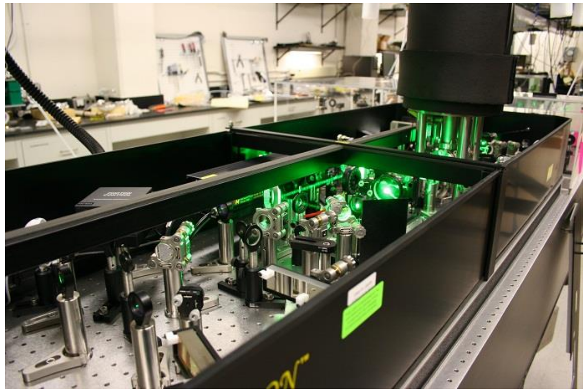
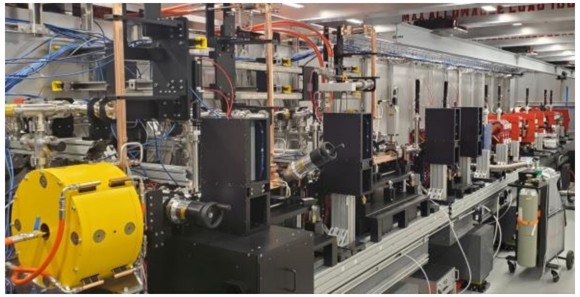
Need for a compact coherent x-ray source

Table-top Laser Harmonics



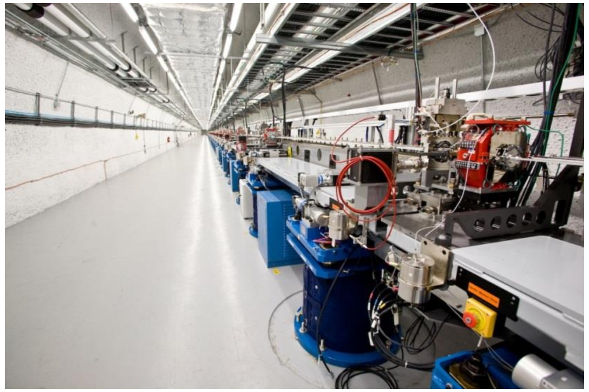
Size ~ 1 meter

Compact X-ray Free Electron Laser (CXFEL)



Size ~ 10 meter

Free Electron Laser (FEL)



Size ~ 1000 meter

	Laser Harmonics	ASU CXFEL	Free Electron Laser
Pulse duration	0.1-10 fs	0.5-10 fs	1-100 fs
Photon energy	0.02-0.1 keV	0.1-10 keV	1-10 keV
Pulse energy	1 nJ	10 nJ	1000 nJ
Size	1 m	10 m	1000 m
Cost	$1 M	$10 M	$1000 M

CXFEL Parameters

Photon Energy	250	1000	2500	eV
Average flux	8.0×10^{11}	1.1×10^{11}	4.4×10^{10}	photons/sec
Peak brilliance	1.2×10^{28}	5.6×10^{28}	1.4×10^{29}	photons/(s .1% mm^{2}mrad^2)
RMS source size	0.9	0.5	0.3	um
RMS source divergence	440	188	117	urad
Photons per pulse	8.0×10^{8}	1.1×10^{8}	4.4×10^{7}	Photons/shot
Pulse length FWHM	1-20	0.6-20	0.5-10	fs
Bandwidth FWHM	0.01 - 1	0.01 - 1	0.01 - 1	%
RMS timing jitter	<10	<10	<10	fs
Repetition rate	1000	1000	1000	Hz

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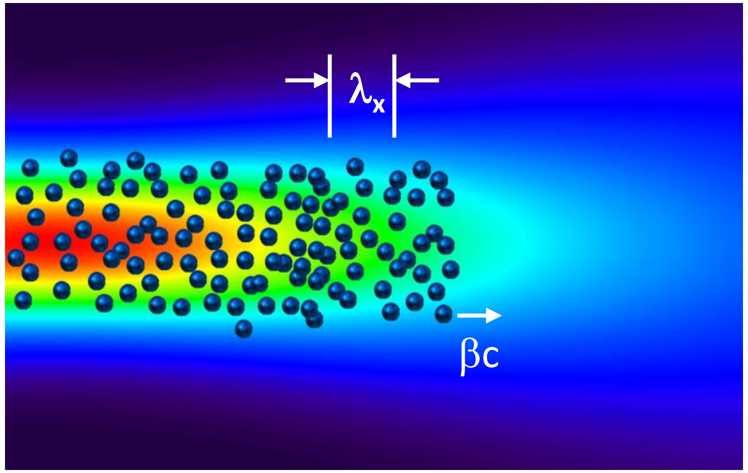
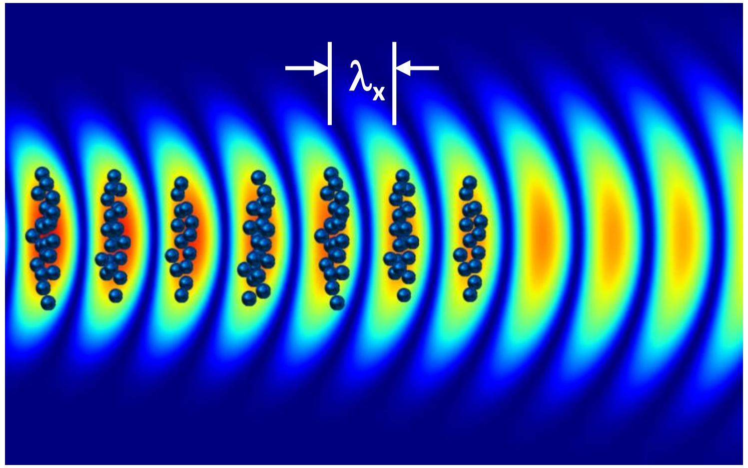
CXFEL: Coherent X-rays Require Coherent Electron Bunching



Random electron positioning for Undulator radiation through Inverse Compton Scattering (ICS)

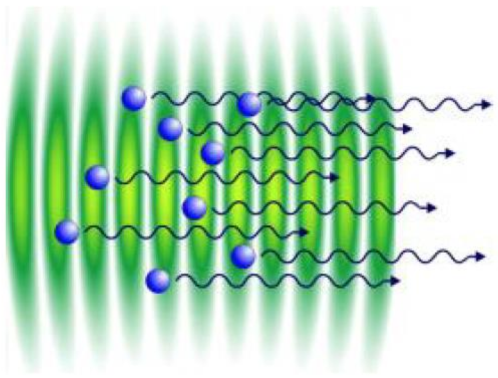


Coherently bunched electrons for **XFEL** radiation through coherent ICS
→ Compact **CXFEL**

$$\lambda_d = \lambda_{x-ray}$$

$$E_{x\text{-}ray} = 1\ \text{keV}\ \lambda_d = 1.24\ \text{nm}$$

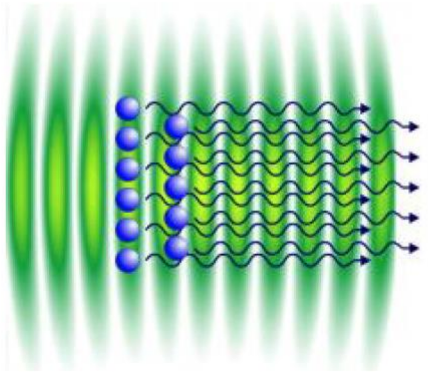
- **Randomly distributed electron beam**



Regular:

$I_{x\text{-ray}} \sim N$

- **Bunched electron beam**



Coherent:

$I_{x\text{-ray}} \sim N^2$

$N > 10^6$

Graves et al, Phys Rev Lett 108, 263904 (2012)

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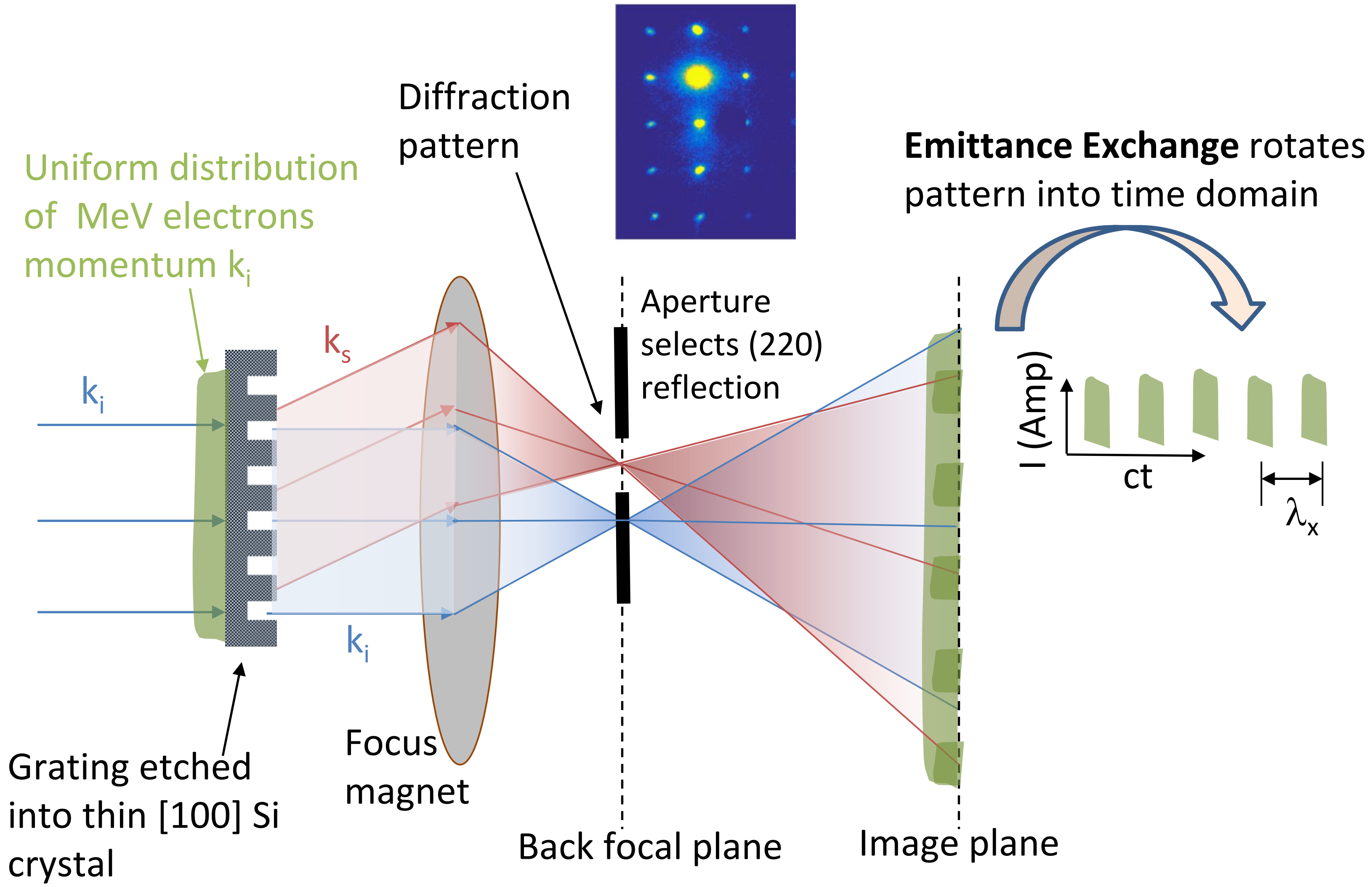
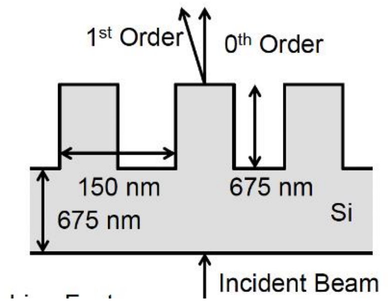
Nanopatterning Electrons via Diffraction



- Tune the modulation spacing of the diffracted beam with patterned Si substrate

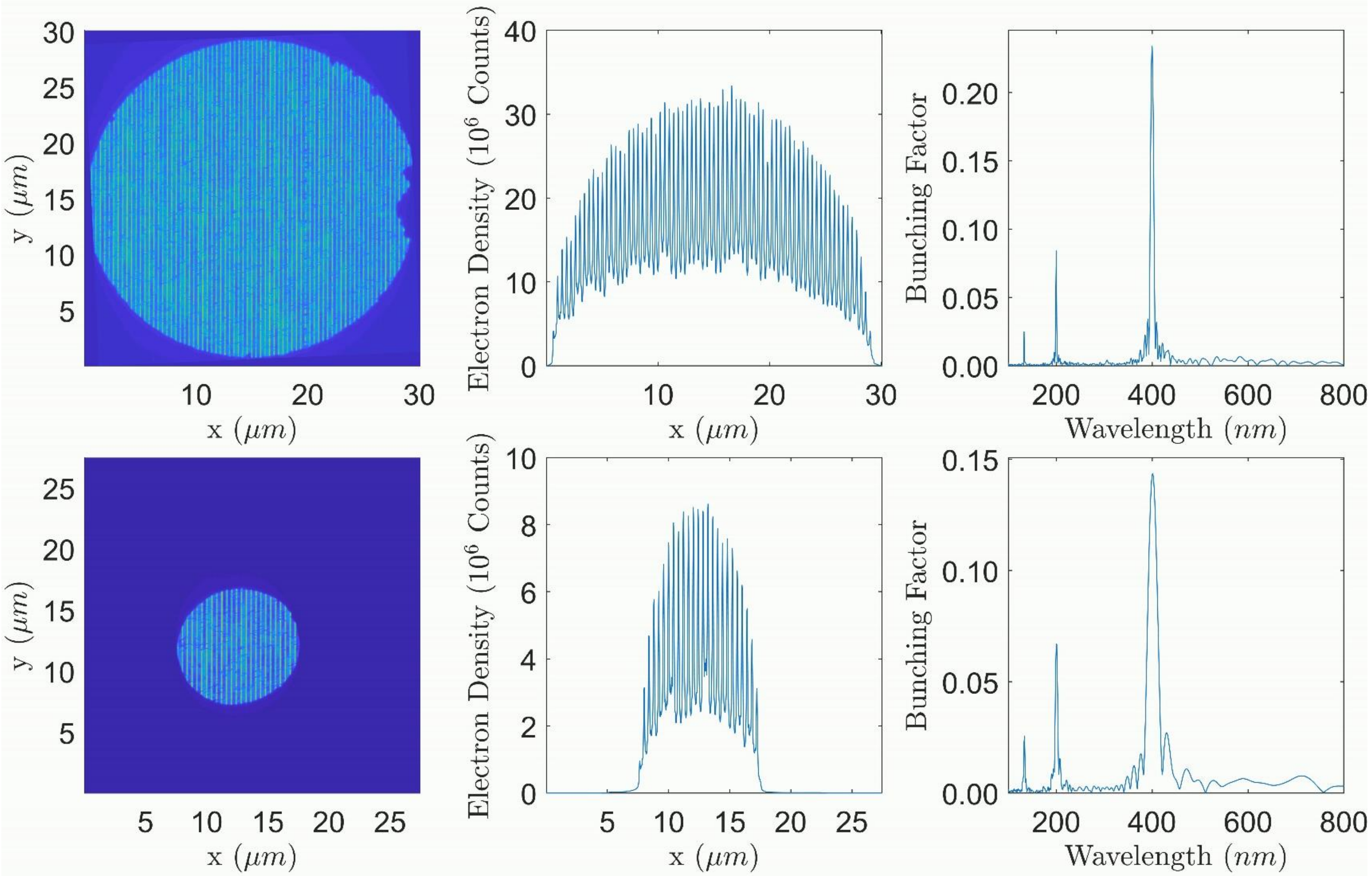


Phys. Rev. Acc. Beams **21**, 014401 (2018)

CXFEL Labs

Pulse Length and Bandwidth Control

Varying ebeam spot size on grating controls CXFEL x-ray pulse length and bandwidth.
Unique deterministic control of these properties



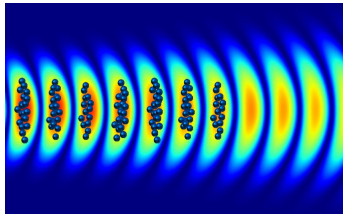
After diffraction and acceleration use emittance exchange to convert transverse pattern to temporal pattern

Malin, Graves, et. al.

CXFEL: Laser Requirements for ICS

a_0^2 is small (Order 0.05)

Undulator Wavelength



Target wavelength ~ 1 nm

$$\lambda_x = \frac{\lambda_u\left(1 + \frac{a_0{}^2}{2}\right)}{2\gamma^2}$$

~60 (for optimal beam properties)

$$\lambda_u = 1\,nm \times 2(60)^2 = 7.2\mu m$$

No high-power, high rep-rate lasers available. How do we achieve this?

Overtaking Geometry for longer wavelength

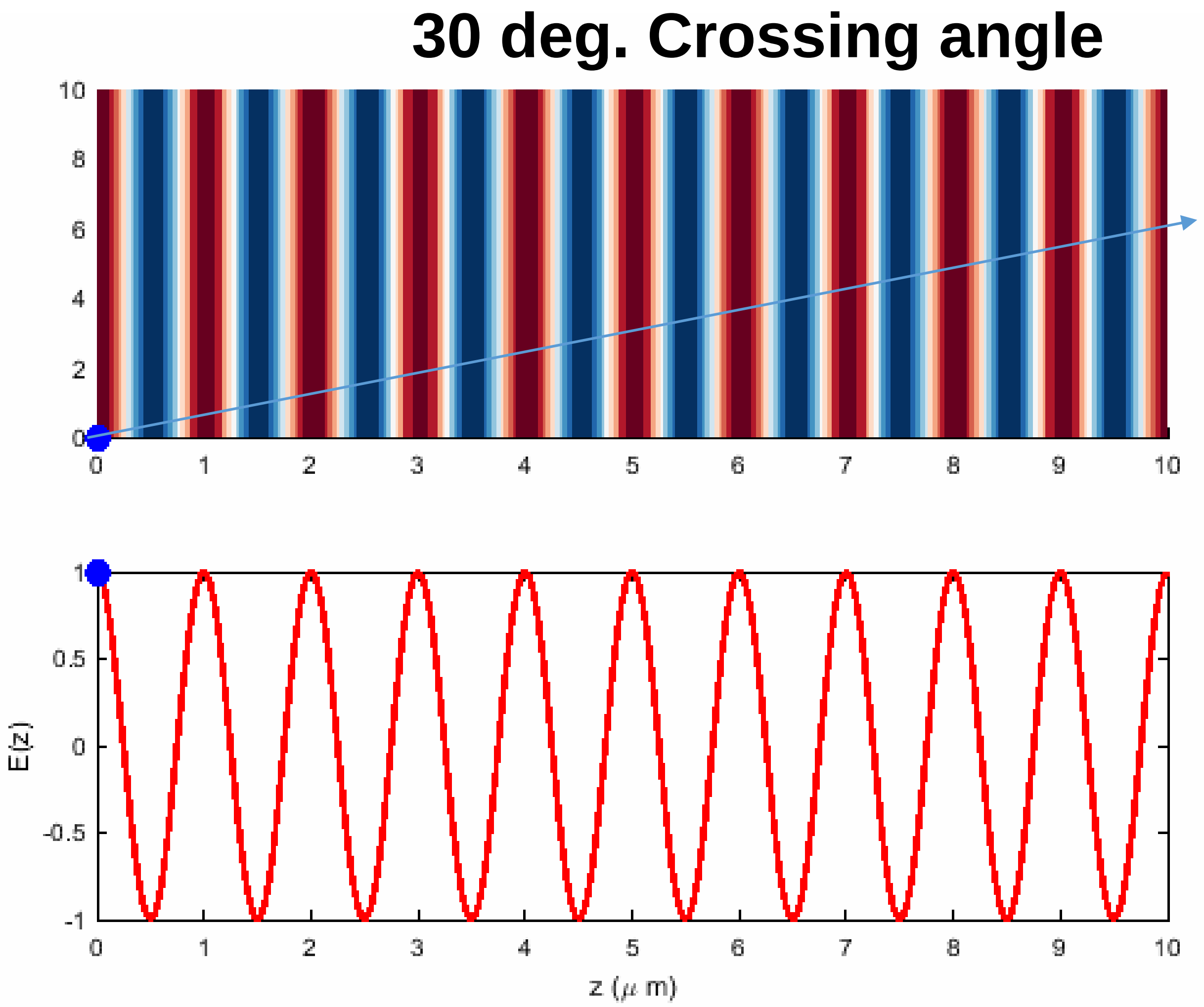
$$a_0 = \lambda_l \sqrt{\frac{I}{13.7\ GW}}$$

X-ray wavelength

Laser wavelength

$$\lambda_x = \frac{\lambda_u (1 + \frac{{a_0}^2}{2})}{2\gamma^2 (1 - \beta \cos \phi)}$$

Crossing angle



Teitelbaum et. al.

Overtaking Geometry: High intensity over long focus

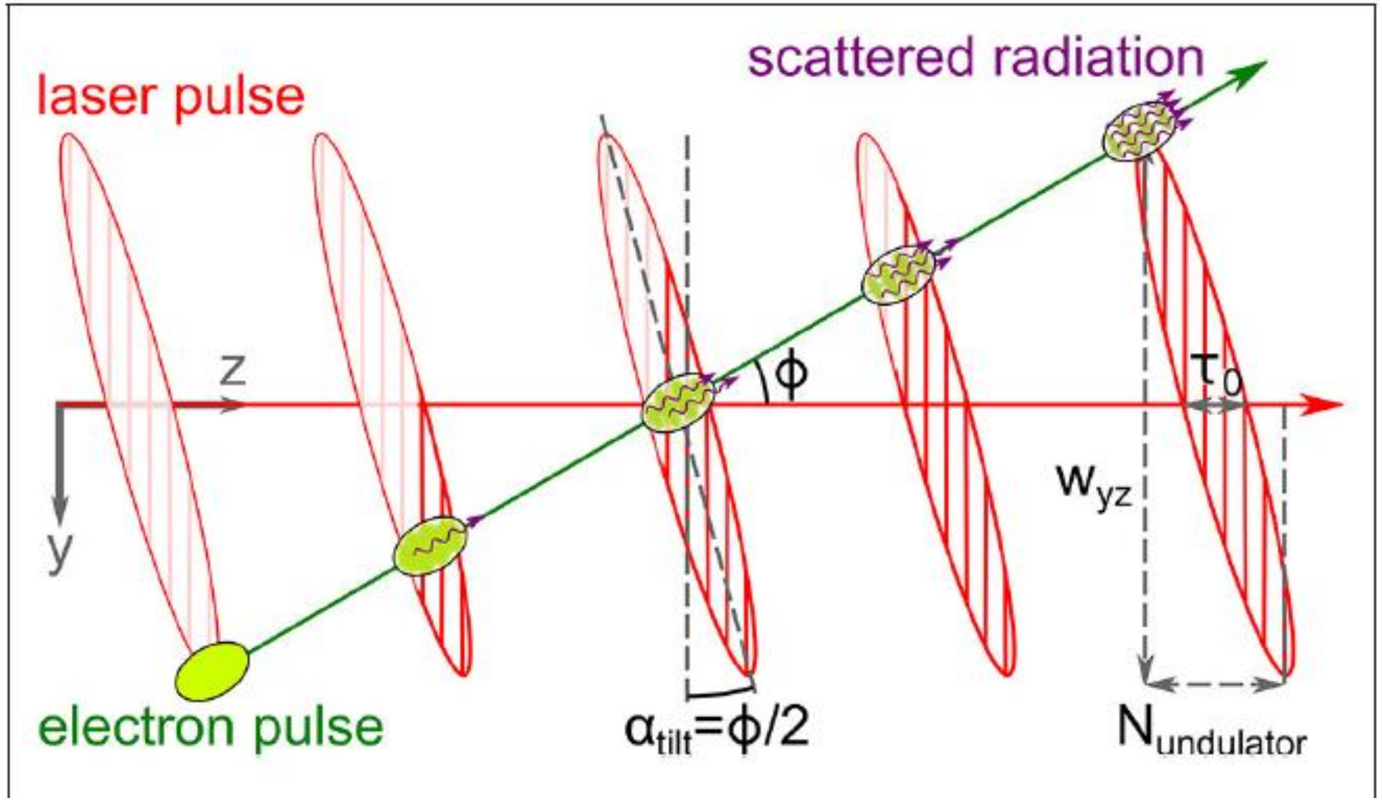
$$a_0 = \lambda_l \sqrt{\frac{I}{13.7\ GW}}$$

$a_0 > 0.3$ **XFEL lasing requires high laser strength**

$$I > 10^{17}\ W/cm^2$$

For 1 micron laser

Need femtosecond laser pulses to achieve ~8 TW peak power



K. Steiniger *et al.* Frontiers in Physics 6, 155 (2019)

See also: Milburn, PRL, 10,30 p 75, (1963)

Teitelbaum et. al.

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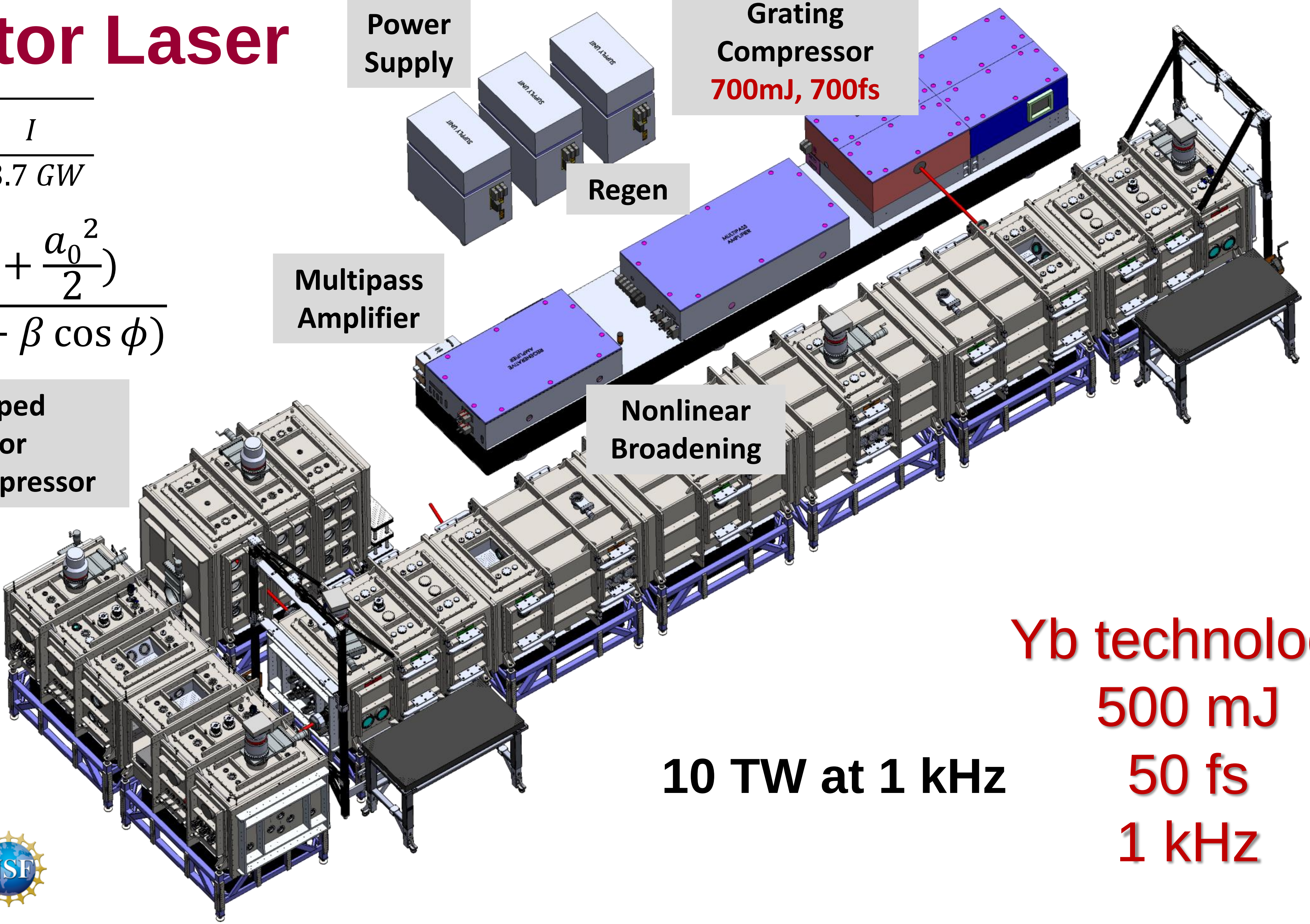
Undulator Laser

$$a_0 = \lambda_l \sqrt{\frac{I}{13.7\ GW}}$$

$$\lambda_x = \frac{\lambda_u \left(1 + \frac{a_0{}^2}{2}\right)}{2\gamma^2 (1 - \beta \cos \phi)}$$



10 TW at 1 kHz

Yb technology
500 mJ
50 fs
1 kHz

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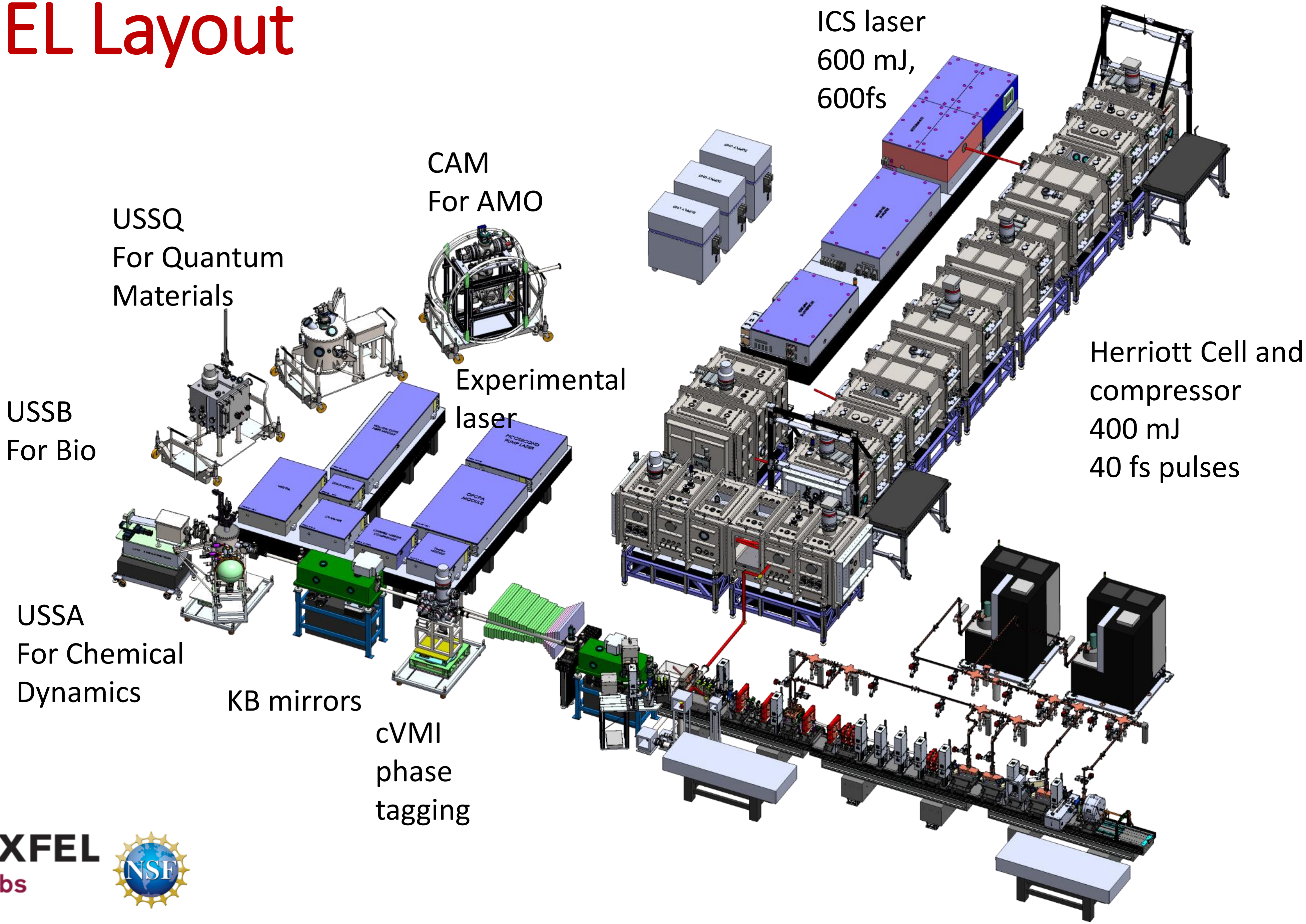
CXFEL Layout



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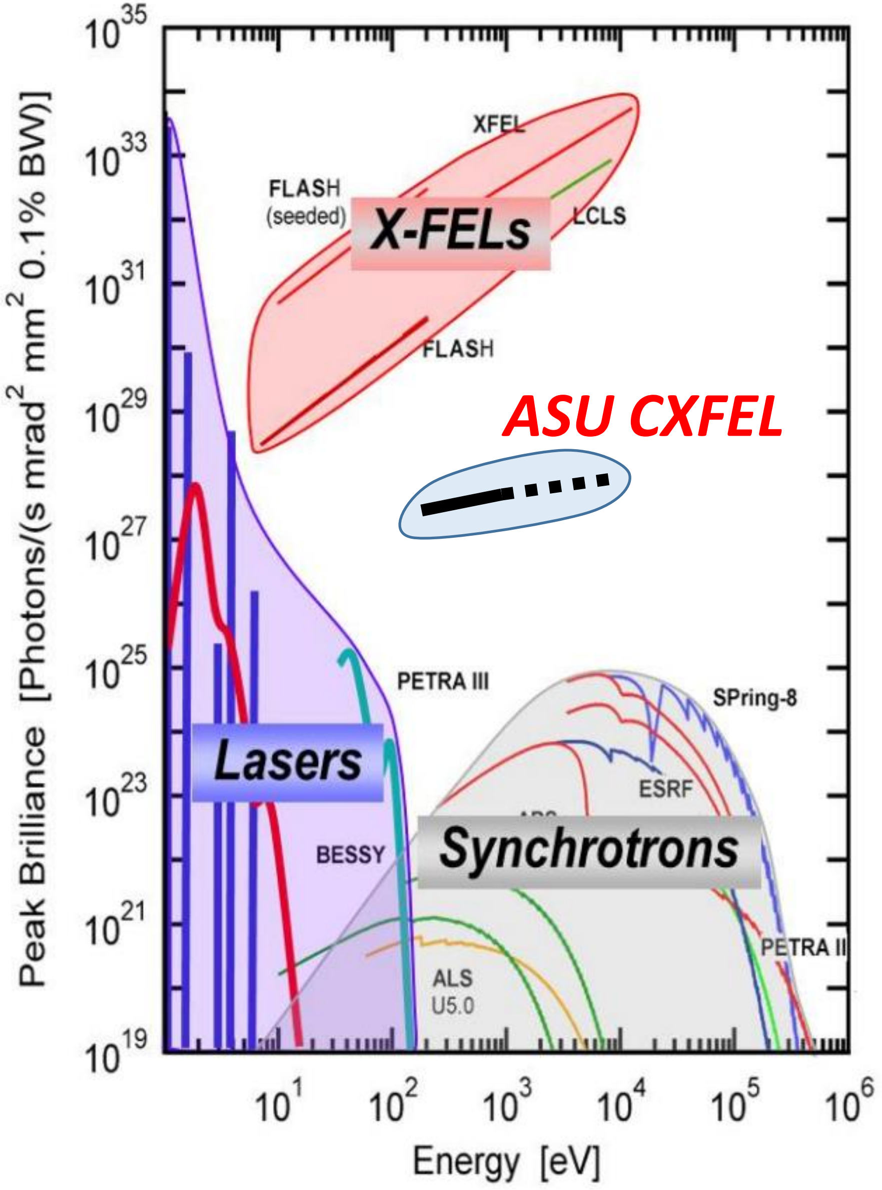
CXFEL Estimated Performance



Full coherence in temporal and transverse dimensions, but lower power than large XFELs.

The ASU CXFEL uniquely controls the x-ray phase and amplitude.

CXFEL can seed large XFELs to increase their brilliance X100

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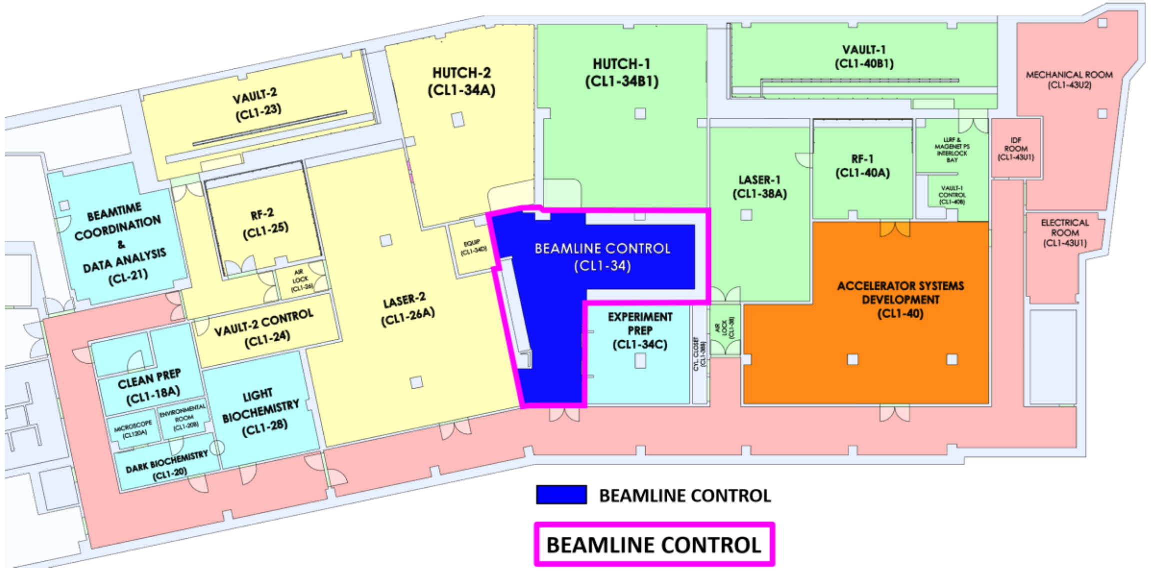
Beamline Control



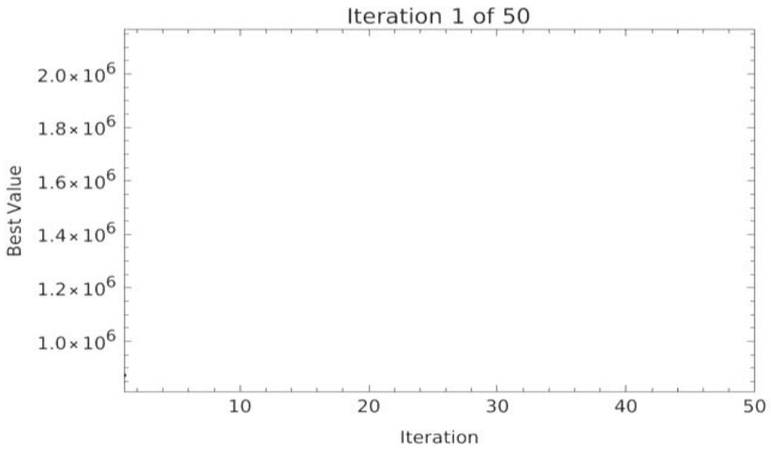
FEATURES:

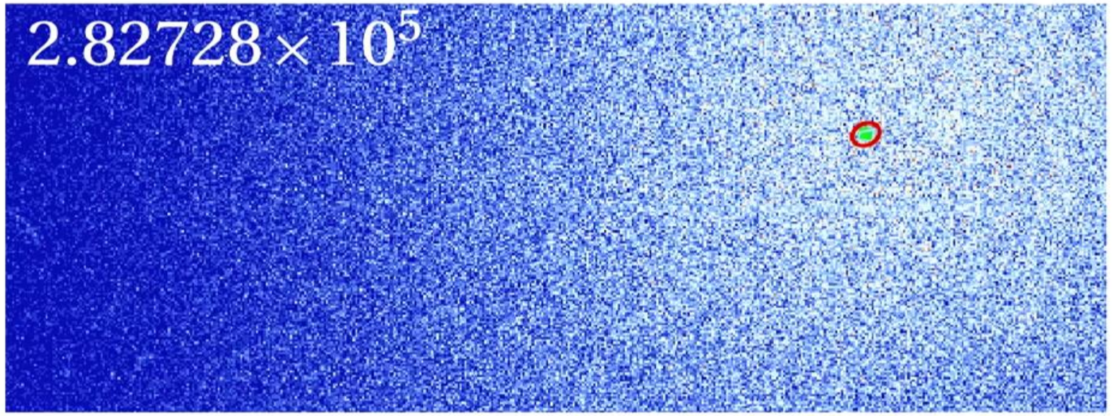
- Electron accelerator control
- Laser control
- Experiment control
- EPICS control framework
- User workstations for user developed routines:
    - Matlab
    - Mathematica
    - Jupyter Notebook

The Need for Automation

- CXLS has more than 40 knobs for tuning the electron beam and the laser–IP interaction
- Initial commissioning took days to weeks
- Day-to-day operation needs to be automated
- Tuning the machine for a given user request should take minutes, not hours
- Our goal is to run the machine without expert operators

With feedback from the X-ray detector, the search to align the laser beam with the e-beam across four dimensions took only minutes
{X, Y, Z (focal point), and timing}



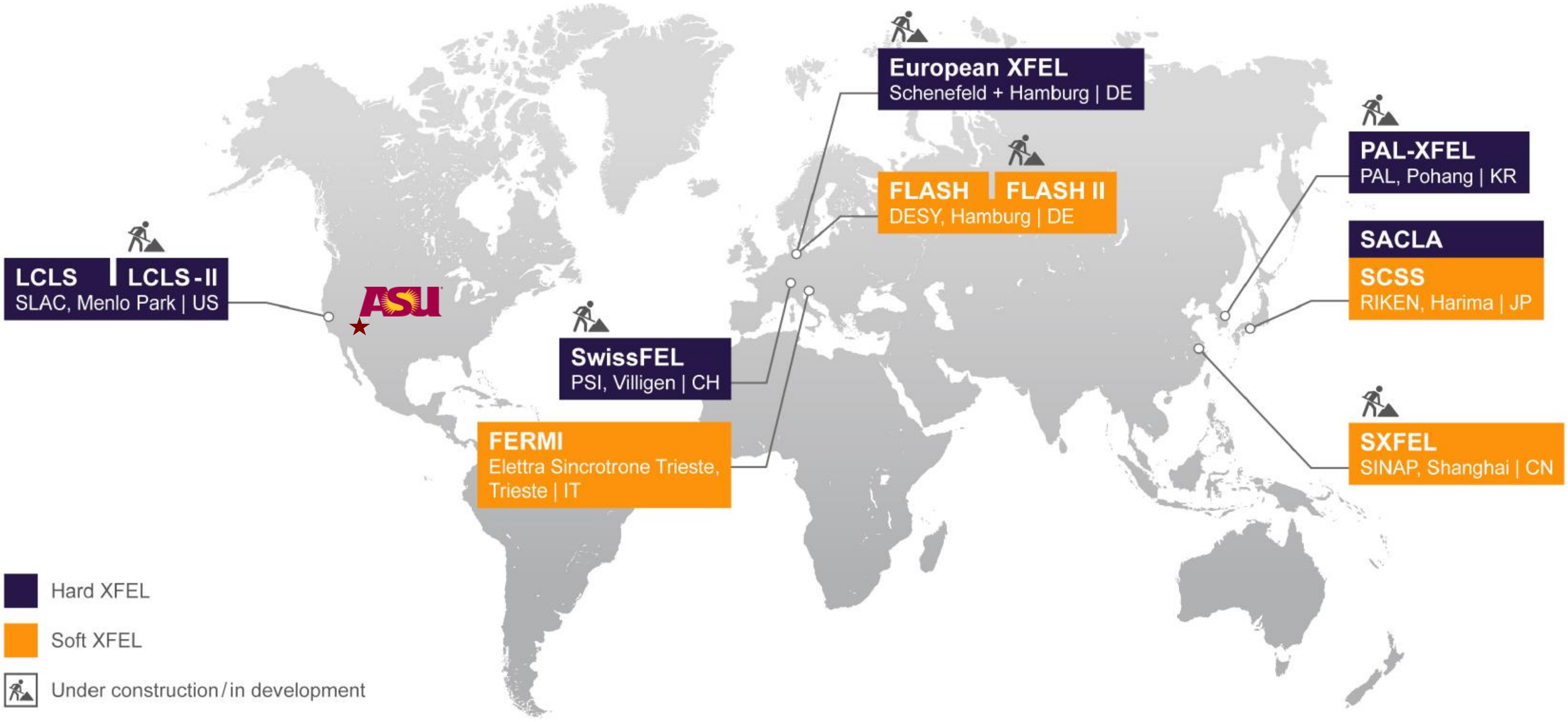


Tantawi, et. al.

Active and Planned Automation

- Photocathode Laser Transport
- Electron Beam Transport
- Inverse Compton Scattering (ICS) Laser Transport
- ICS Interaction Point Targeting (Space and Time)
  - Electron bunches
  - ICS Laser pulses
- X-ray Optics Alignment
  - Launch Optic
  - Focusing Optic
- Sample Alignment
- Detector Alignment
- Pump Laser Alignment (Space and Time)
- X-ray Characterization
- Detector Calibration
- Endstation Alignment

XFELs Worldwide



Zastrau, March 2017**

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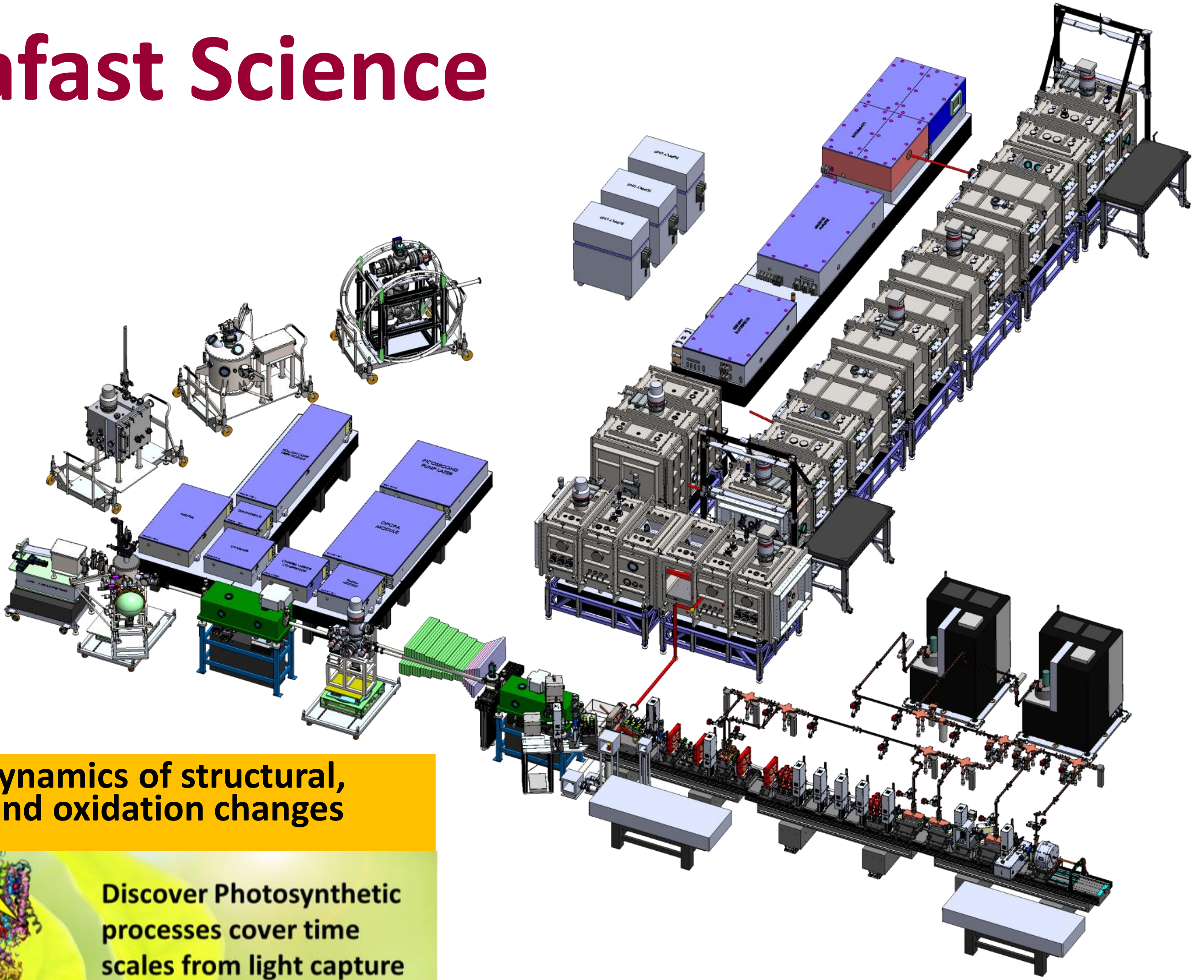
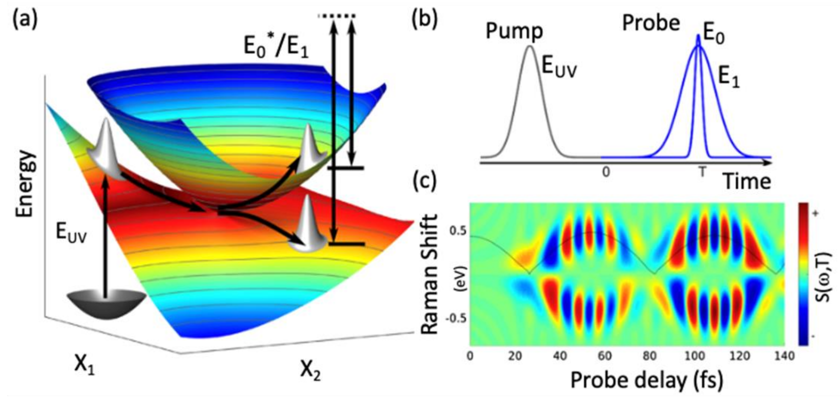
CXFEL Ultrafast Science

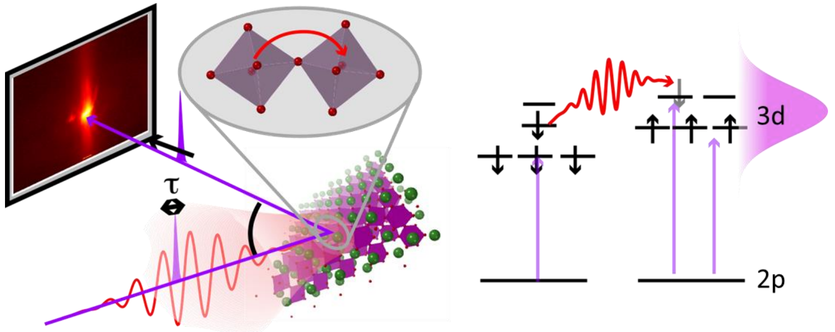


Track electronic wavepackets through conical intersections of molecules

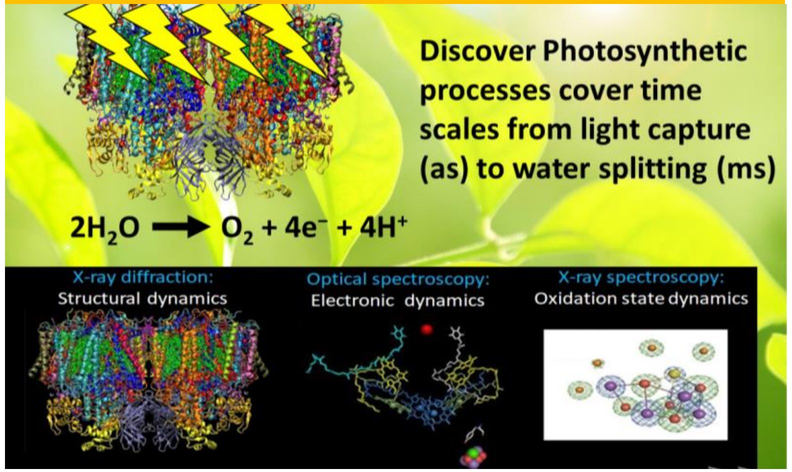
Phys. Rev. Lett. ***115***, *193003 (2015)*



Manipulate and track coherences in correlated electron materials



Study the dynamics of structural, electronic and oxidation changes



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ASU Team

Arvinder Sandhu, Sami Tantawi, Bill Graves, Petra Fromme, Sam Teitelbaum, Nicholas Matlis, Robert Kaindl, Mark Holl, Sabine Botha, Alexandra Ros, Aaron LaForge, Islam Shalaby, Siyang Wang, Adil Ansari, Hao Hu, Sean Tilton, Kevin Eckrosh, Casey Timms, Alex Gardeck, Deanna Clarke, Engineering team, Graduate students, Undergraduate students

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Overall: CXFEL includes 80+ People in 13 Institutions

CXFEL Positions

- Accelerator Beam Dynamics
- RF Systems
- LLRF Systems
- RF Structure Fabrication and Process Control

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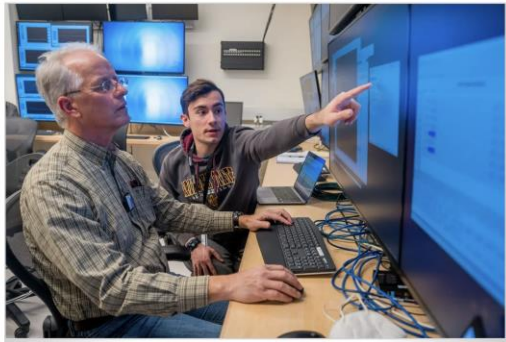

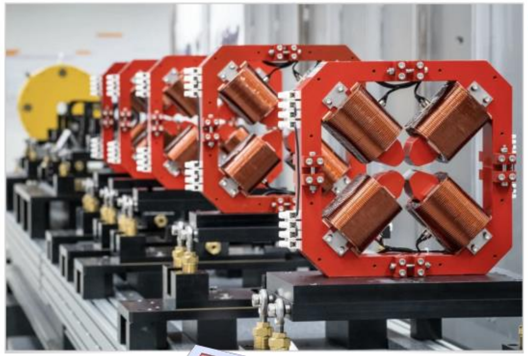
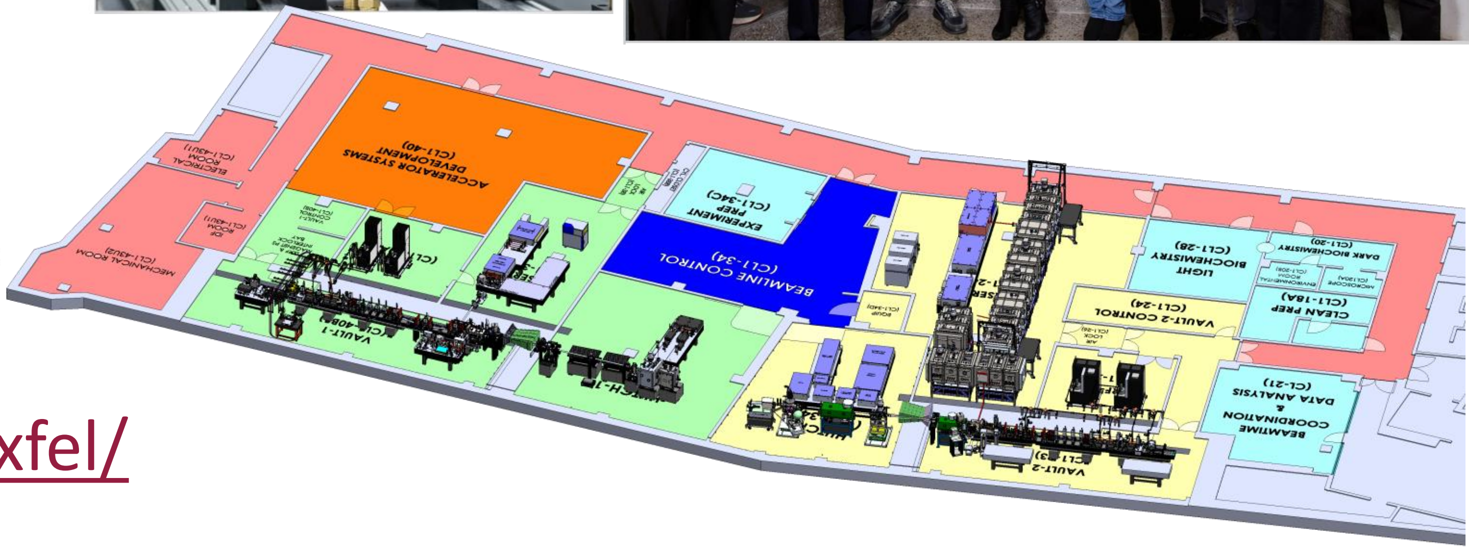

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https://biodesign.asu.edu/cxfel/