CXFEL Project

William Graves

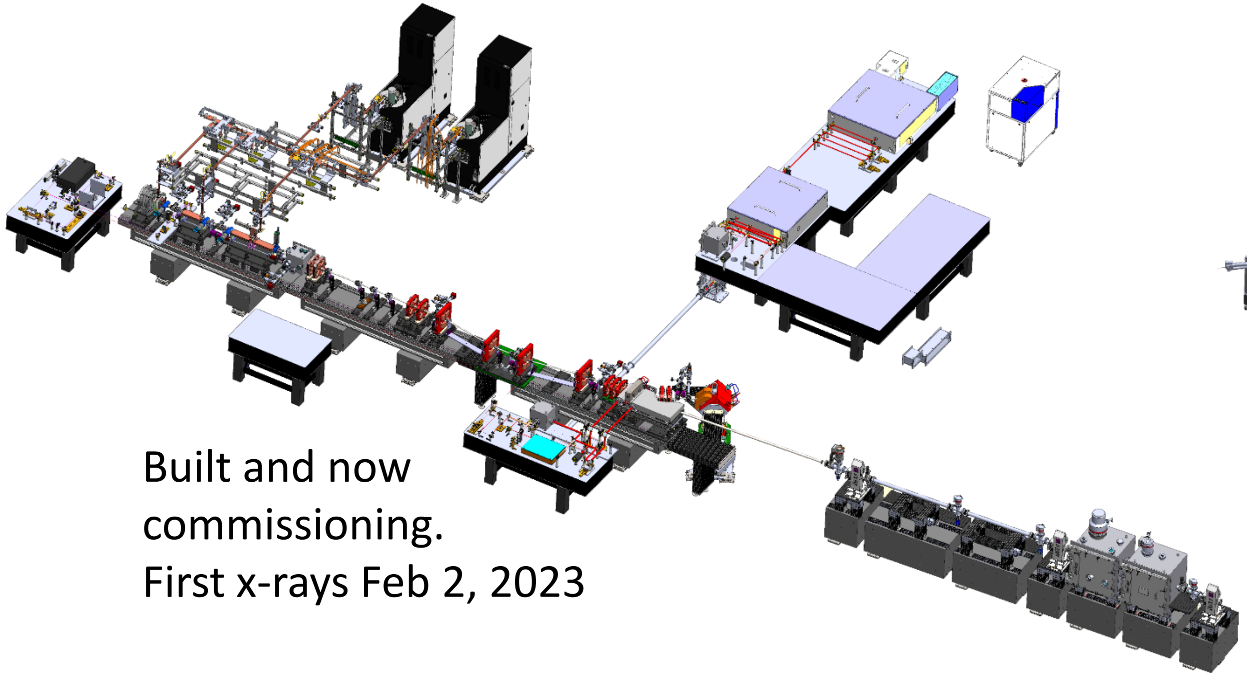
Biodesign Institute and CISA
Arizona State University

CXFEL Project – What is it?

A two-phase project to build a compact fully coherent x-ray laser

CXLS

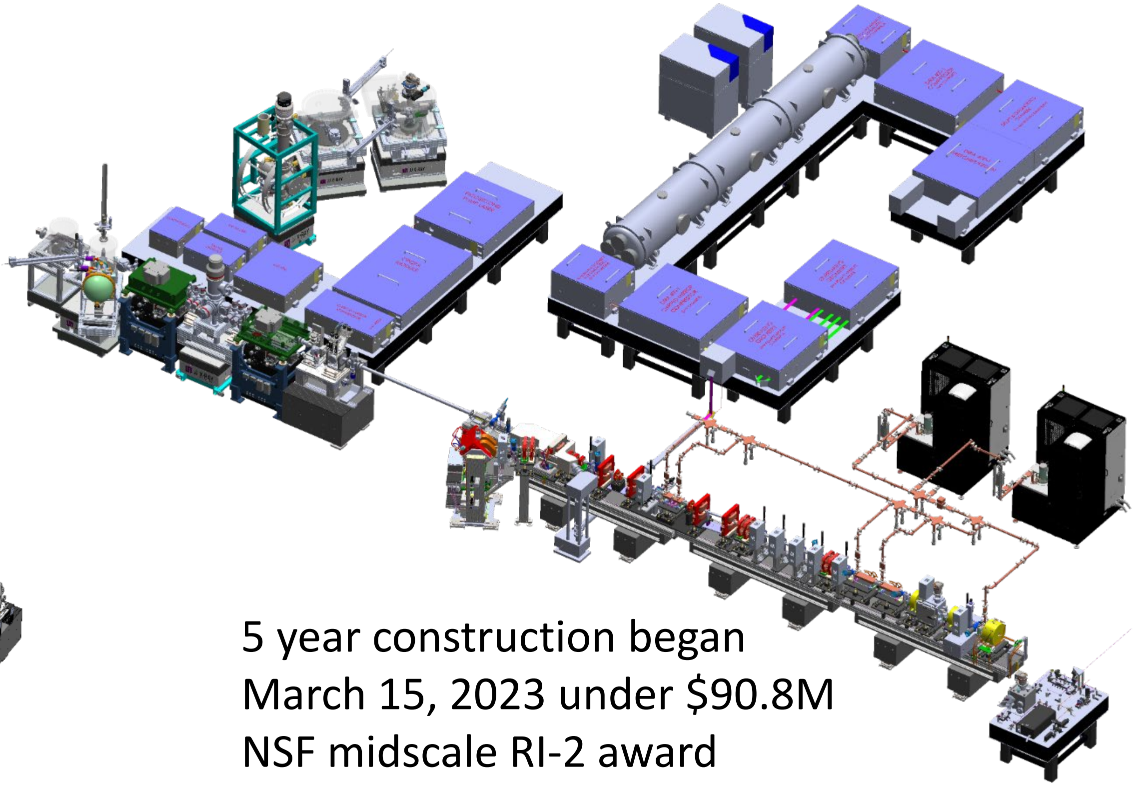
Phase 1 Hard X-ray ICS Source



Built and now commissioning.
First x-rays Feb 2, 2023

CXFEL

Phase 2 Soft X-ray Coherent Laser



5 year construction began March 15, 2023 under $90.8M NSF midscale RI-2 award

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CXFEL includes 80+ People in 16 Institutions

Biochem

Fromme, Petra (Science Dir)
Botha, Sabine
Brown, Michael (U AZ)
Frank, Matthias (UC Davis)
Fung, Russell (UW-Mil)
Grant, Tom (U. Buff.)
Kirian, Rick
Kuhl, Tonya (UC Davis)
Lattman, Eaton
Liu, Wei
Ourmazd, Abbas (UW-Mil)
Phillips, George (Rice)
Ros, Alexandra
Schmidt, Kevin
Schmidt, Marius (UW-Mil)
Schwander, Peter (UW-Mil)
Weierstall, Uwe

Quantum Materials

Teitelbaum, Sam (QM lead)
Kaindl, Robert (CXFEL Lab Dir)
Tongay, Sefaatin
Abbamonte, Peter (UIUC)
Botana, Antia
Comin, Riccardo (MIT)
Chuang, Yi-De (LBL)
Erten, Onur
Gedik, Nuh (MIT)
Mahmood, Fahad (UIUC)
Mitrano, Matteo (Harvard)
Reis, David (Stanford)
Roy, Sujoy (LBL)
Trigo, Mariano (SLAC)

Attosecond AMO

Sandhu, Arvinder (U AZ, AMO lead)
Berrah, Nora (UConn)
Centurion, Martin (U Neb)
Cryan, James (SLAC)
DiMauro, Louis (OSU)
Gessner, Oliver (LBL)
Nelson, Keith (MIT)
Rolles, Daniel (KSU)
Rudenko, Artem (KSU)
Shivaram, Niranjan (Purdue)
Weber, Thorsten (LBL)

Management

Winkel, David (Prog Mgr)
Clark, Deanna
Cottrell, Erica
Reichanadter, Mark

Instrument

Graves, William (Proj Dir)
Dolgashev, Valery (SLAC)
Karkare, Siddharth
Li, Zenghai (SLAC)
Loos, Henrik
Malin, Lucas
Nanni, Emilio (SLAC)
Qiang, Ji (LBL)
Tantawi, Sami (SLAC)
Thornton, Trevor
Tilton, Sean

Engineering

Holl, Mark (Chief Eng)
Brown, Paul (MIT)
Cook, Brandon
Gardeck, Alex
Houkal, Jeff
Jachim, Steven
Liebich, Brett
Ness, Richard
Rednour, Steven
Smith, Dean
Vela, Juan

Undergrad Education

Warble, Kelli (Lead)
Babic, Gregory
Bell, Christina
Boyd, Elena
Brown, Taryn
Dela Rosa, Trixia
DeMott, Ross
Dupre, Alan
Eckrosh, Kevin
Everett, Eric
Eyler, Aaron
Falconer, Jasmin
Jaswal, Rejul
Larsen, Rae
Leonard, Nicholas
Ma, Xinyi
Martinez, Anastasia
Ros, Elena
Semaan, Antonella
Staletovic, Anastasia
Stanton, Jade
Tripathi, Shreya
Valentin, Dariannette

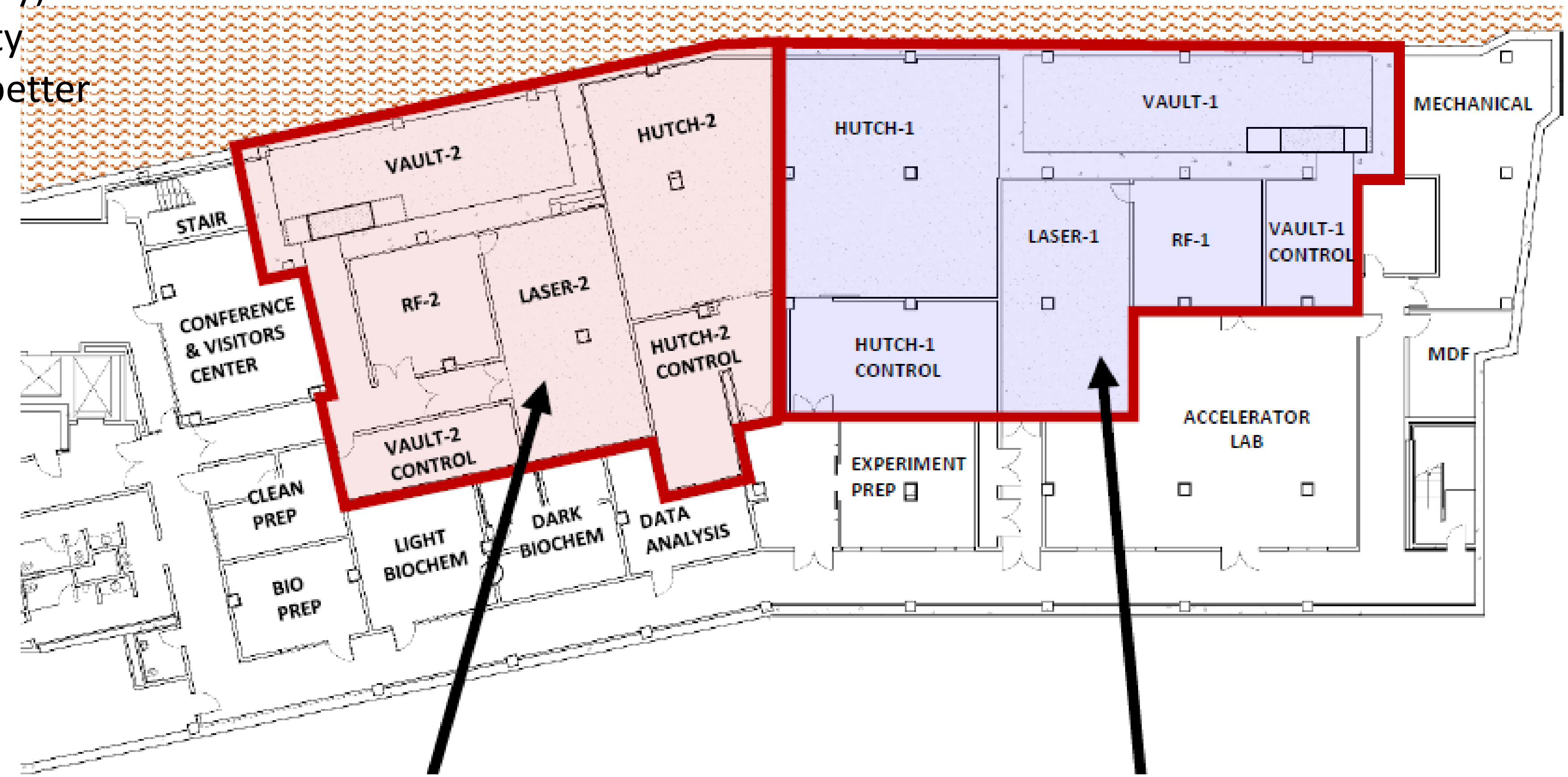
CXFEL Labs

- 2 m thick slab separate from building
- Vibration rated VC-E (TEM quality)
- 0.25 - 0.5 C temperature stability
- Class 100k clean conditions or better
- Low background B-fields
- Faraday cage RF room

The CXFEL Project includes two lab spaces for independent instruments

➢ Hard x-ray CXLS is commissioning; prototype of CXFEL technologies

➢ CXFEL under construction



CXFEL under construction in these labs

CXLS is constructed and commissioning in these labs

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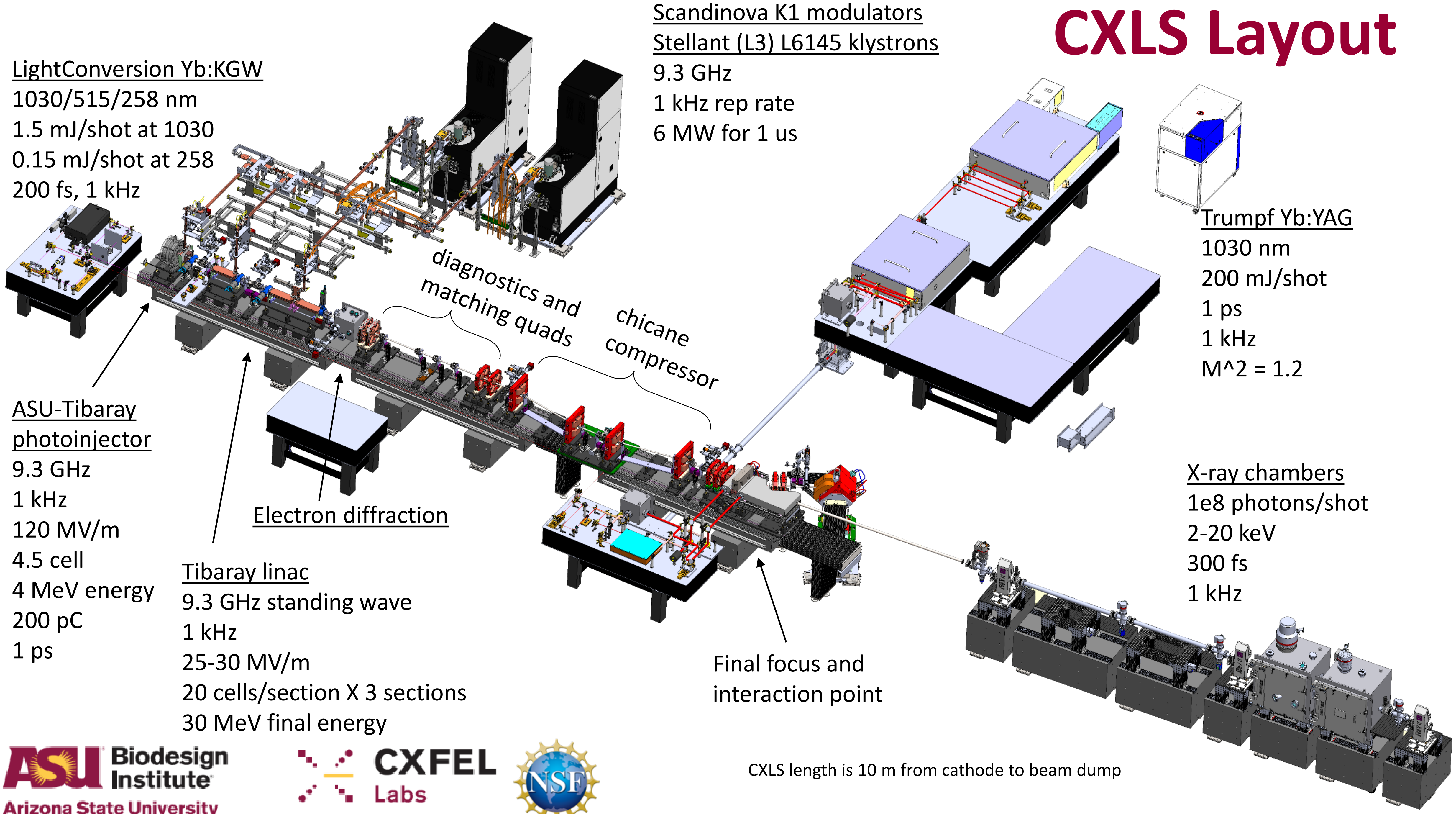
CXLS

Construction Complete and now Commissioning

First x-rays February 2023

CXLS Layout



CXLS length is 10 m from cathode to beam dump

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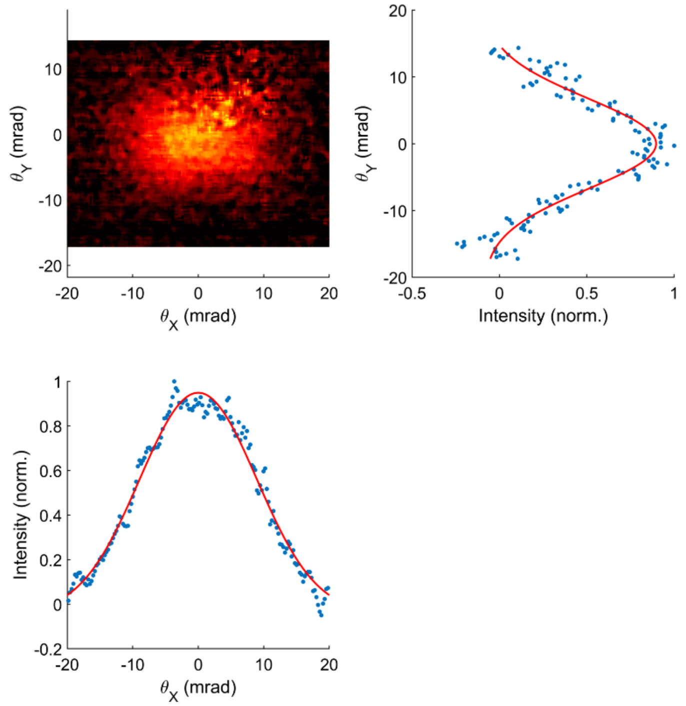
CXLS Hard X-ray Design Parameters

Parameter	**0.1% Bandwidth**	**5% Bandwidth**	**Units**
Photon energy range	2 – 20	2 – 20	keV
Average flux	$5x10^{9}$	$1x10^{11}$	photons/s
Average brilliance	$2x10^{12}$	$5x10^{12}$	photons/(s .1% mm^{2}mrad^2)
Peak brilliance	$3x10^{19}$	$9x10^{18}$	photons/(s .1% mm^{2}mrad^2)
RMS horizontal size	3.0	3.0	microns
RMS vertical size	3.0	3.0	microns
RMS horizontal angle	4.0	4.0	mrad
RMS vertical angle	4.0	4.0	mrad
Photons per pulse	$5x10^{6}$	$1x10^{8}$	
RMS pulse length	<500	<500	fs
RMS timing jitter	<50	<50	fs
Repetition rate	1000	1000	Hz

First x-rays Feb 2023



Initial experiments produce ~3e5 15 keV photons/shot at 1 kHz operating at 80 mJ ICS laser energy and Q = 20 pC

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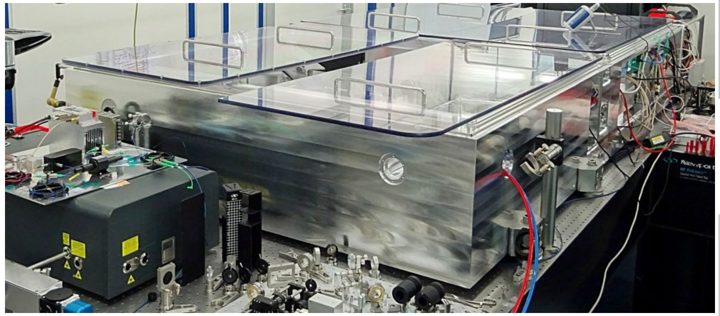
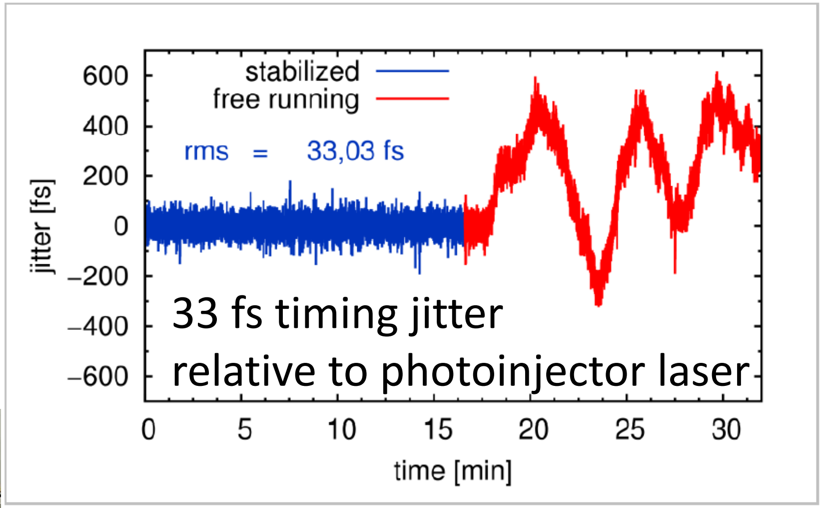
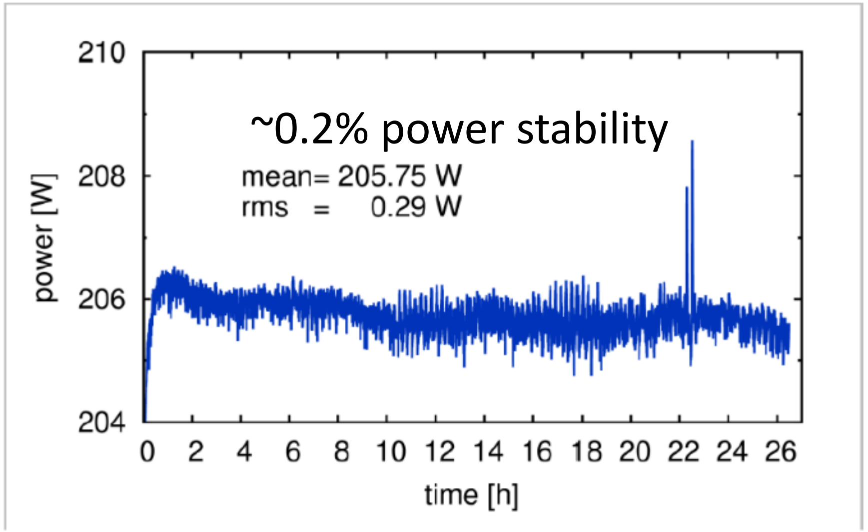
ICS Laser Test Results

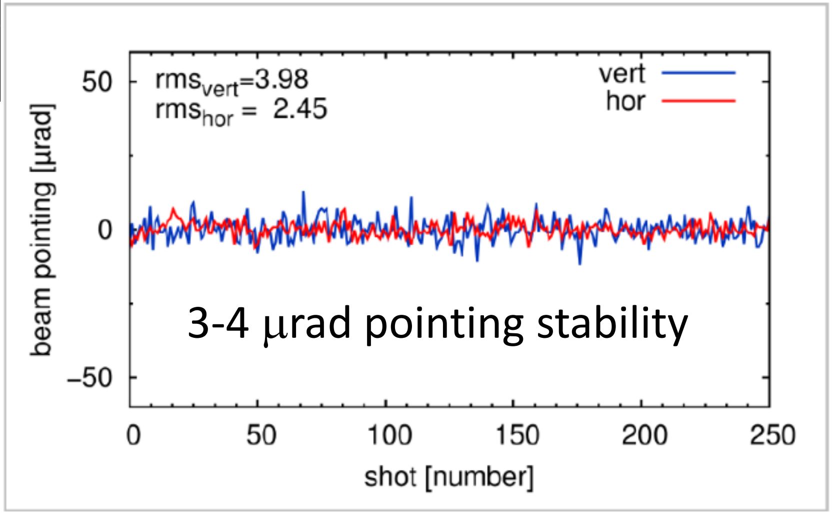
ICS laser

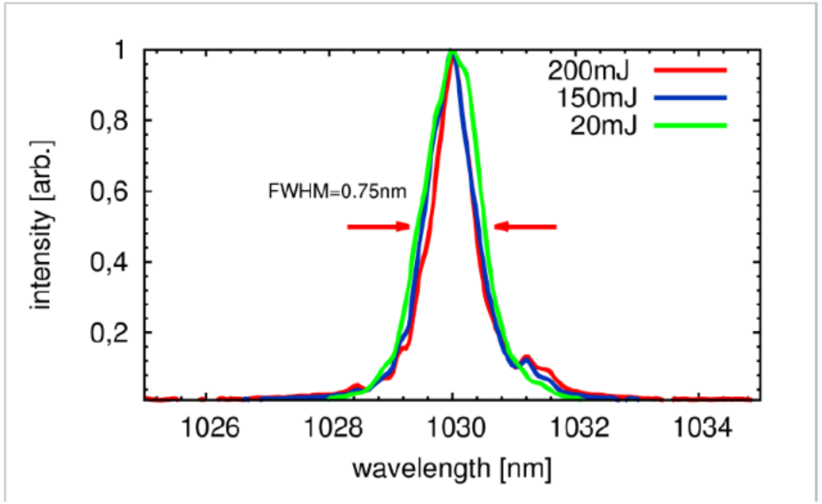
Trumpf Dira 200-1
1030 nm Yb:YAG thin disk regen
200 mJ at 1000 Hz
1.1 ps FWHM











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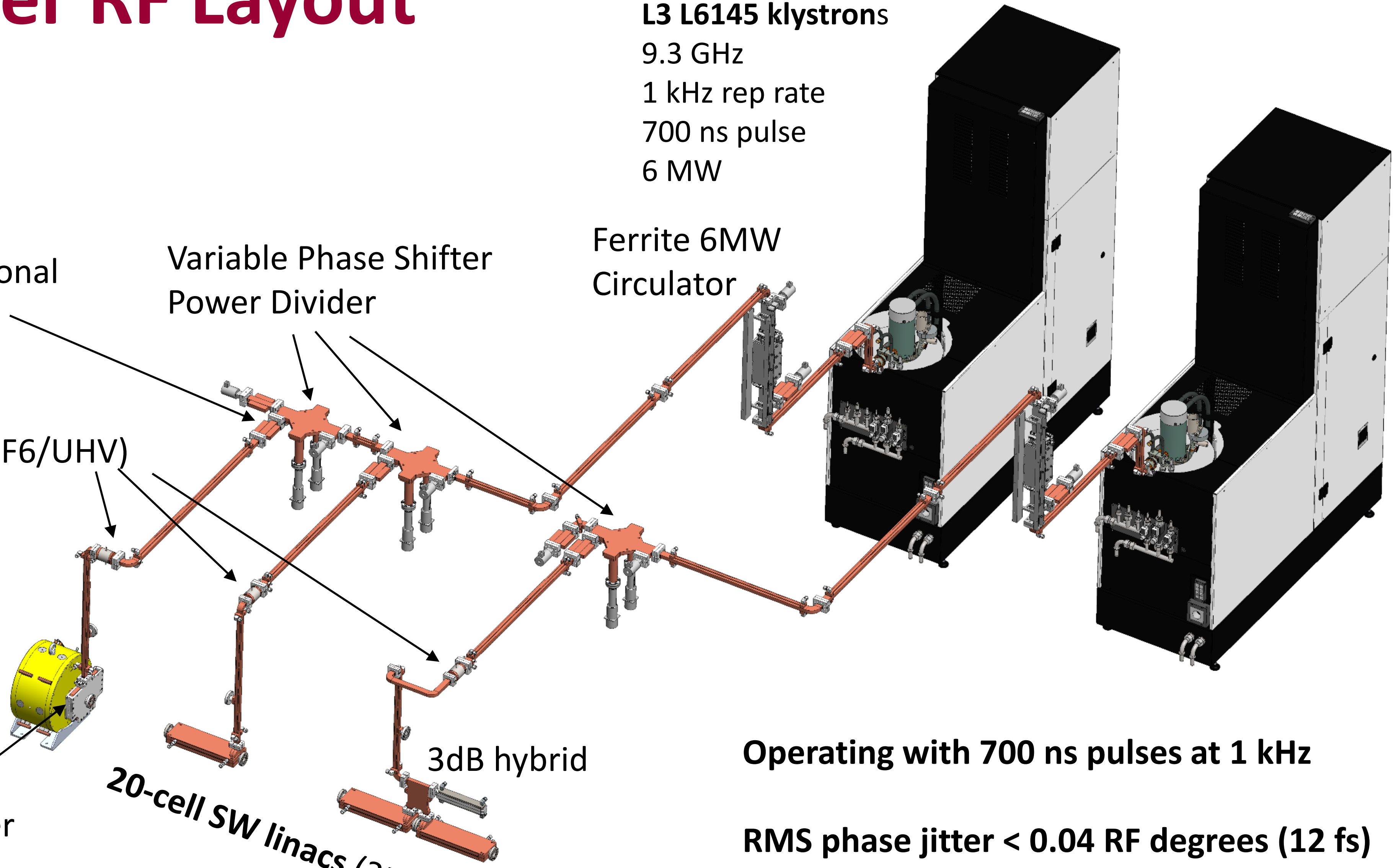
High Power RF Layout

Scandinova K1 modulators
L3 L6145 klystrons
9.3 GHz
1 kHz rep rate
700 ns pulse
6 MW



Operating with 700 ns pulses at 1 kHz

RMS phase jitter < 0.04 RF degrees (12 fs)
RMS amplitude jitter ~500 ppm at 6 MW

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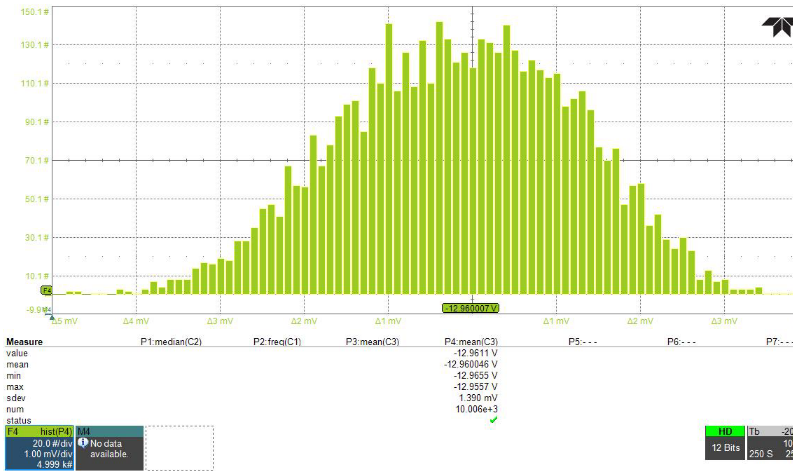
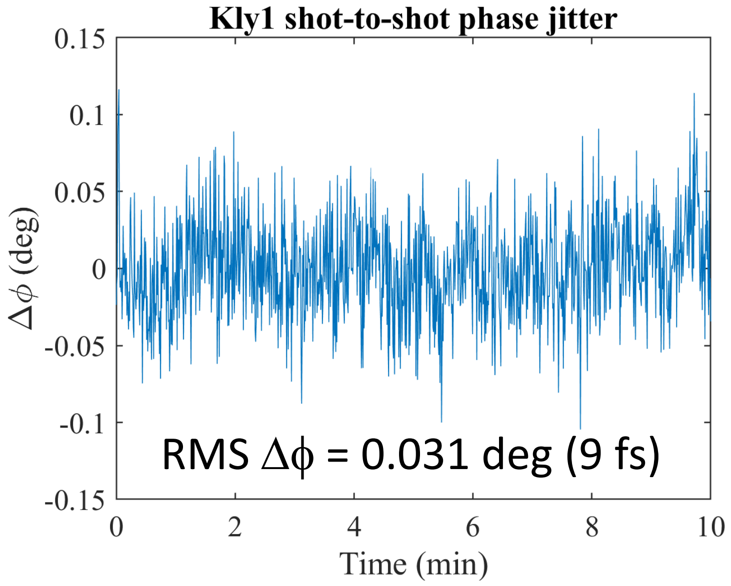
RF Performance

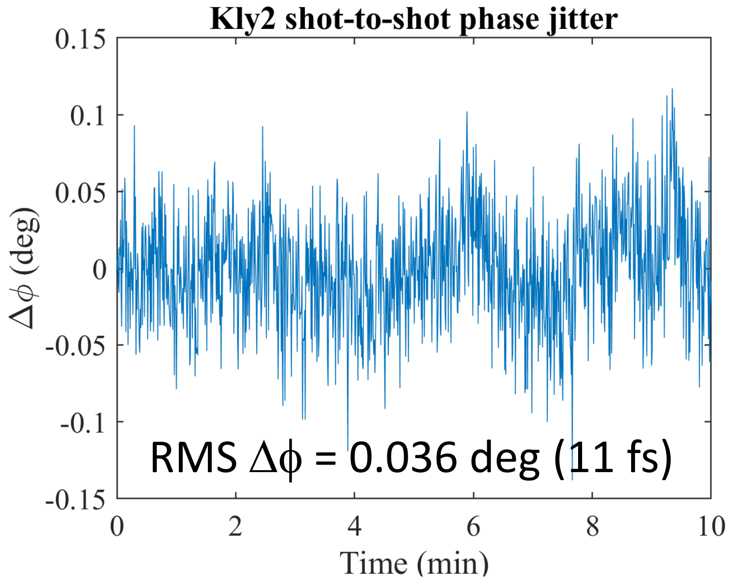
Stellant L-6145 klystrons
6 MW, 700 ns, 1 kHz
59 dB small signal gain

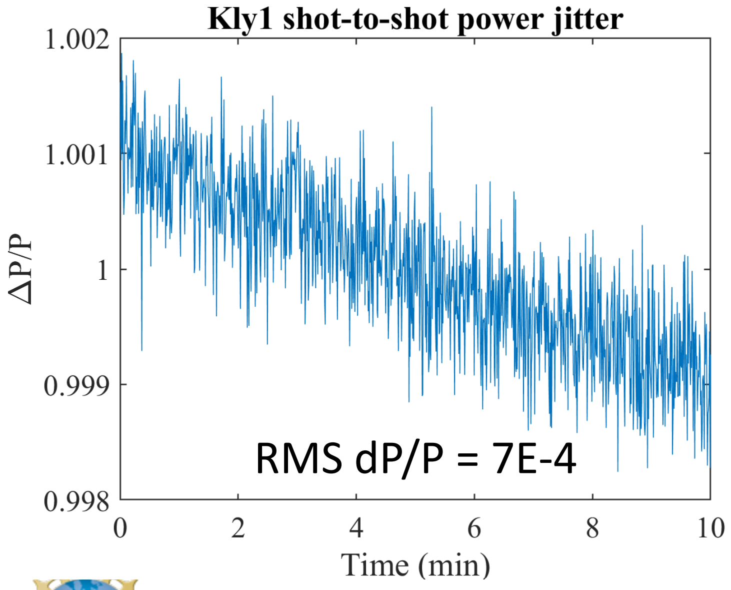
Scandinova K1 modulator
130 kV, 98 A, 2.5 us, 1 kHz

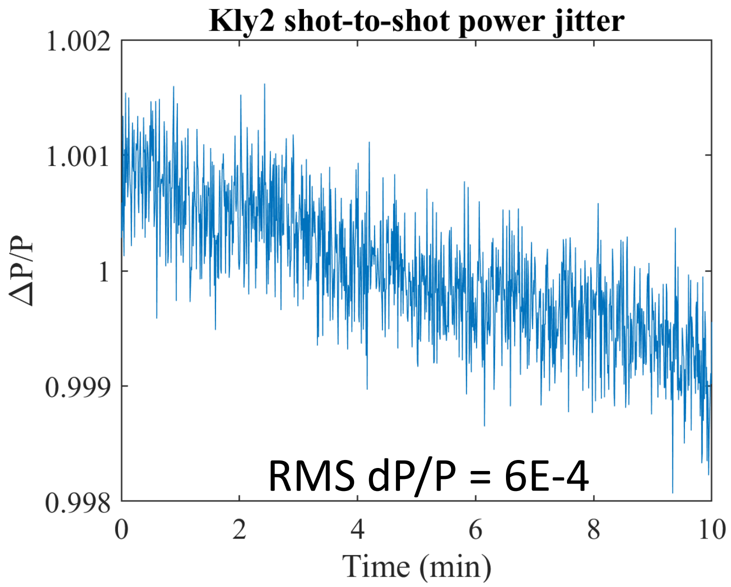
RMS jitter 100 ppm over 10k shots











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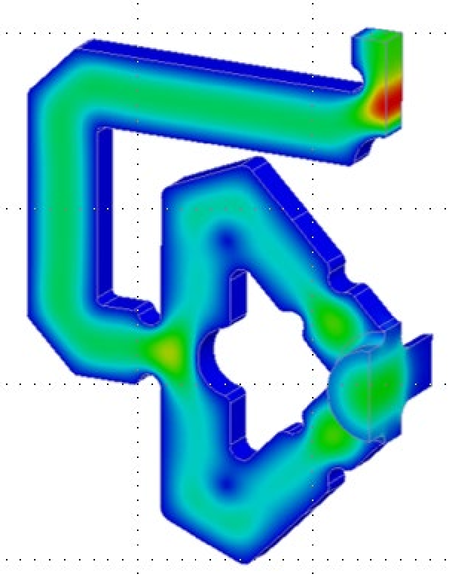
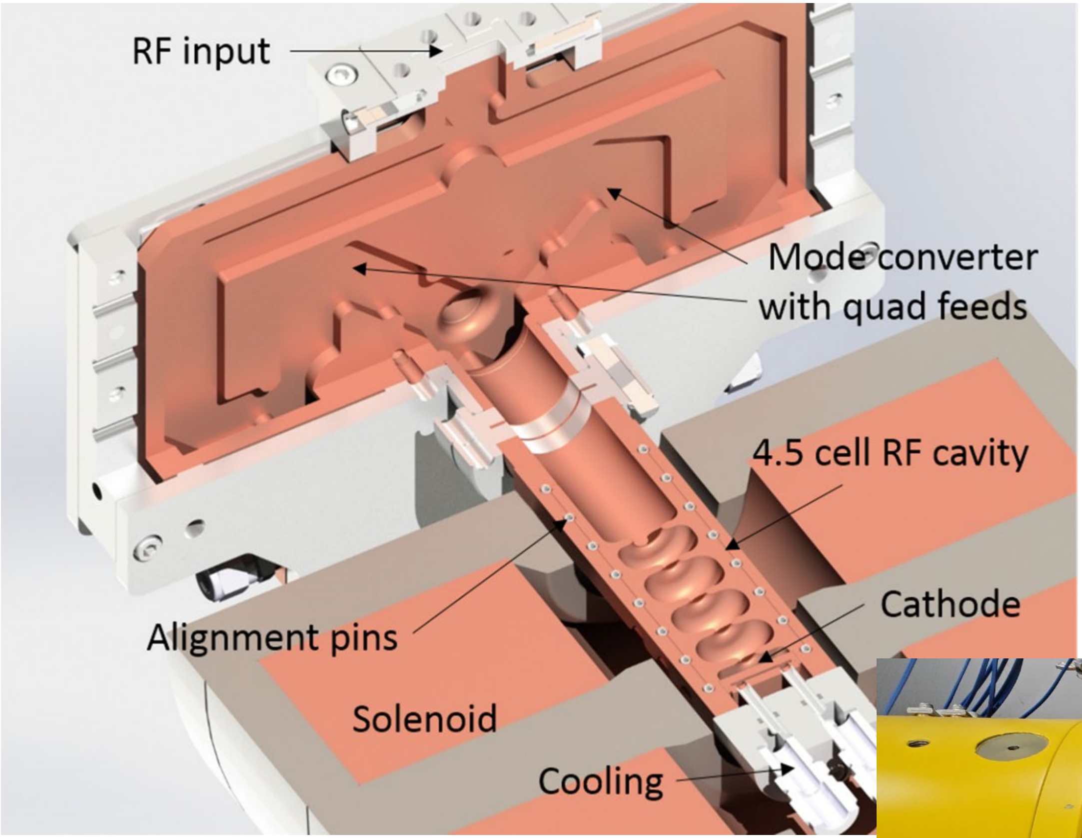
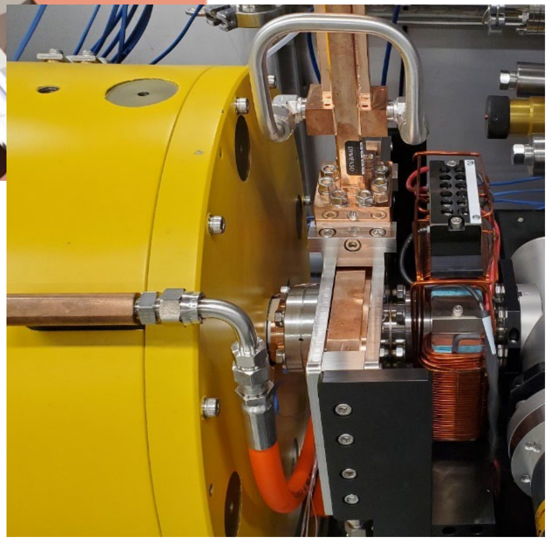
kHz X-band Photoinjector





- V. Dolgashev (SLAC) RF design
- Mode converter with quad RF feeds
- 4.5 cells
- 9.3 GHz RF
- 3 MW peak power
- 4 MeV final energy
- 120 MV/m on cathode
- 1 kHz repetition rate
- Embedded in tape-wound solenoid

Typical ops
2.9 MW
3.8 MeV
114 MV/m



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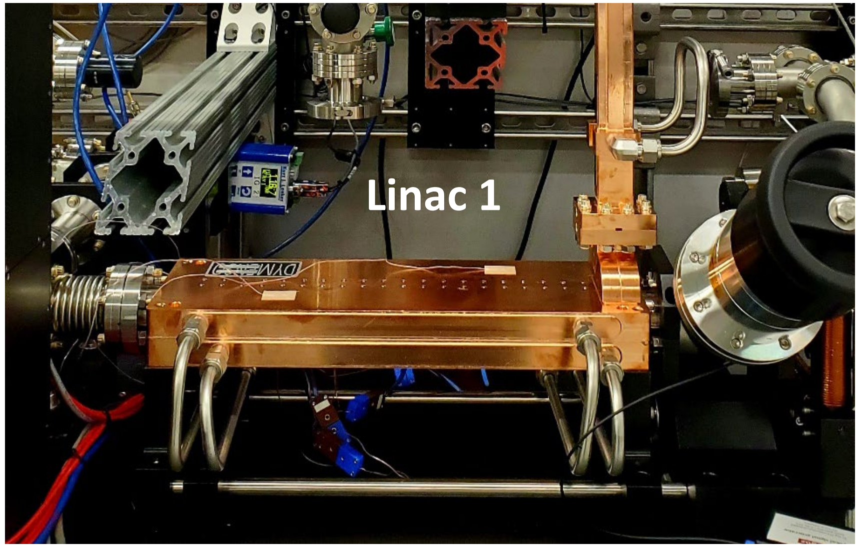
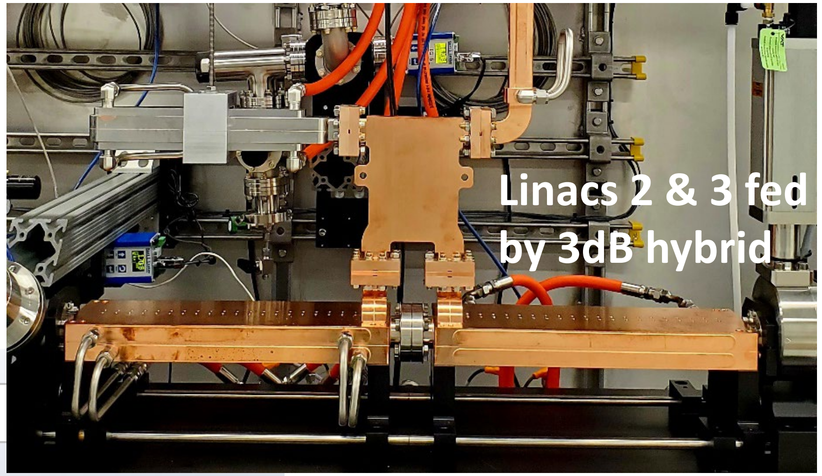
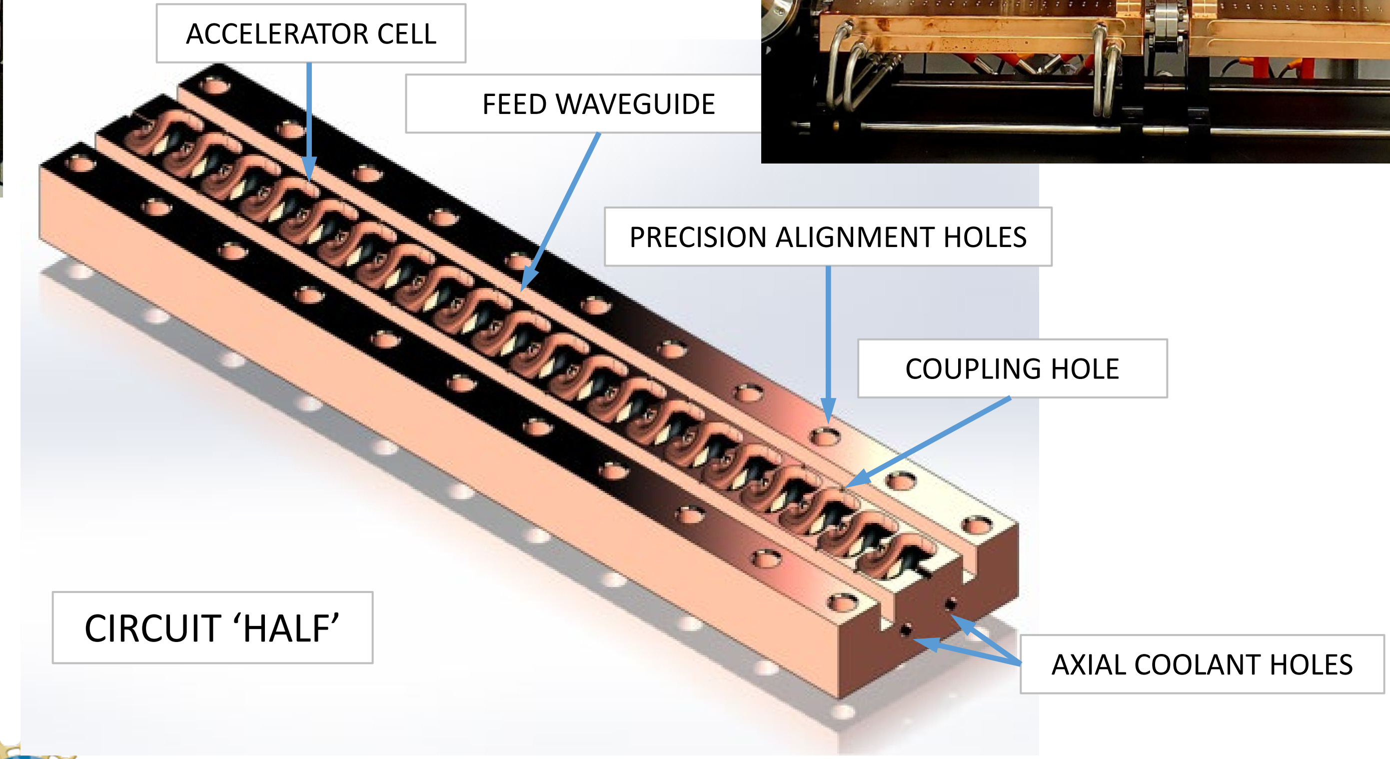
9.3 GHz Distributed-Coupling SW Linac

Tantawi and Li (SLAC and Tibaray)



Tantawi et al, Phys Rev Accel and Beams 23, 092001 (2020)





- 9.3 GHz 20-cell structure, 35 cm long
- 30 MV/m gradient for 2 MW input
- 165 MOhm/m shunt impedance
- 170 ns fill time
- 3 mm apertures
- $E_{surface}$ to E_{accel} = 4:1
- 1 kHz rep rate
- Distributed coupling to each cell
- Inexpensive

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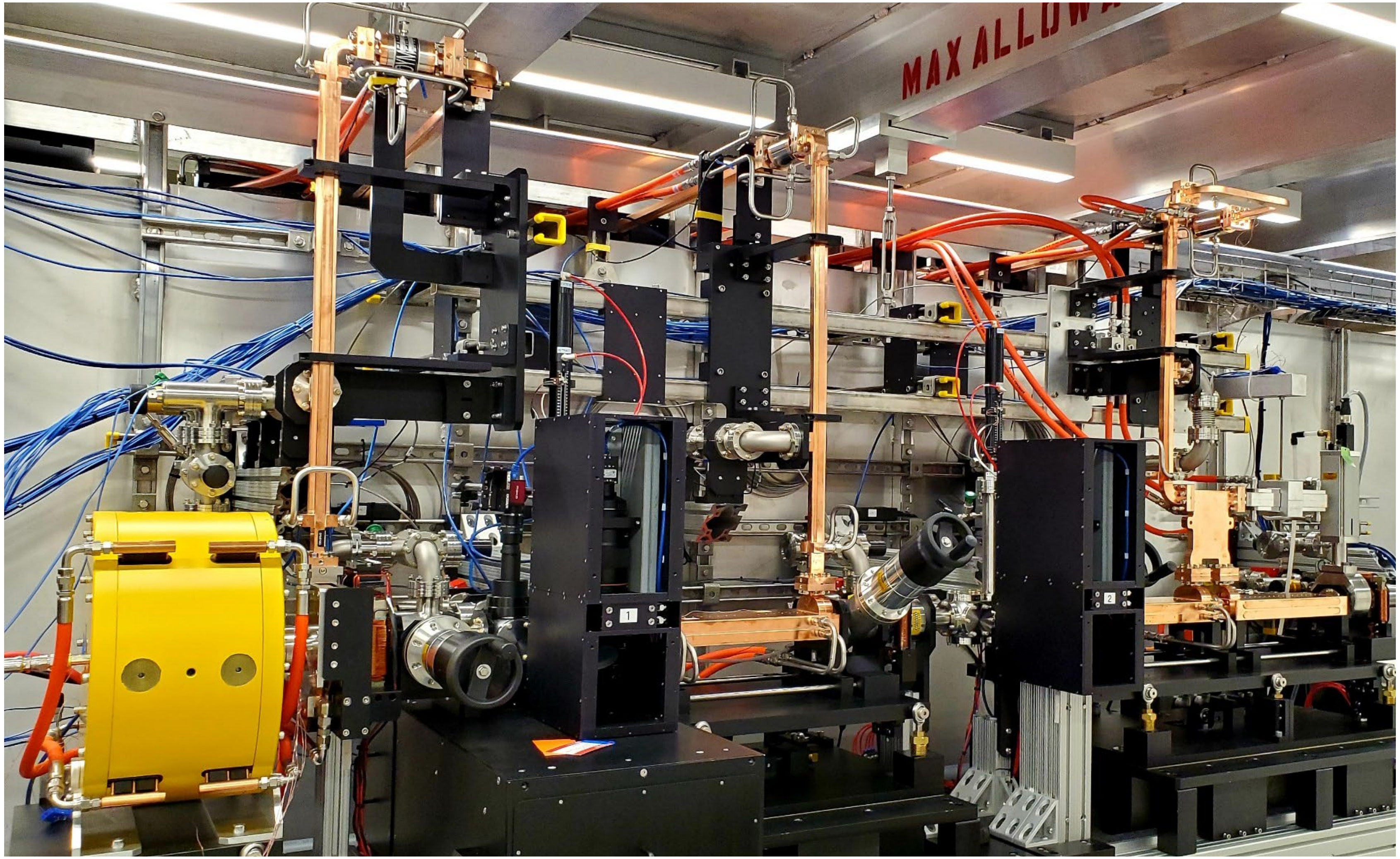
Linac Performance

Commissioned to

- 32 MV/m gradient
- 128 MV/m surface field
- 1000 Hz rep rate
- 700 ns RF pulse
- 2 MW delivered to each structure

- ~10 pC per 700 ns RF pulse dark current
- 30 MeV final beam energy (still tuning)
- RMS dE/E = 50-200 ppm



CXFEL

5 year $91M construction award from NSF Bio Directorate March 2023

Category (incl equipment and labor)	Cost ($)
Accelerator	$10,653,387
Lasers	$20,128,396
Science Endstations	$17,255,770
X-ray Systems	$3,487,768
Facilities and Engineering	$13,895,913
Validation of Operational Capability	$5,355,435
Project Management	$6,621,953
Sub total	**$77,398,622**
Contingency	**$13,401,378**
Total Project Cost	**$90,800,000**

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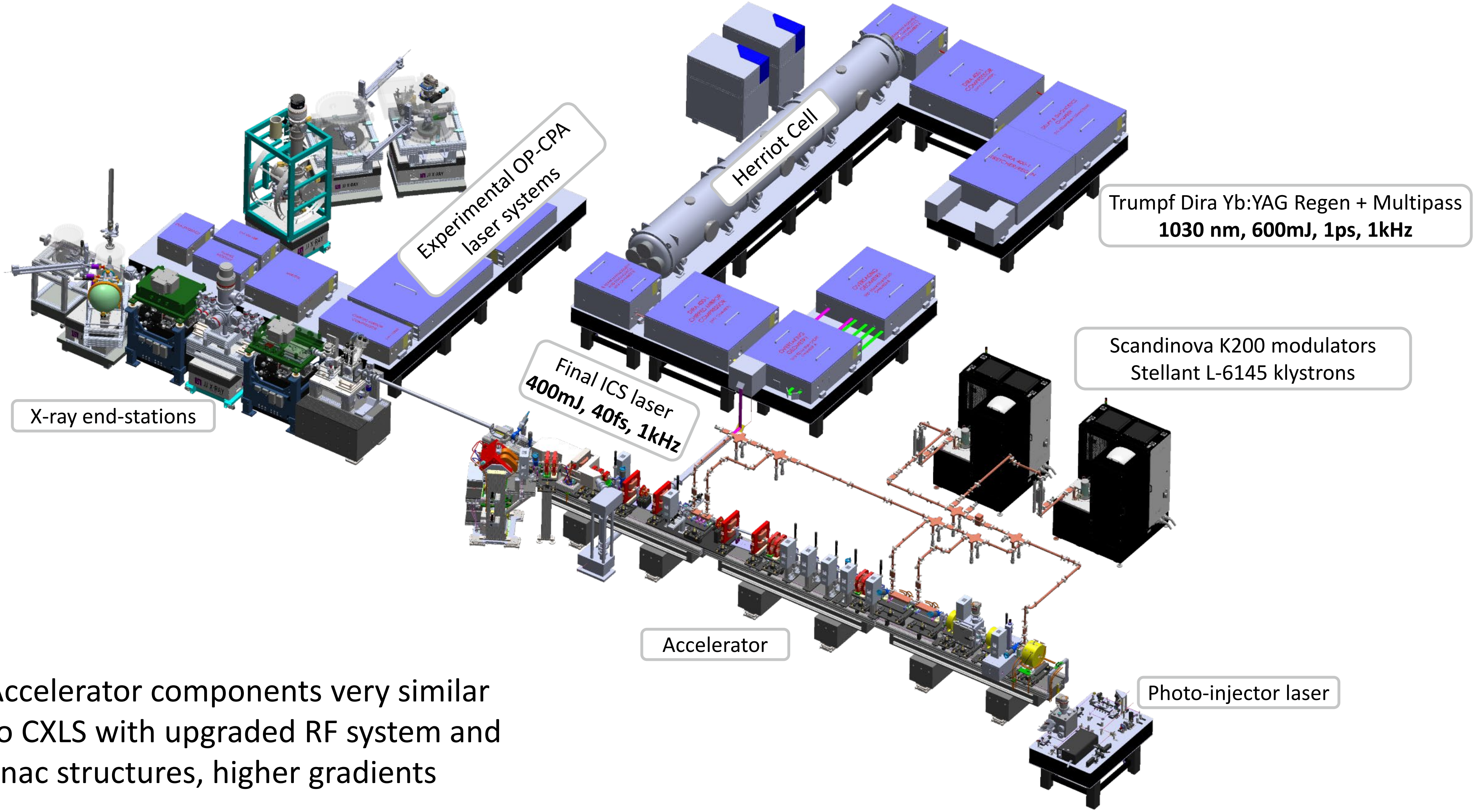
CXFEL Layout



Accelerator components very similar to CXLS with upgraded RF system and linac structures, higher gradients

Laser systems are higher power and shorter pulse compared to CXLS.

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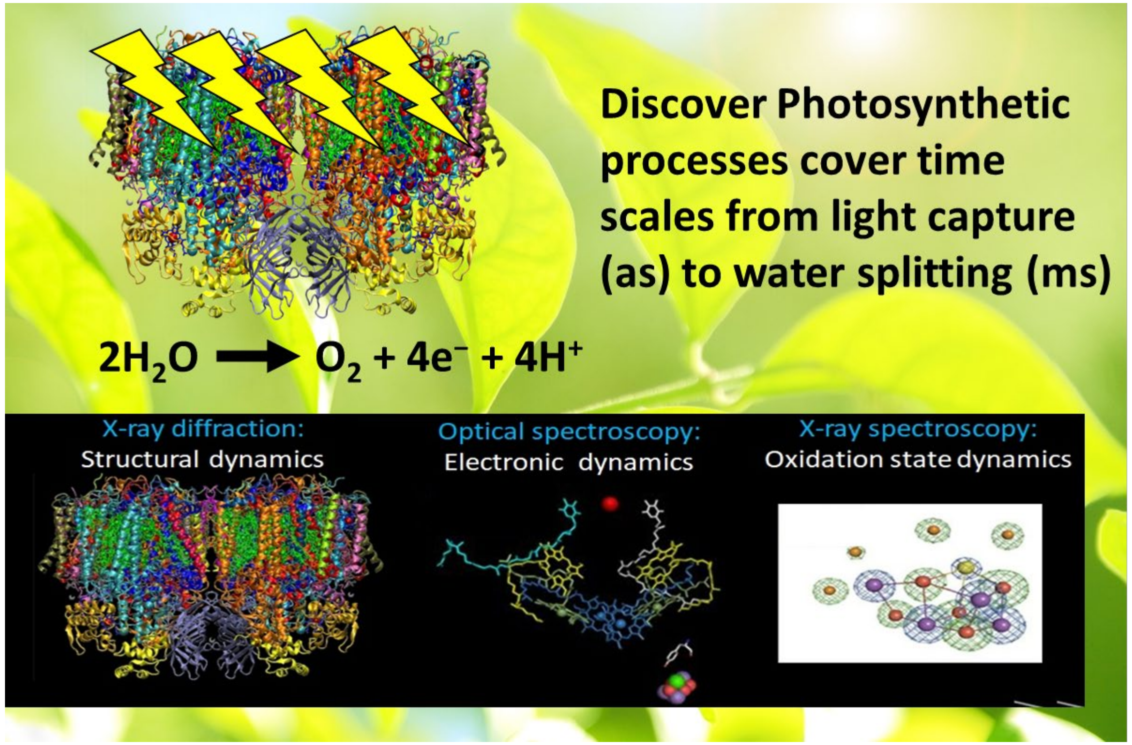
CXFEL Soft X-ray Parameters

Photon energy	250	1000	2500	eV
X-ray wavelength	4.9	1.2	0.49	nm
Average flux at 1 kHz	8.0E+11	1.1E+11	4.4E+10	photons/sec
Average brilliance	1.3E+15	1.2E+16	7.3E+16	ph/s/mm^2/mrad^2
Peak brilliance	1.2E+28	5.6E+28	1.4E+29	ph/s/mm^2/mrad^2
RMS source size	0.9	0.5	0.3	um
RMS source divergence	440	188	117	urad
X-ray flux per shot - energy	32	18	18	nJ
Photons per pulse	8.0E+08	1.1E+08	4.4E+07	Photons/shot
Pulse length FWHM	9.1	4.6	1.9	fs
Bandwidth FWHM	0.18	0.09	0.08	%
RMS timing jitter	<10	<10	<10	fs
Repetition rate	1000	1000	1000	Hz
Electron beam energy	14	29	46	MeV

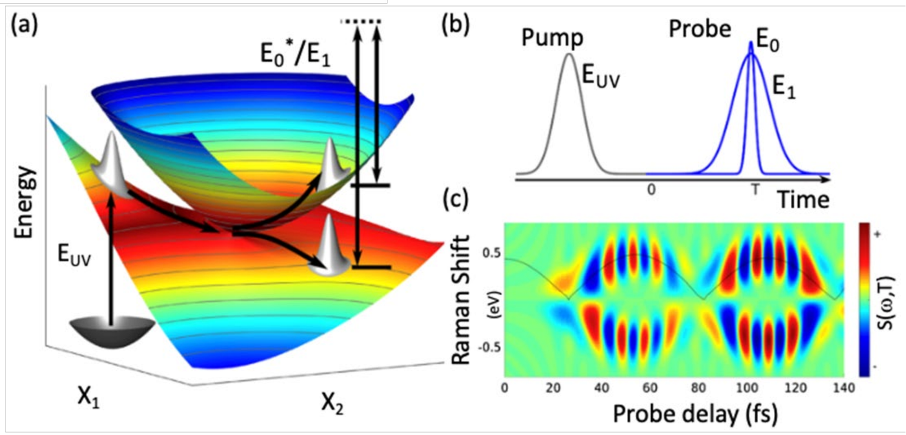
CXFEL Ultrafast Science

Bio: Study the dynamics of structural, electronic and oxidation changes

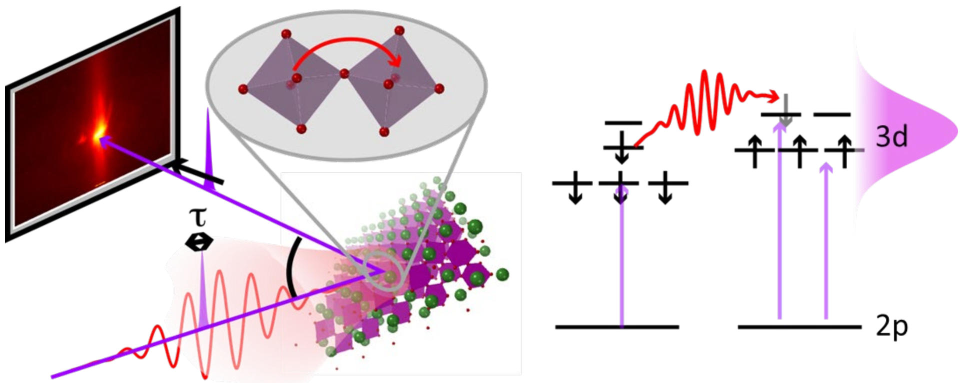


AMO: Track electronic wavepackets through conical intersections of molecules

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



QM: Manipulate and track coherences in correlated electron materials



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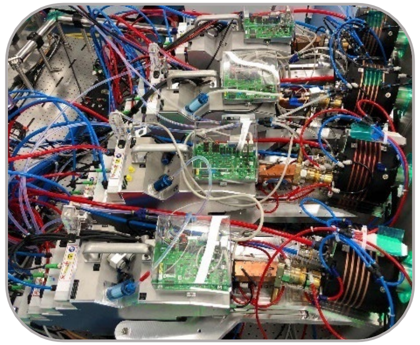
ICS Laser for CXFEL - ASU

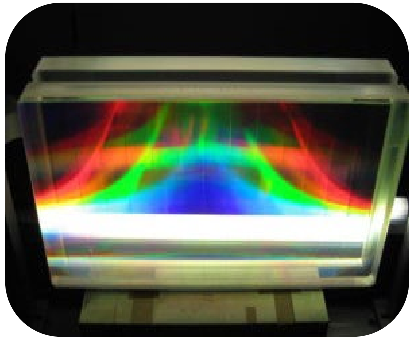
Courtesy of Gaia Barbiero | TRUMPF Scientific Lasers

Based on

European Commission

Laser Lighting Rod Project



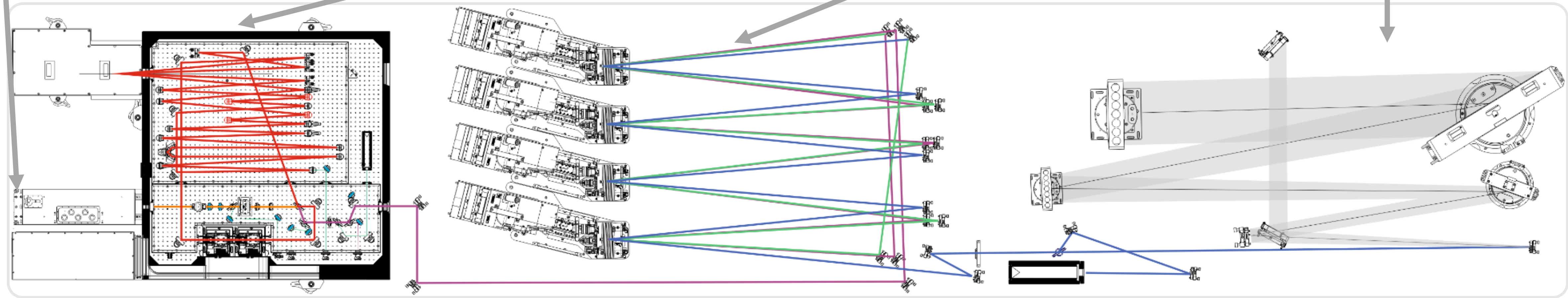


Custom oscillator + TruMicro 2000
100 µJ, 10 W

Dira 350-1
> 300 mJ, > 300 W

Mutlipass 600-1
600 mJ, 600 W

Compressor 500-1
> 480 mJ, > 480 W, < 850 fs



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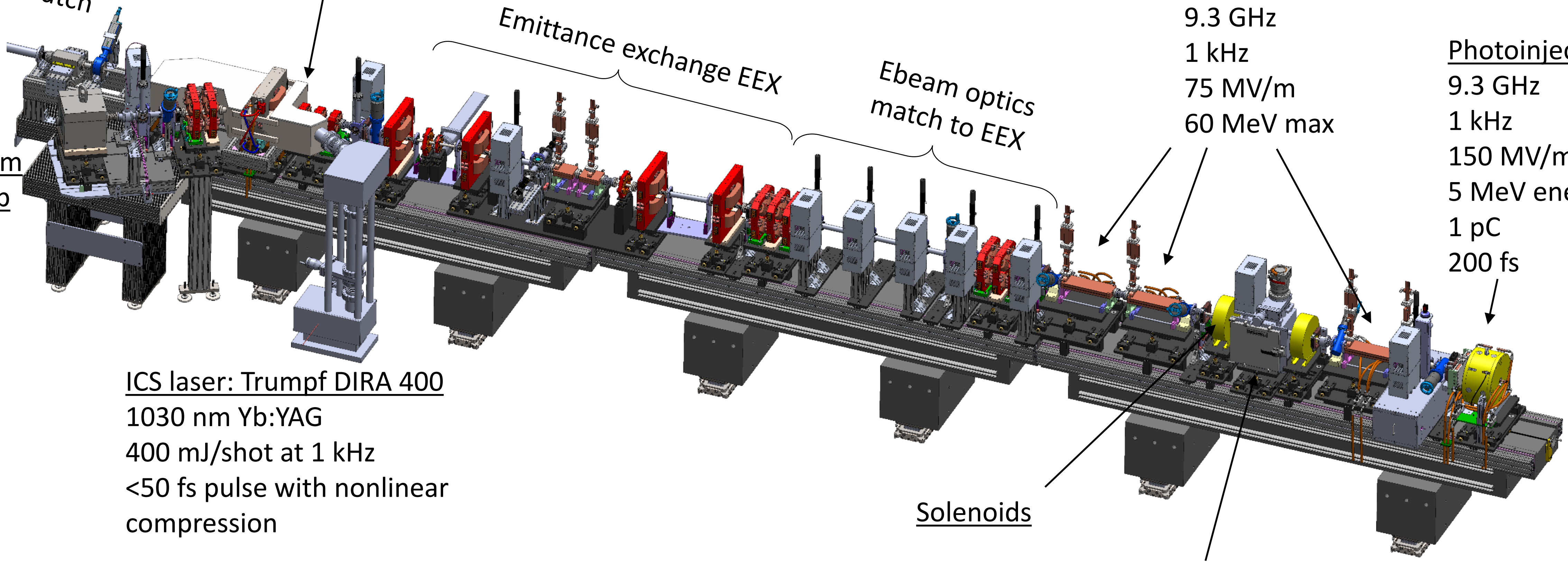
CXFEL Accelerator Layout



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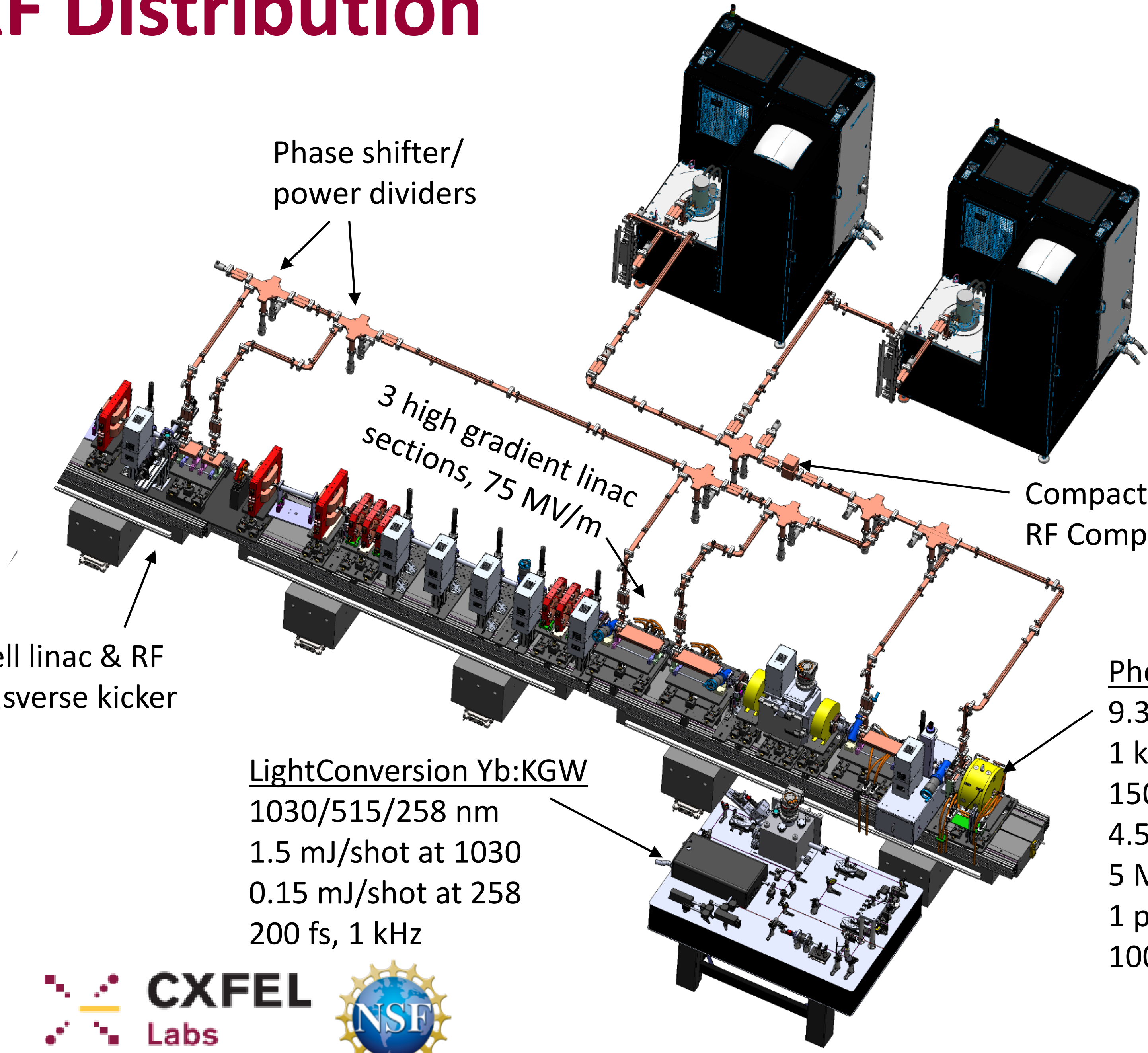
CXFEL RF Distribution



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Summary

- CXFEL is a 2-stage project involving 80 researchers at 12 institutions
  - Stage 1 CXLS hard x-ray source is complete and now commissioning.
  - Stage 2 CXFEL has just begun construction.

- Initial CXLS performance is very stable. Now increasing charge to reach full flux. User operations start 2024.

- CXFEL coherent soft x-ray source construction over next 5 years. Technologies closely based on CXLS with addition of electron diffraction and emittance exchange to produce nanobunched ebeam.

- **We are hiring scientists and engineers (and students!) in laser, accelerator, and x-ray science.** Positions available from postdocs to the most senior scientists. Please contact me at wsg@asu.edu for more information.