illuminating x-ray science™

The Lyncean Compact Light Source

A Stepping Stone to a Large Synchrotron Facility

Challenges to Building a Synchrotron

- Once a commitment has been made, it can take 10 to 20 years to build a synchrotron facility
- Design, development and construction costs can range from \$0.5B to >\$1B
- Operating costs can be in the \$10s M annually
- It takes highly skilled and diverse experts to design and build a synchrotron → accelerator physicists, optical physicists, beamline scientists, and specialized engineers and technicians
- Skilled operators and users are required to be productive and generate scientifically relevant research

lyncean TECHNOLOGIES, INC.

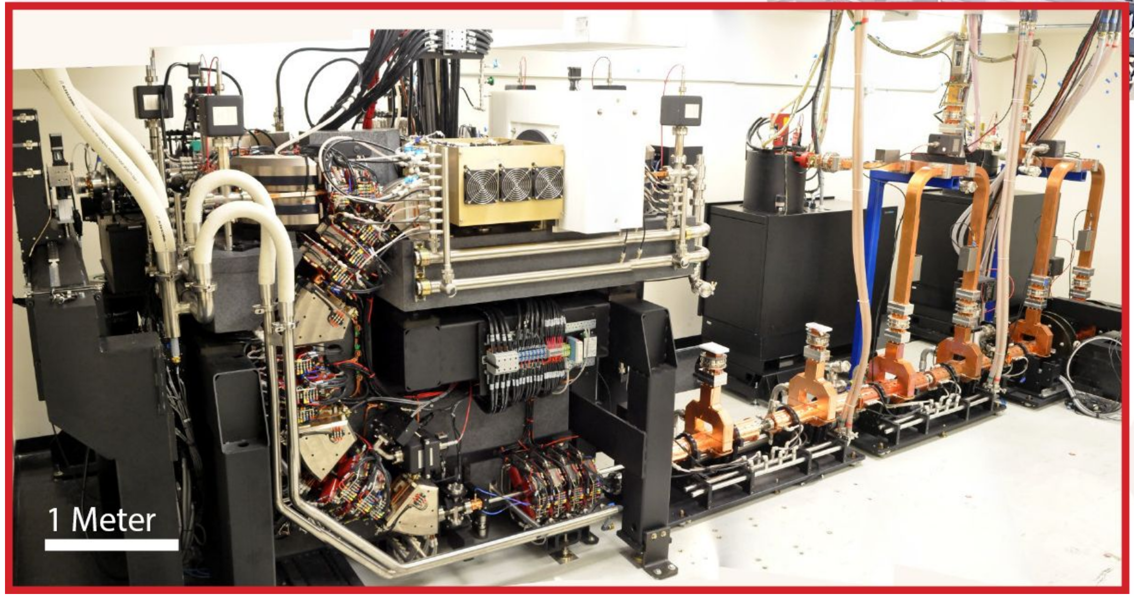
How the Compact Light Source can be a Stepping Stone Towards Building a Synchrotron Facility

1. Lyncean's Compact Light Source mini-Synchrotron
2. A Synchrotron Quality, Multi-Disciplined X-ray Facility

The Lyncean Compact Light Source (CLS)

- **Synchrotrons are the “super computers” of X-ray science**
- **They require high energy storage rings that are large and expensive (scale $1B)**
- **Access can be difficult as most are over subscribed by 2x to 3x**

Advanced Photon Source



Lyncean Compact Light Source

- **The CLS provides similar functionality as synchrotron bend magnet beam lines**
- **The CLS is much smaller & much lower cost making it the “workstation” of X-ray science**

A Laboratory Size Synchrotron

How to shrink a synchrotron by 100X
………. And still make hard x-rays

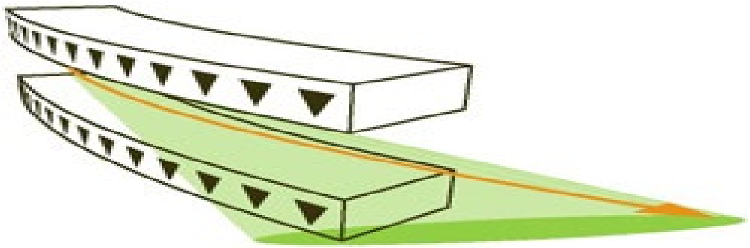
	Synchrotron
Storage Ring Dia	~60-300 m
Electron Energy	2-5 GeV
Undulator Period	~ 10 mm
Undulator Type	Permanent Magnet

A Laboratory Size Synchrotron

How to shrink a synchrotron by 100X
………. And still make hard x-rays

	Synchrotron	Compact Light Source
Storage Ring Dia	~60-300 m ~100X	~1 m
Electron Energy	2-5 GeV	
Undulator Period	~ 10 mm	
Undulator Type	Permanent Magnet	

- Shrinking size by 100X means reducing the bend radius of electrons accordingly
- Fixed bend magnet strength (~1Tesla)
  → Bend radius proportional to E
  → Need to reduce electron energy by 100X



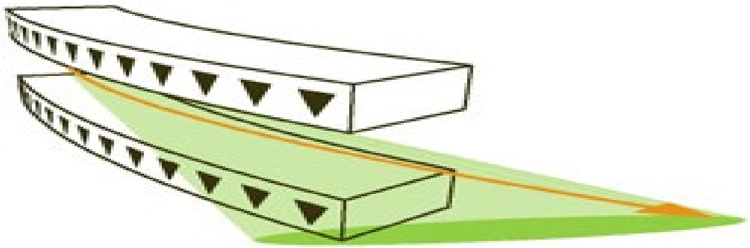
A Laboratory Size Synchrotron

How to shrink a synchrotron by 100X
………. And still make hard x-rays

	Synchrotron	Compact Light Source
Storage Ring Dia	~60-300 m	~1 m
Electron Energy	2-5 GeV	25-45 MeV
Undulator Period	~ 10 mm	
Undulator Type	Permanent Magnet	

~100X

- Shrinking size by 100X means reducing the bend radius of electrons accordingly
- Fixed bend magnet strength (~1Tesla)
  → Bend radius proportional to E
  → Need to reduce electron energy by 100X
- Bend magnet emission X-ray → IR

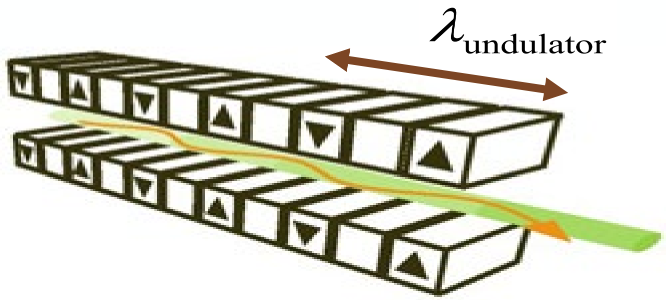


A Laboratory Size Synchrotron

How to shrink a synchrotron by 100X
………. And still make hard x-rays

	Synchrotron	Compact Light Source
Storage Ring Dia	~60-300 m	~1 m
Electron Energy	2-5 GeV	25-45 MeV
Undulator Period	~ 10 mm	
Undulator Type	Permanent Magnet	

~100X



$$\lambda_{\text{x-ray}} = \frac{\lambda_{\text{undulator}}}{2\gamma^2} \propto \frac{\lambda_{\text{undulator}}}{E^2}$$

- X-ray generation requires undulator with ultra-short period (10,000X smaller)

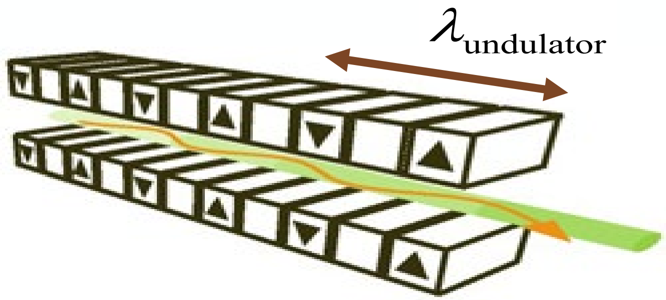
A Laboratory Size Synchrotron

How to shrink a synchrotron by 100X
……….. And still make hard x-rays

	Synchrotron	Compact Light Source
Storage Ring Dia	~60-300 m	~1 m
Electron Energy	2-5 GeV	25-45 MeV
Undulator Period	~ 10 mm	~ 0.5 μm
Undulator Type	Permanent Magnet	Laser Field (1μm λ)

~100X

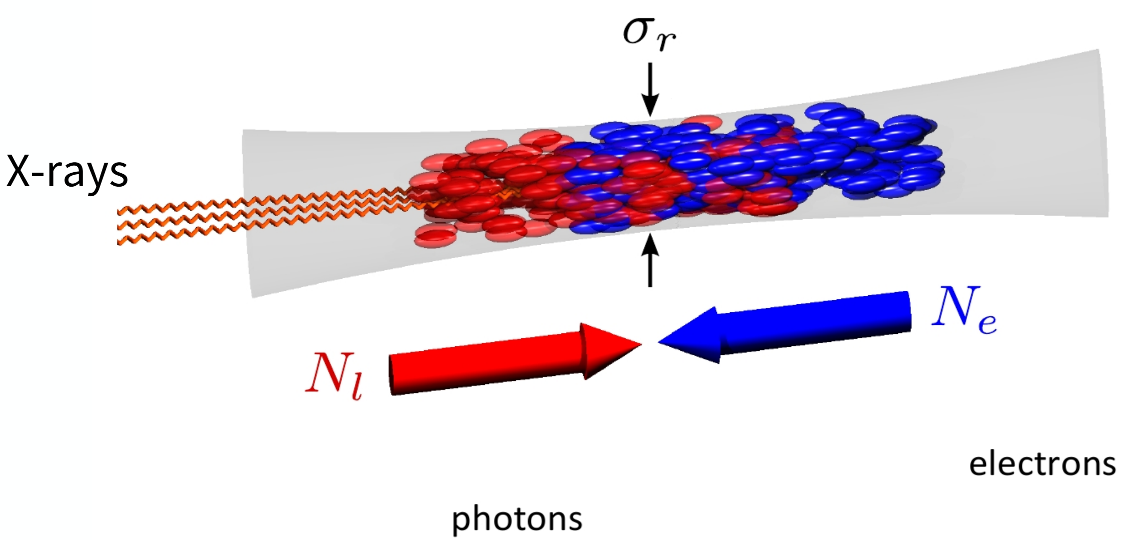
~10,000X



$$\lambda_{\text{x-ray}} = \frac{\lambda_{\text{undulator}}}{2\gamma^2} \propto \frac{\lambda_{\text{undulator}}}{E^2}$$

- X-ray generation requires undulator with ultra-short period (10,000X smaller)

How To Produce High Flux with a 1m Ring



$$\dot{N}_x = \sigma_{Th} \cdot \mathcal{L}_0$$

$\dot{N}_x$ = X-ray flux (ph/s):

$$\sigma_{\mathrm{Th}} = \frac{8\pi}{3} r_e^2 = 6.65 \times 10^{-29}\,\mathrm{m}^2$$

Need high Luminosity:

$$\mathcal{L}_0 = f_{\mathrm{coll}} \frac{N_l N_e}{4\pi\sigma_r^2}$$

$$\sigma_r^2 = \tfrac{1}{2}\sqrt{\sigma_{e,x}^2 + \sigma_{e,y}^2}\sqrt{\sigma_{l,x}^2 + \sigma_{l,y}^2} = \sigma_e \sigma_l$$

Optimizing CW x-ray output by

→ f_{coll}: maximize collision frequency – **electron storage ring for 65 MHz rate**

→ N_l : maximize laser pulse power – **high finesse, power amplifying laser cavity**

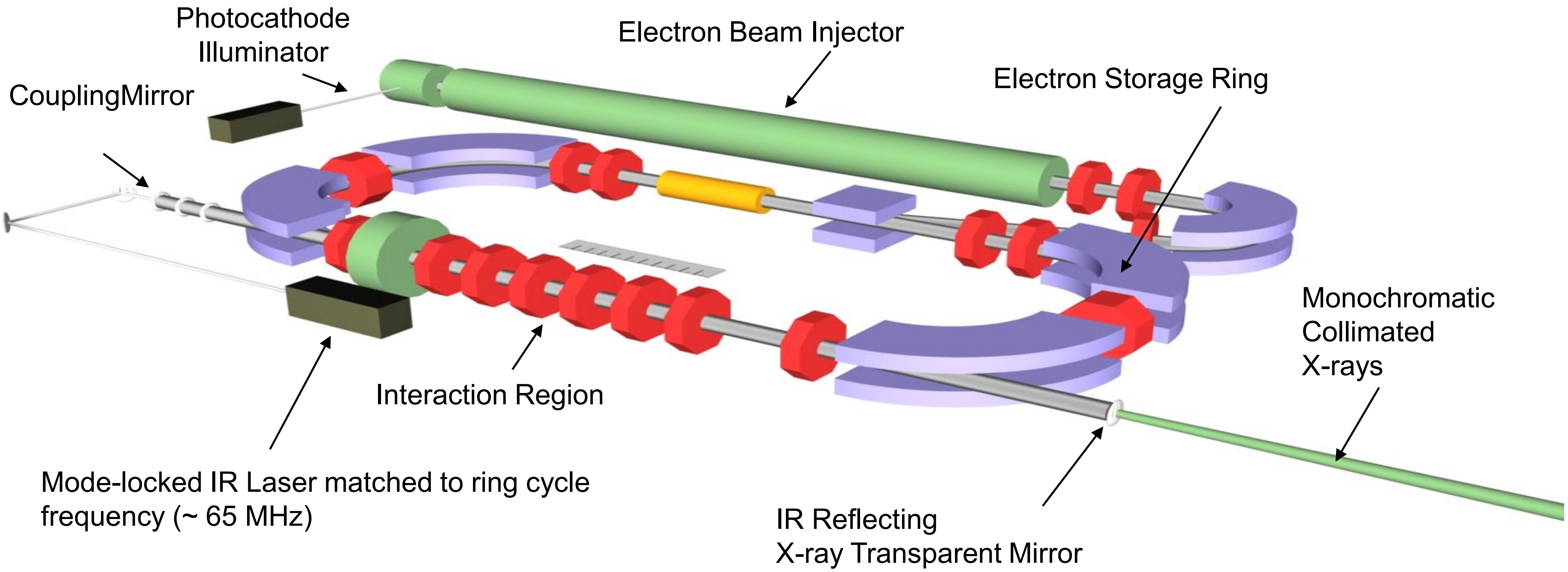
→ N_e: maximize electron bunch charge – **high charge, low emittance LINAC**

→ σ_r: minimize source size – **optimize size of e-beam and laser waist**

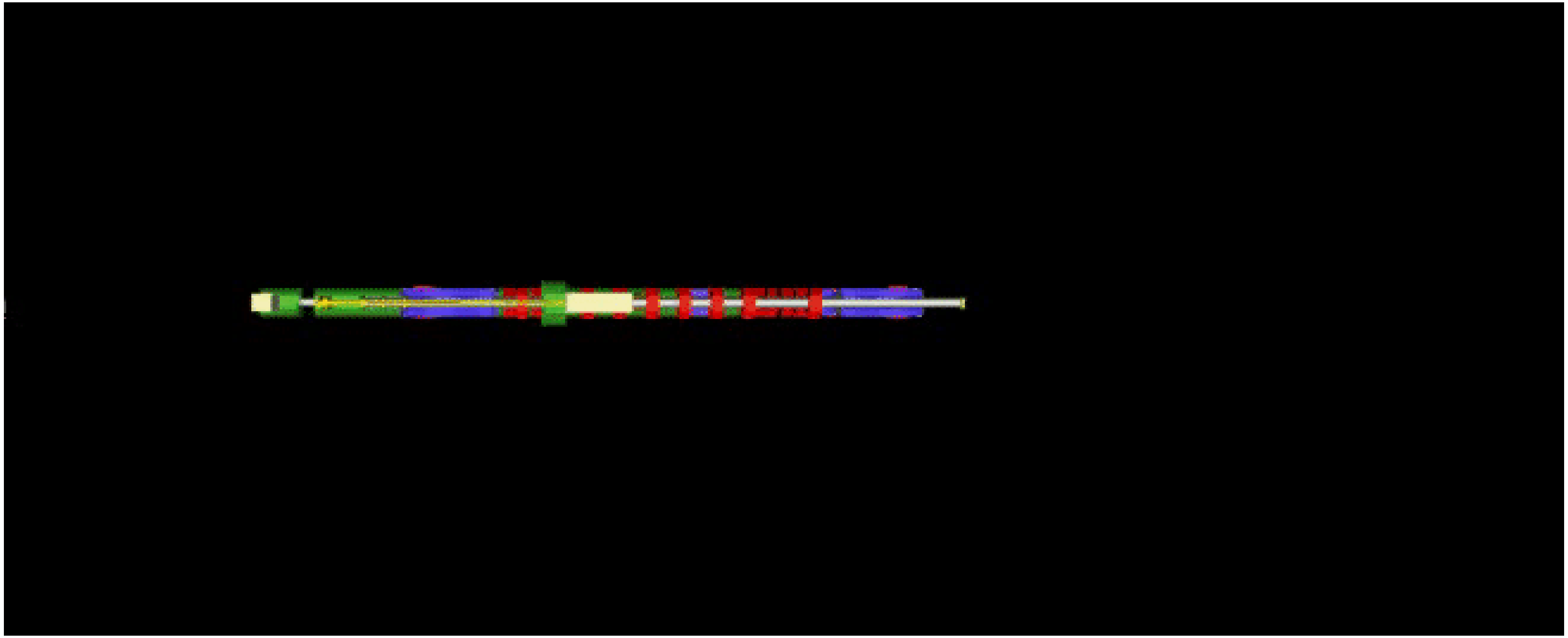
adapted from Schleede et al., J. Sync. Rad. 19, 525 (2012)

The Compact Light Source

- A miniature synchrotron x-ray source
  - Electron bunch stored in a miniature electron storage ring
  - Picosecond laser pulse stored in high-finesse optical cavity providing electron “undulation” to produce x-rays in interaction region

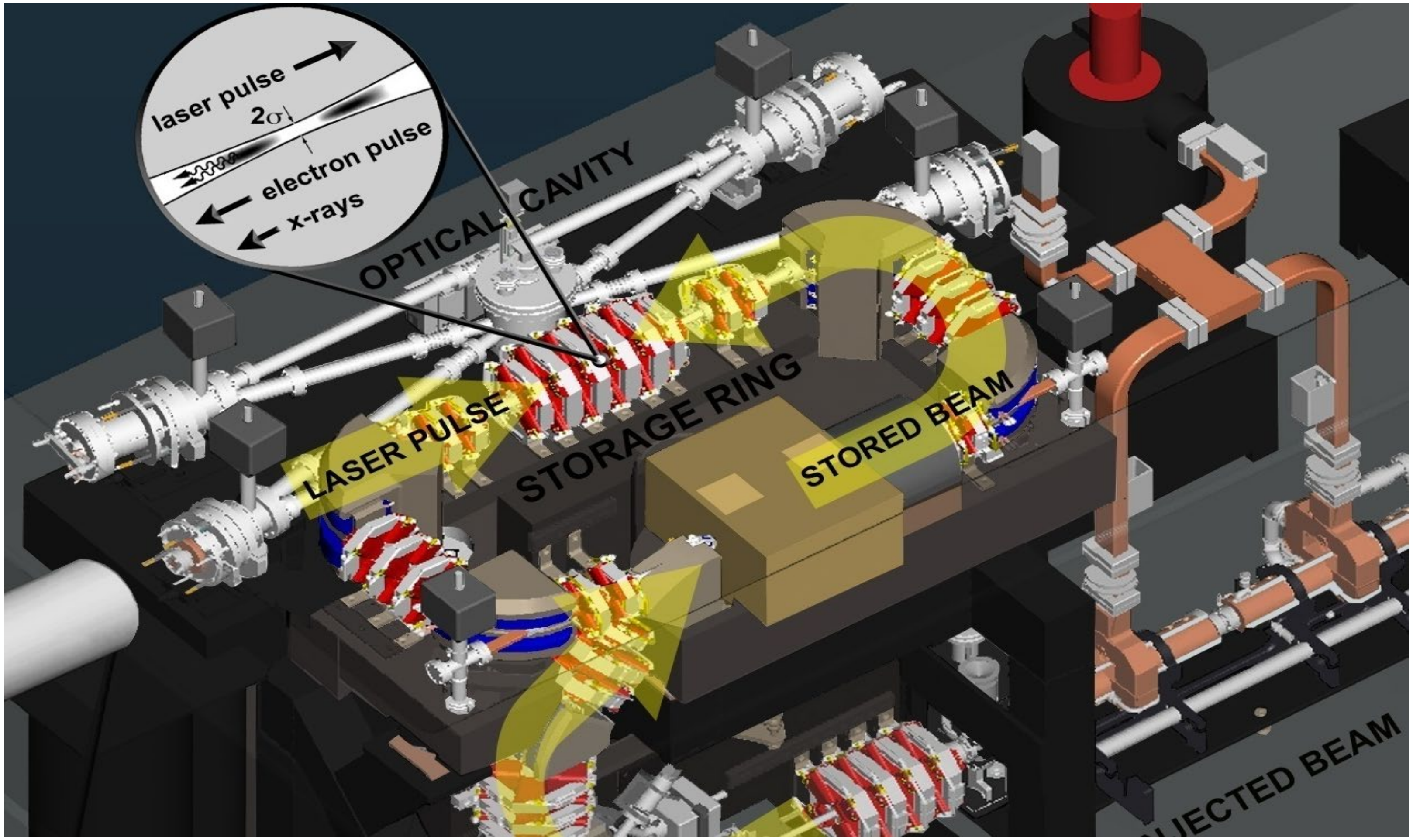


The Compact Light Source Animation

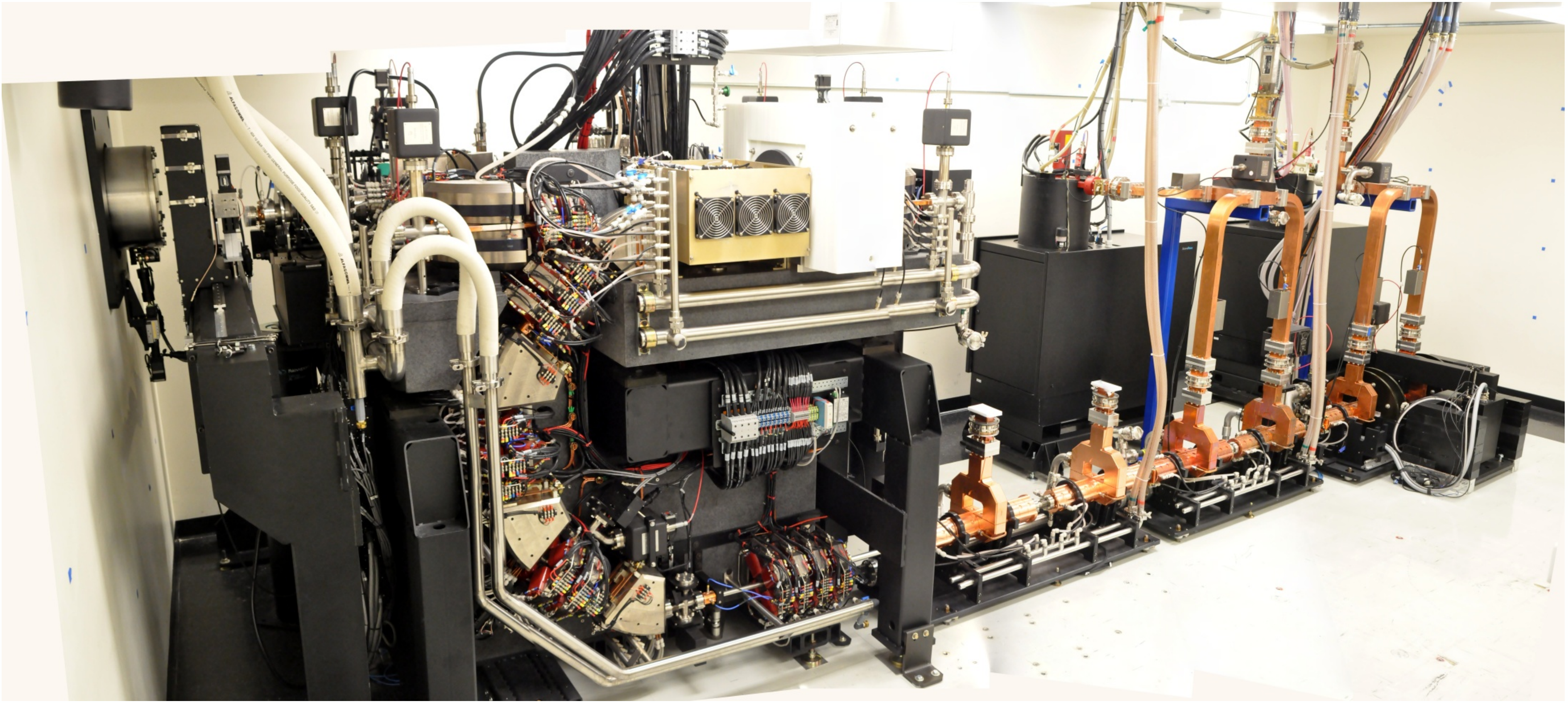


Red pulse = CW mode-locked laser pulse resonantly driving an optical cavity (shown here as a 2-mirror Fabry-Perot).
Green pulse = electron beam injected and then circulating in storage ring.
Purple pulse = X-rays generated at the collision point (IP) and exiting to right.

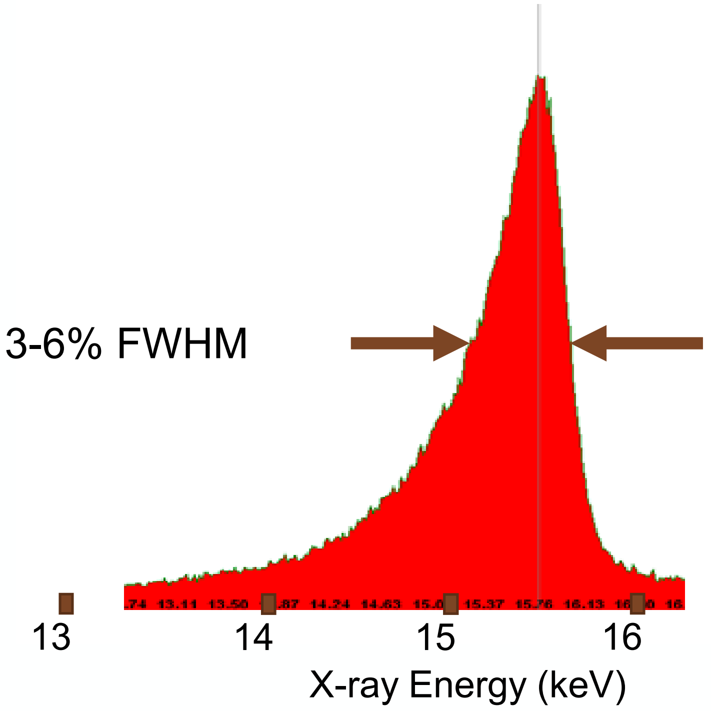
The Compact Light Source CAD Drawing

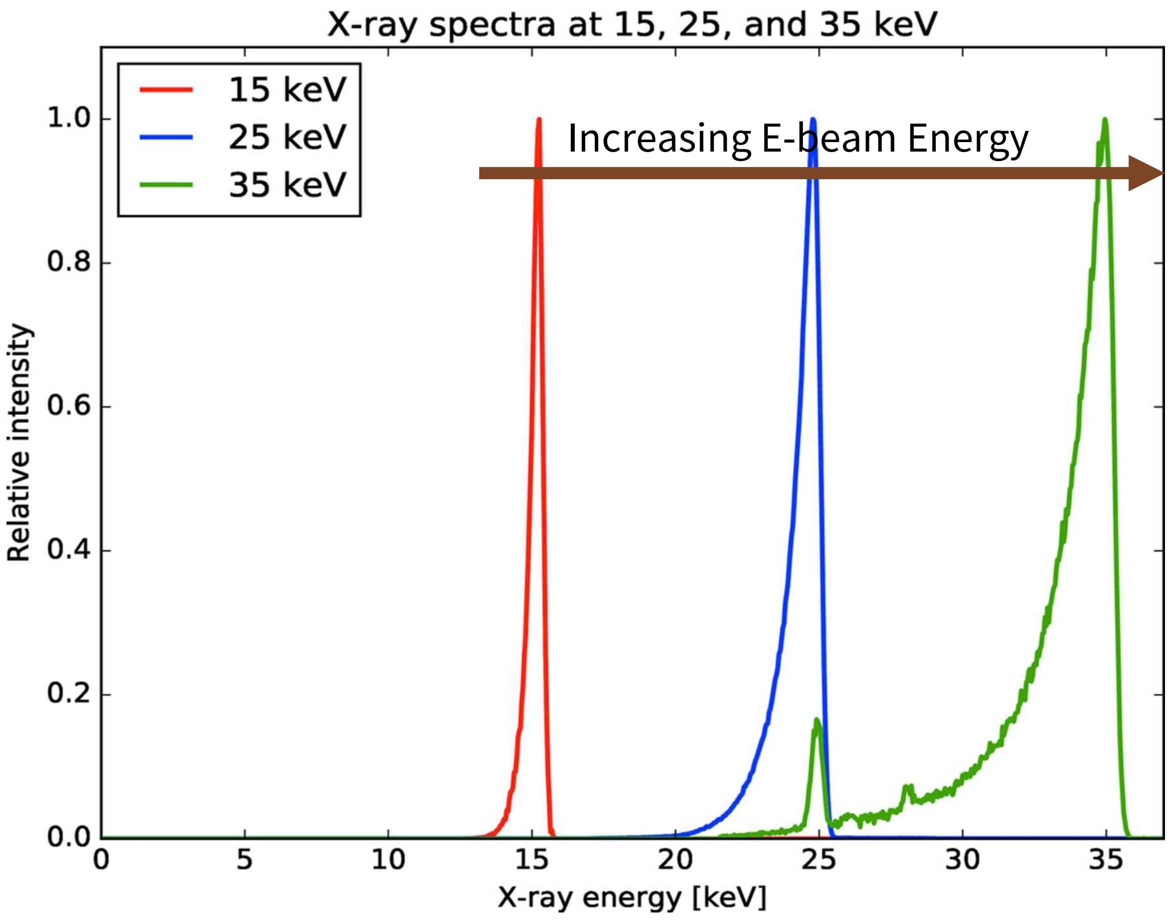


The Munich Compact Light Source



Energy Spectrum and Tunability





- "Undulator" monochromatic spectrum with 3-6% FWHM Bandwidth
- Peak energy tuned by changing e-beam energy in storage ring

CLS X-ray Source Parameters

Parameter	CLS 1.1 (Munich CLS)	CLS 2.0 (Next system)	CLS Roadmap (Future)
Total Flux (~4% BW) – [ph/s]	>3 * 10^{10}	4 * 10^{11}	4 * 10^{12}
Source size [μm rms]	45	40	30
Source divergence [mrad] (Flattop Cone)	4	6	6
Source Brightness – Full Bandwidth [ph/s/mrad^2/mm^2/4% BW]	5 * 10^{11}	4 * 10^{12}	1 * 10^{14}
Tunable x-ray energy range [keV]	8-35 (IR 1um laser)	8-35 (IR 1um laser)	4-22 (IR – 2um) 8-40 (IR – 1um) 16-80 (Vis – 0.5um)
X-ray energy bandwidth [dE/E FWHM]	3-5%	3-5%	2-4%
X-ray Pulse Length (rms) [ps]	60		
X-ray Repetition Rate [MHz]	65		

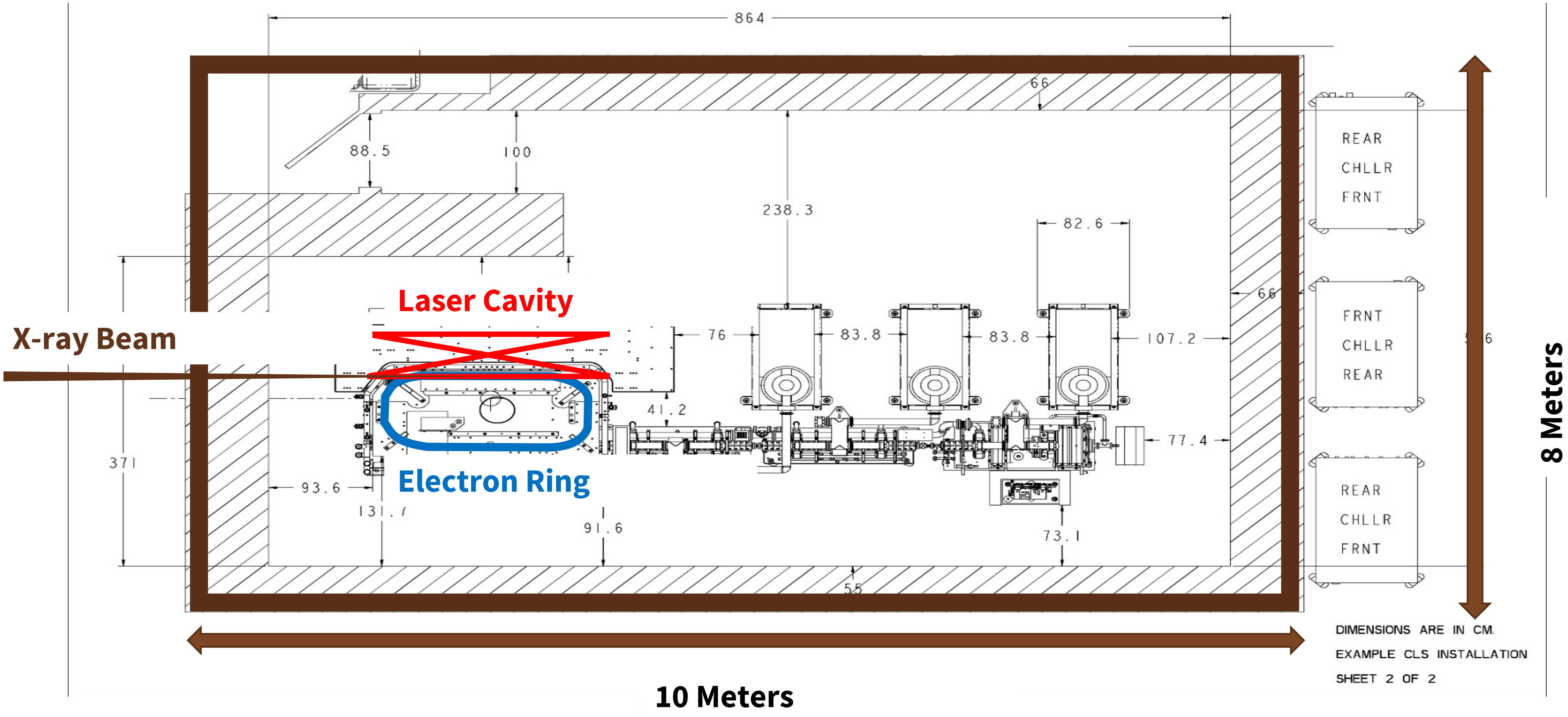
Characterization of Munich CLS: Eggl et al., J. Sync. Rad. 23 (5), Sept. 2016

- Future developments to
  - Extend energy range coverage from 4keV to 80keV
  - Match or exceed synchrotron bend performance even for crystal monochromator measurements

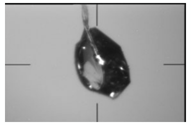
How the Compact Light Source can be a Stepping Stone Towards Building a Synchrotron Facility

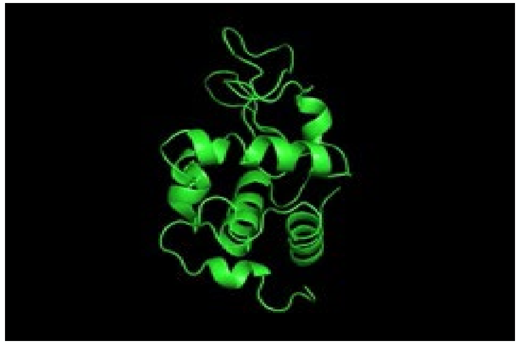
1. Lyncean's Compact Light Source mini-Synchrotron
2. A Synchrotron Quality, Multi-Disciplined X-ray Facility

Lyncean Compact Light Source Facility Layout



A Multi-Disciplined X-ray Facility Layout



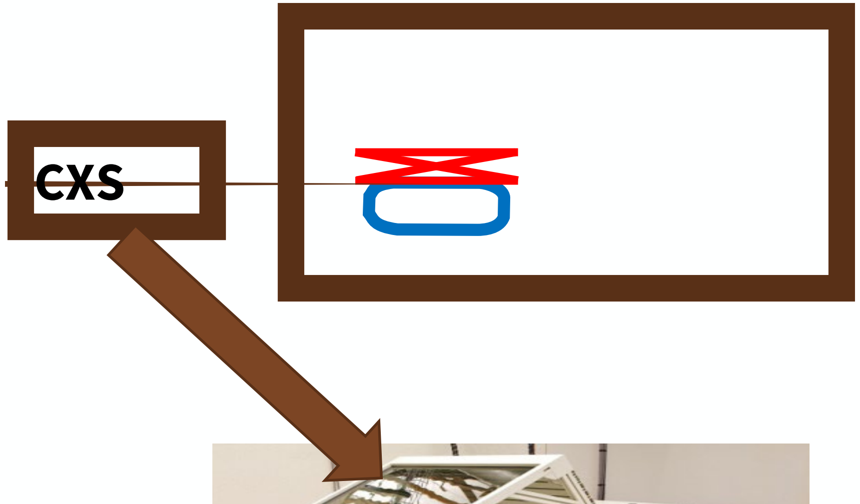


Protein Crystallography
20 minute acquisition
1.7 Å reconstruction resolution

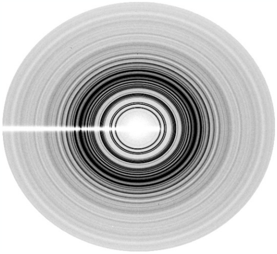
Micro & Nano Tomography

ZEISS Xradia Ultra Synchrotron Microscope

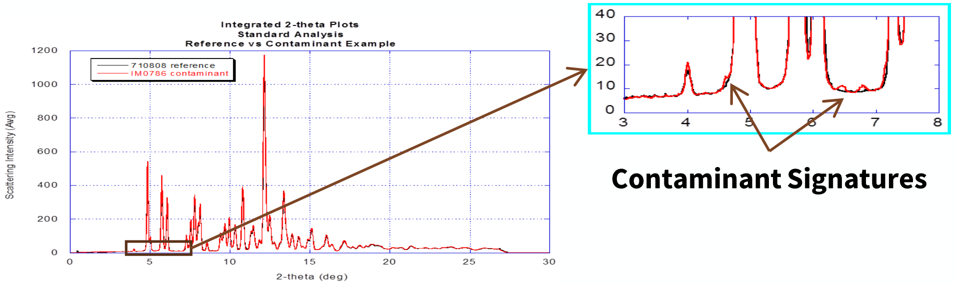
End-station close to source



Compact X-ray Station (CXS)



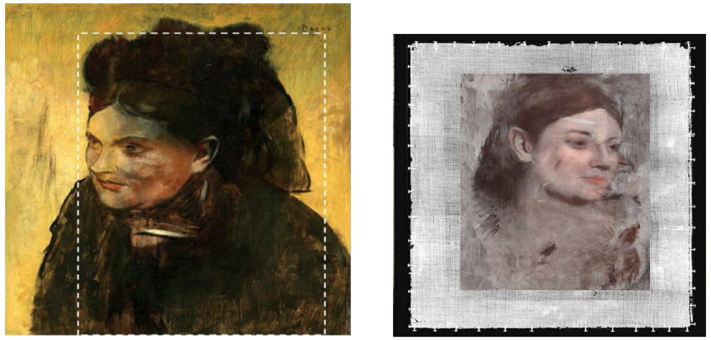
Powder Diffraction
20 ppm contamination detection



Contaminant Signatures

A Multi-Disciplined X-ray Facility Layout

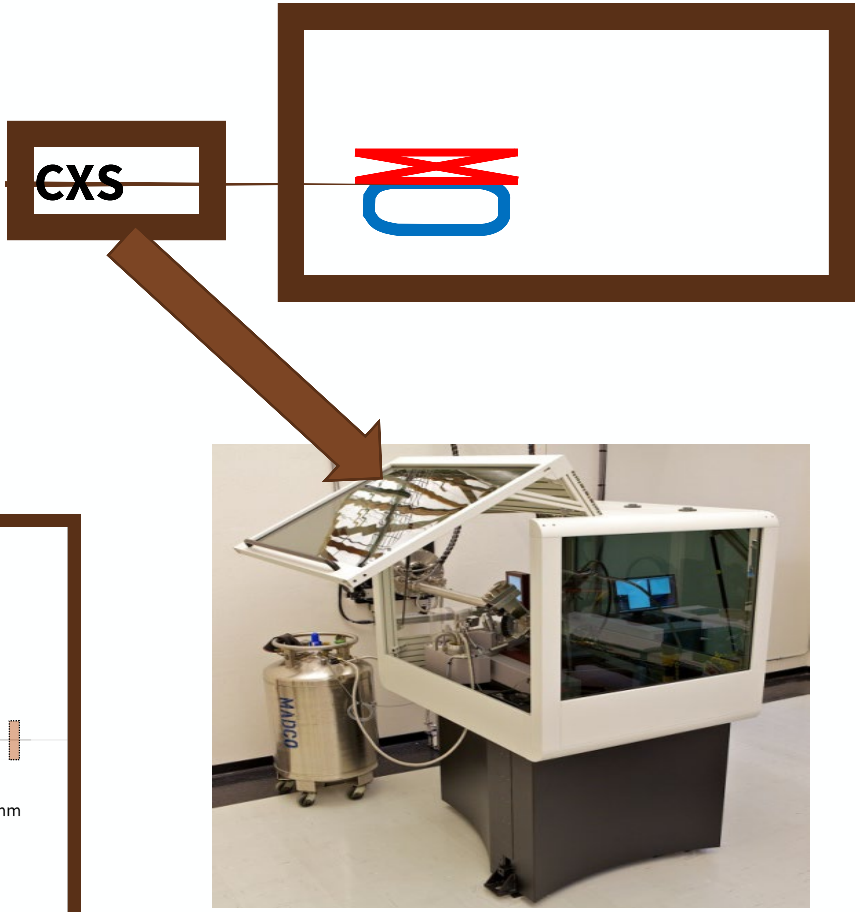
Fluorescence Mapping
31.6 Mpixel scanning
Energy tunability to avoid Pb interference



Australian Synchrotron

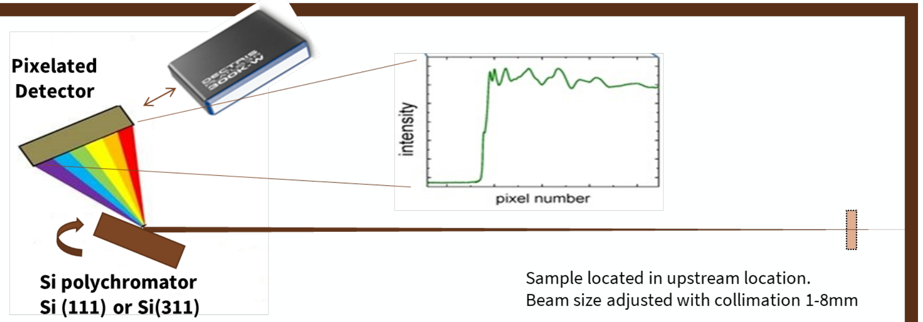
Thurrowgood, D. *et al.* A Hidden Portrait by Edgar Degas. *Sci. Rep.* **6**, 29594 (2016).

End-station close to source



Compact X-ray Station (CXS)

ED-XAFS
Conceptual design
>70 elements accessible using K & L3-edge for the standard CLS energy

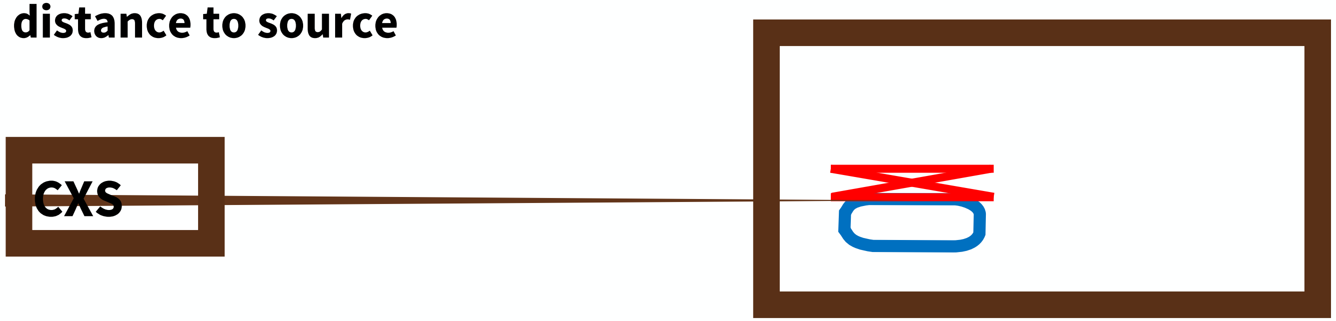


Flux is dispersed by Si crystal so that each horizontal pixel column corresponds to energy resolution for XAS, *e.g.* ~ 1 eV

lyncean TECHNOLOGIES, INC.

A Multi-Disciplined X-ray Facility Layout

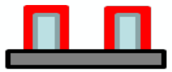
Medium distance to source



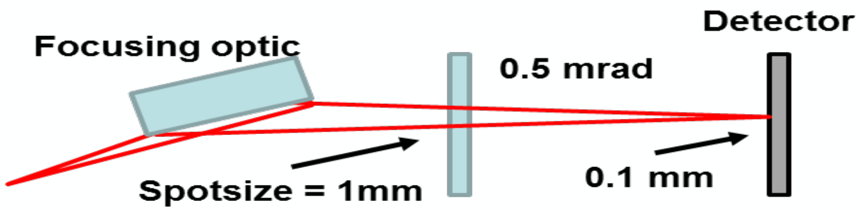
Small Angle X-ray Scattering

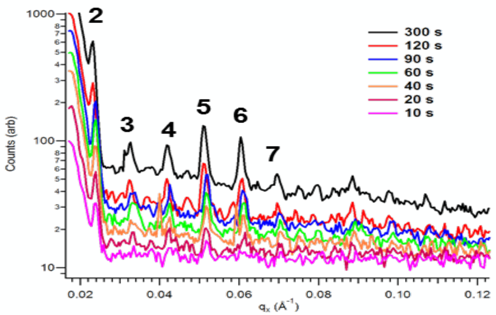
Modeled throughput for CLS 2.0 is just 5x slower than APS

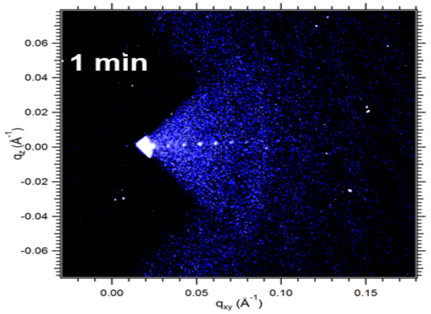
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

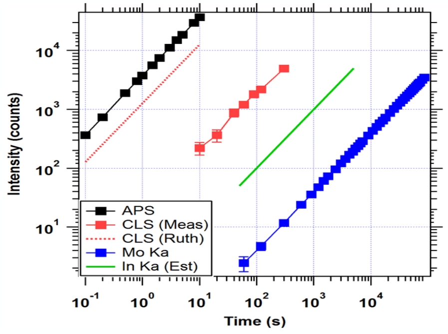


High-K FinFET







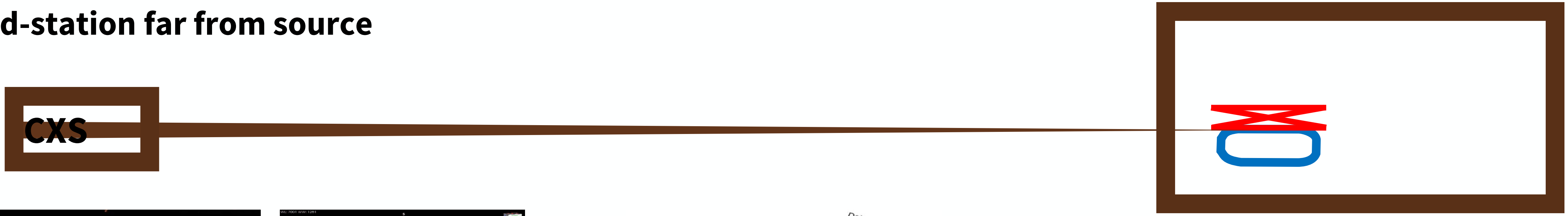


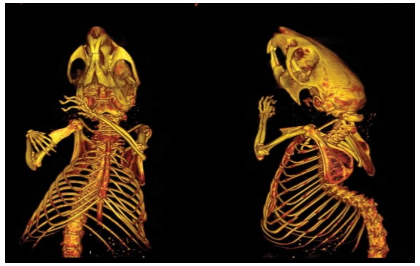
Compact X-ray Station (CXS)

lyncean TECHNOLOGIES, INC.

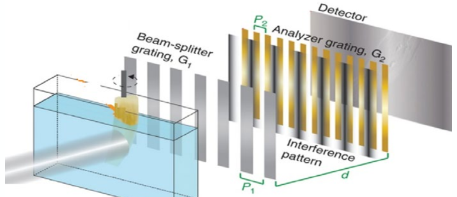
A Multi-Discipline X-ray Facility Layout

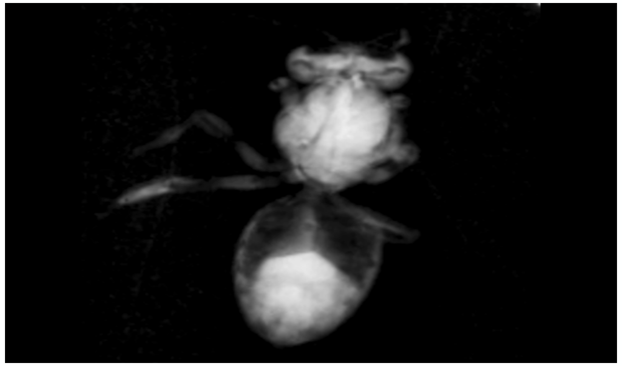
End-station far from source





Large Sample Imaging
No beam hardening artifacts
Elemental contrast using absorption edges
Dynamic experiments for activity in the ms timescale





Phase Contrast Imaging
Propagation phase contrast
Grating based phase contrast

Compact X-ray Station (CXS)

The Lyncean Compact Light Source

- **A Stepping Stone Towards a Large Synchrotron Facility**
  - A CLS provides substantial synchrotron capabilities, turn-key ready, at a moderate cost
  - It is available and operating within a short timeframe (1-2 years)
  - It attracts and enable training of accelerator resources required for designing and constructing a large synchrotron
  - It avoids brain-drain by providing local talent a working machine to conduct research in X-ray diffraction, spectroscopy, scattering and imaging instead of moving elsewhere
  - It allows training of user and beamline scientists in X-ray techniques and operations
  - End-stations can be developed in preparation for installation at a beamline
  - It reduces the risk and possibly cost for the synchrotron project by providing early hands-on access to a working machine promoting faster learning

illuminating X-ray science