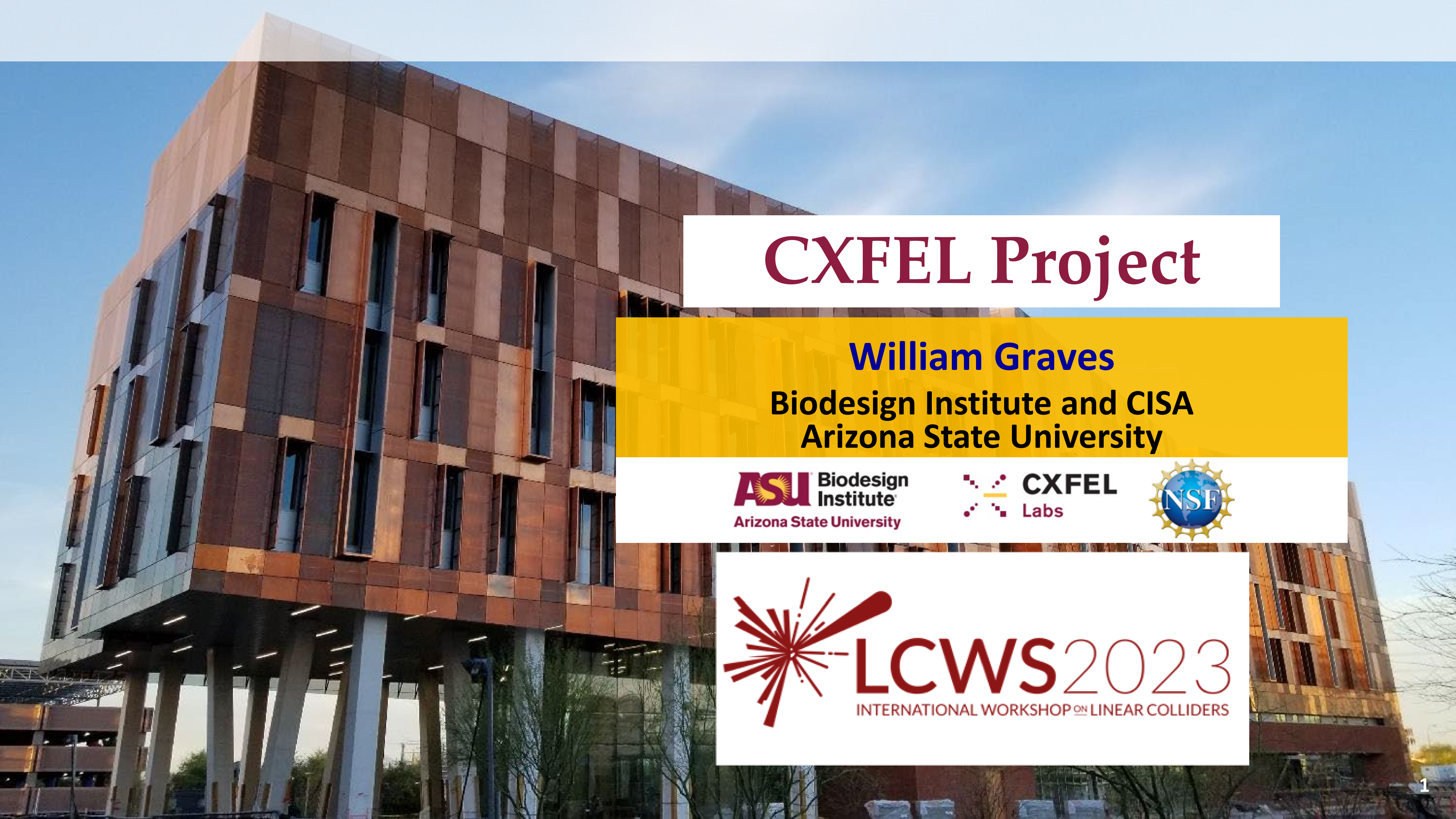

CXFEL Project

William Graves

Biodesign Institute and CISA
Arizona State University

ASU Biodesign Institute Arizona State University

CXFEL Labs

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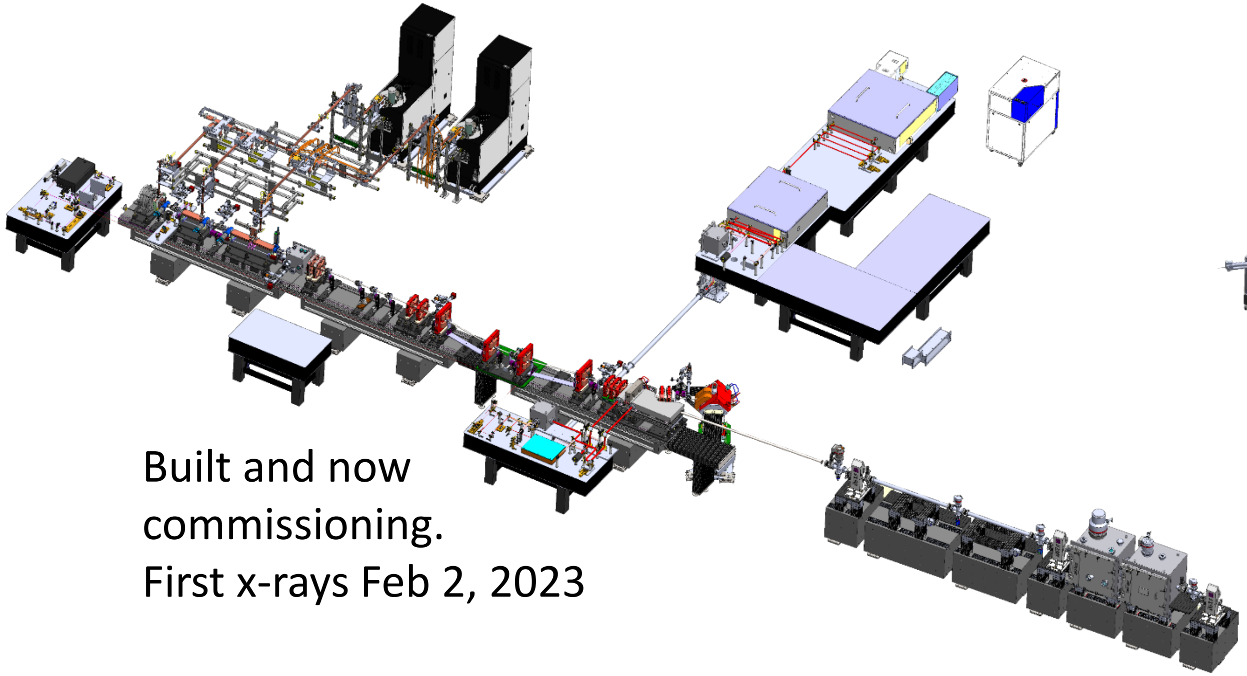
LCWS2023
INTERNATIONAL WORKSHOP ON LINEAR COLLIDERS

CXFEL Project – What is it?

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

CXLS

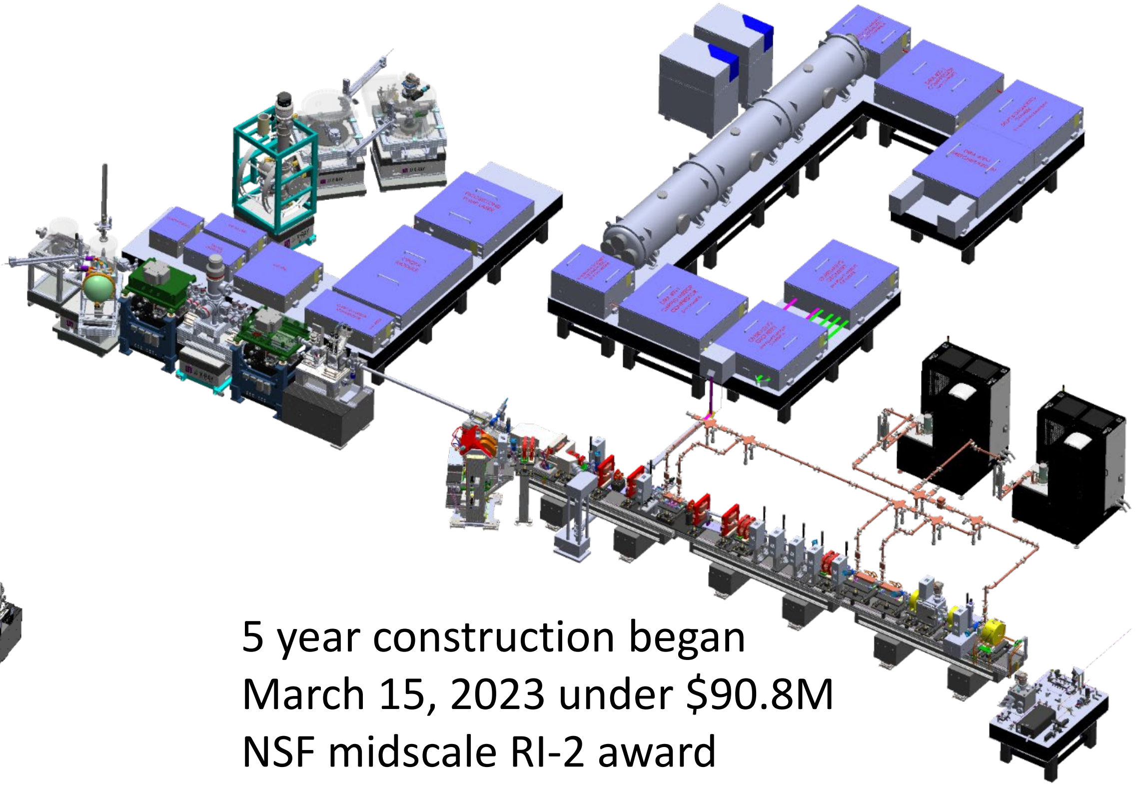
Phase 1 Hard X-ray ICS Source



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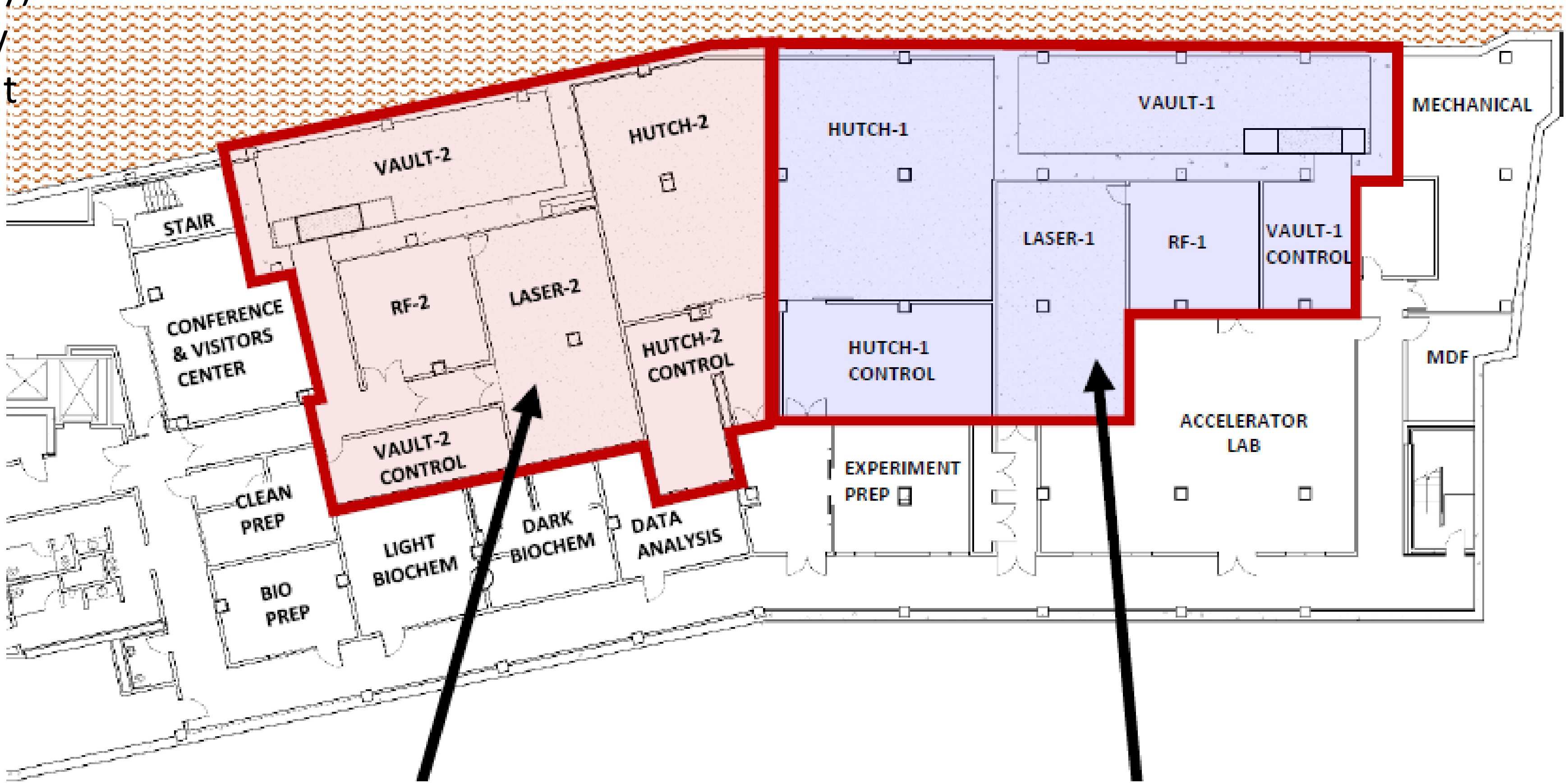
- 2 m thick slab separate from building
- Vibration rated VC-E (TEM quality)
- 0.25 - 0.5 C temperature stability
- Class 100k conditions throughout
- Low background B-fields
- Faraday cage RF room

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

CXFEL includes 80+ People in 16 Institutions

Biochem

Fromme, Petra (Science Dir)
Botha, Sabine
Brown, Michael (U AZ)
Frank, Matthias (UC Davis)
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)
Weber, Thorsten (LBL)

Management

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

Instrument

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

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

Education

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

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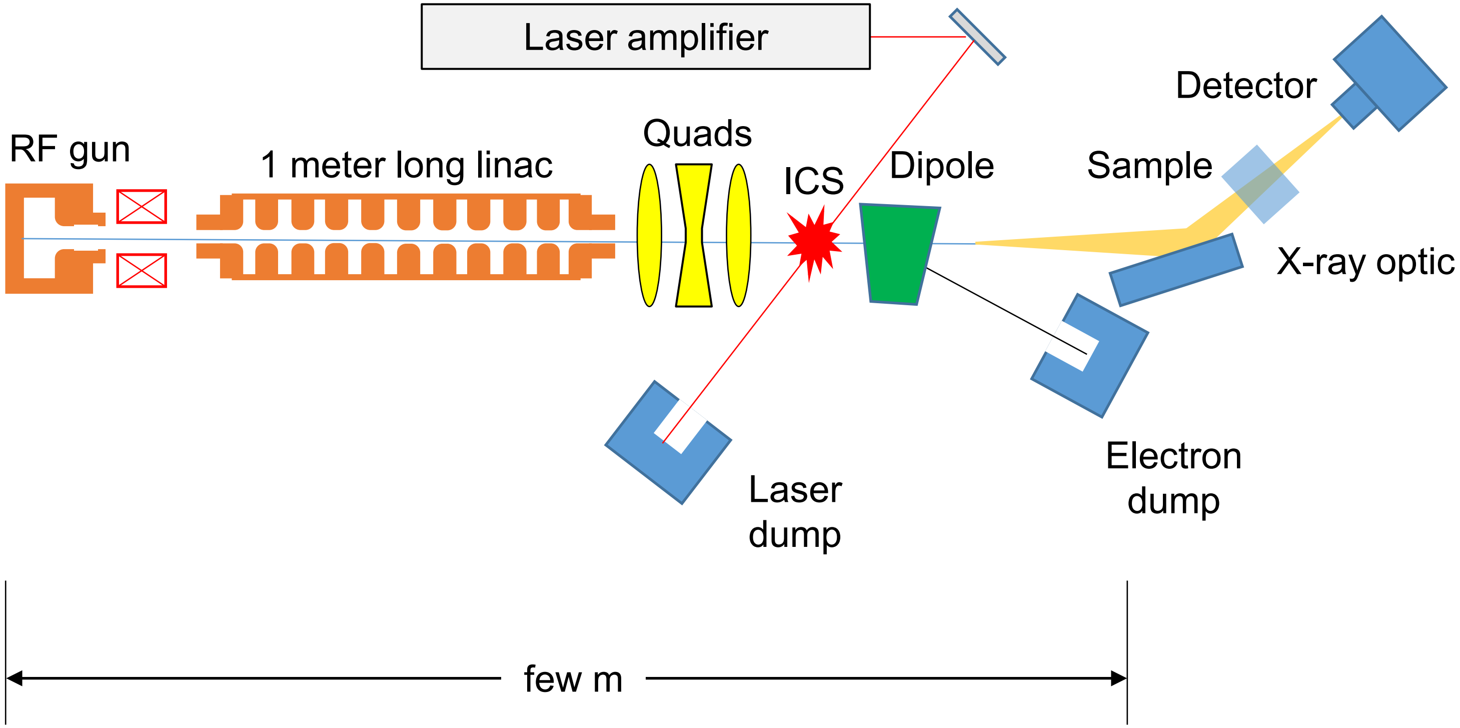
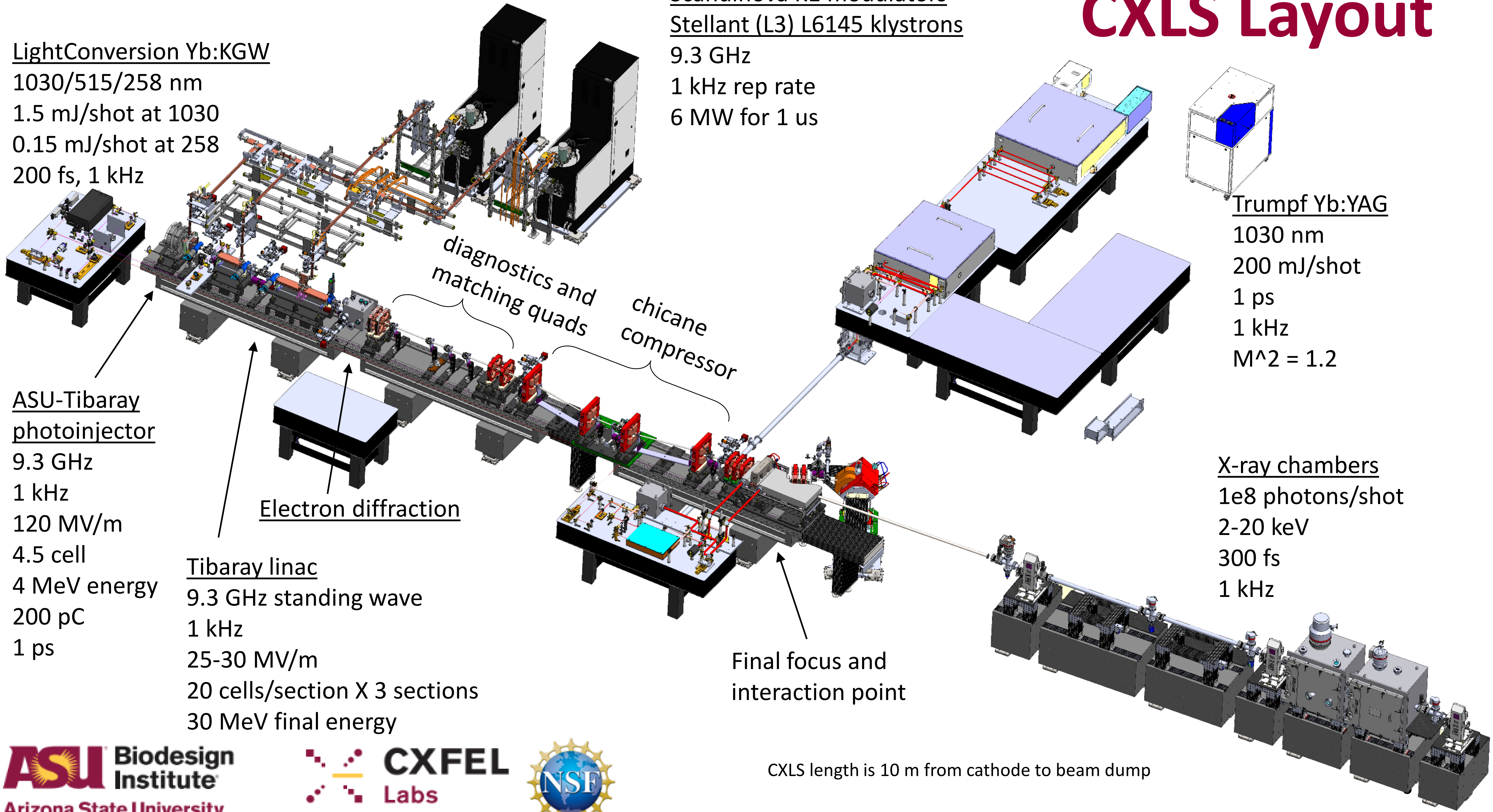
Basic Layout for Inverse Compton Scattering (ICS)



CXLS Layout



LightConversion Yb:KGW
1030/515/258 nm
1.5 mJ/shot at 1030
0.15 mJ/shot at 258
200 fs, 1 kHz

Scandinova K1 modulators
Stellant (L3) L6145 klystrons
9.3 GHz
1 kHz rep rate
6 MW for 1 us

Trumpf Yb:YAG
1030 nm
200 mJ/shot
1 ps
1 kHz
M^2 = 1.2

ASU-Tibaray photoinjector
9.3 GHz
1 kHz
120 MV/m
4.5 cell
4 MeV energy
200 pC
1 ps

Tibaray linac
9.3 GHz standing wave
1 kHz
25-30 MV/m
20 cells/section X 3 sections
30 MeV final energy

X-ray chambers
1e8 photons/shot
2-20 keV
300 fs
1 kHz

CXLS length is 10 m from cathode to beam dump

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CXLS Construction

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CXLS Laser Systems

Timing of PI laser oscillator to RF MO via Menlo Systems Sync achieves 100 fs rms jitter

Timing of ICS laser amplifier to PI amplifier has 33 fs rms jitter

Up to 150 uJ of UV for cathode.

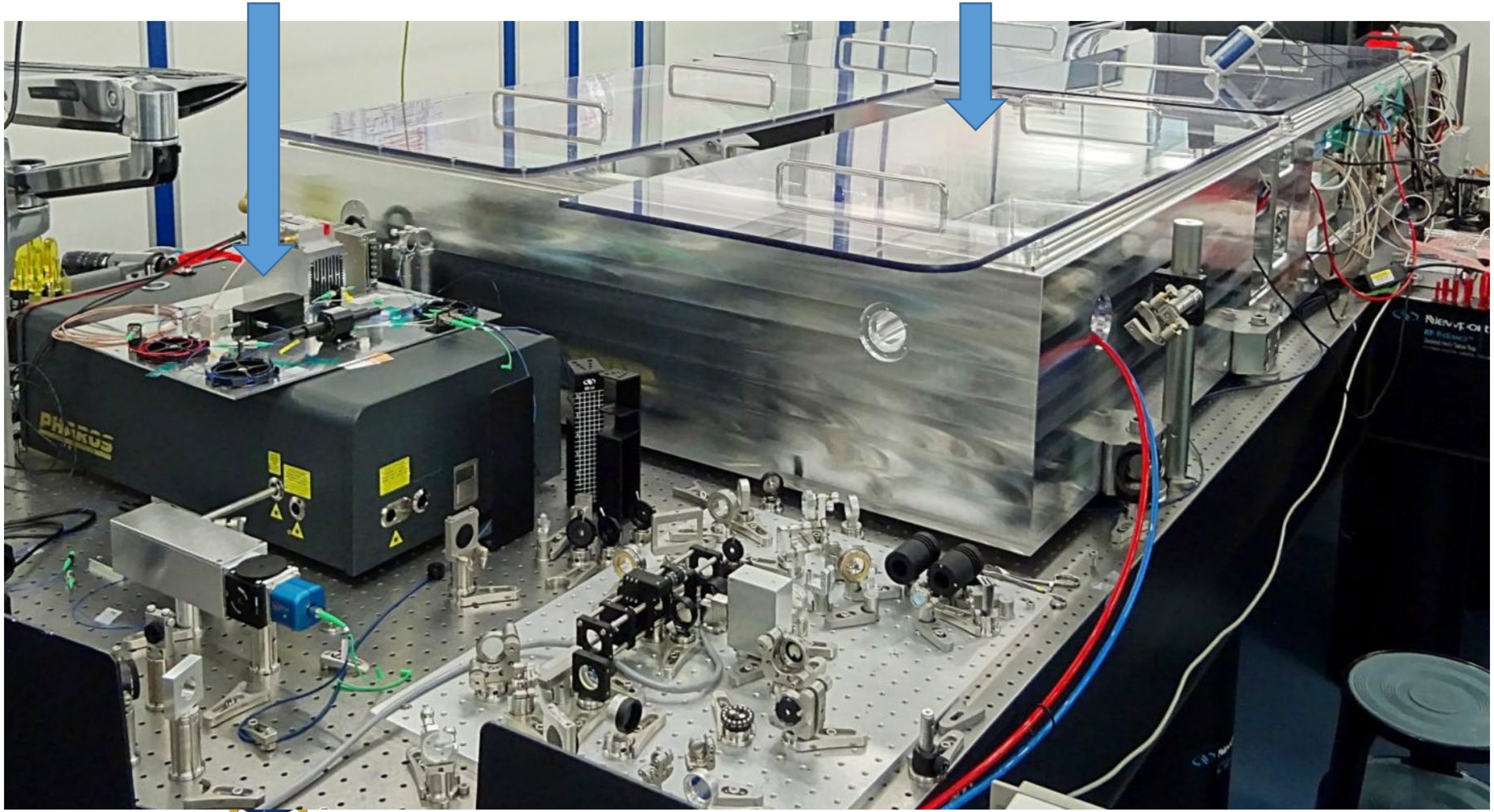
Optics challenges with short UV pulse and high rep rate of PI laser

Photoinjector laser

LightConversion Pharos
1 mJ at 1000 Hz, 165 fs FWHM
1030/515/258 nm Yb:KGW regen

ICS laser

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



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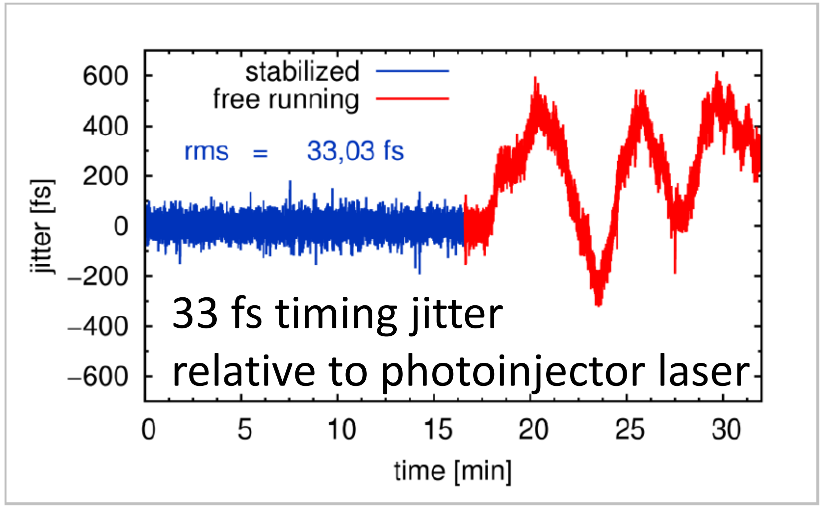
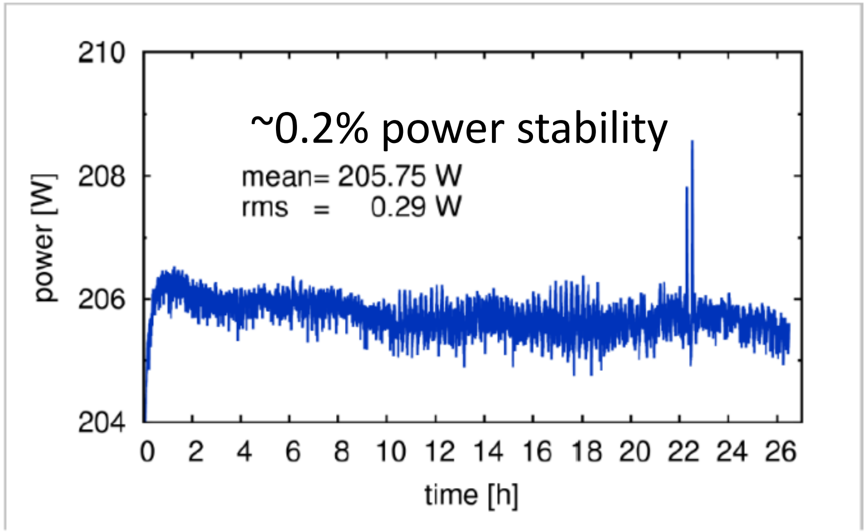
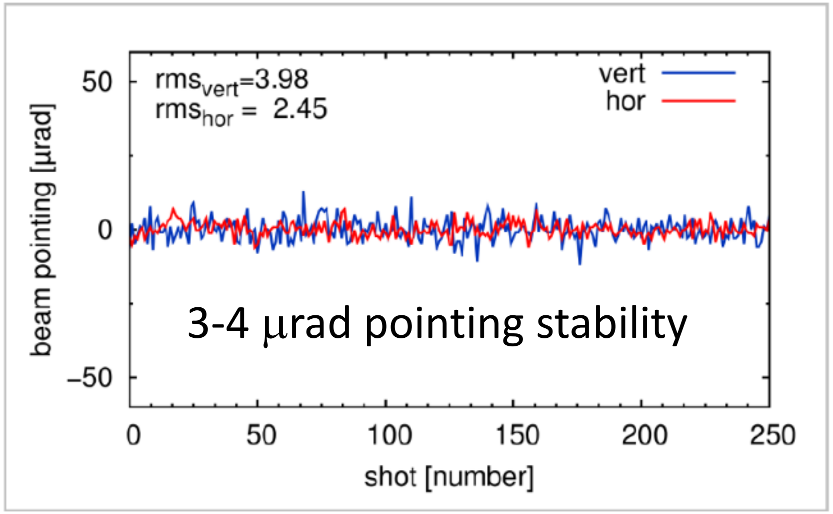
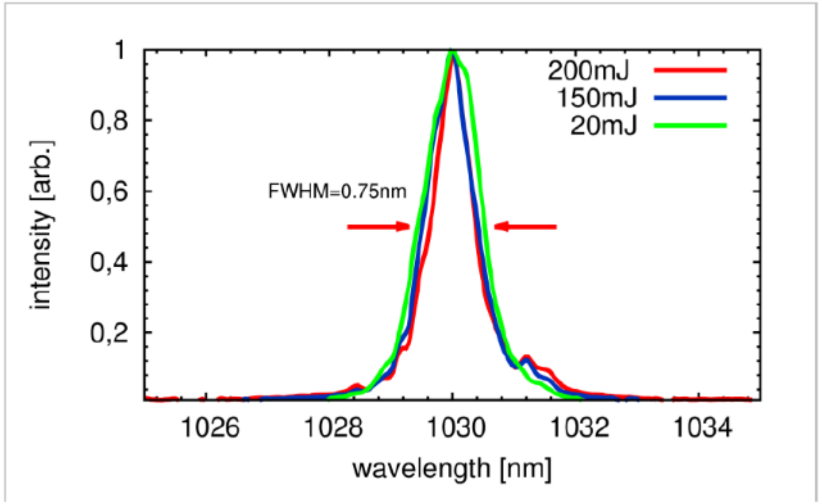
ICS Laser Test Results









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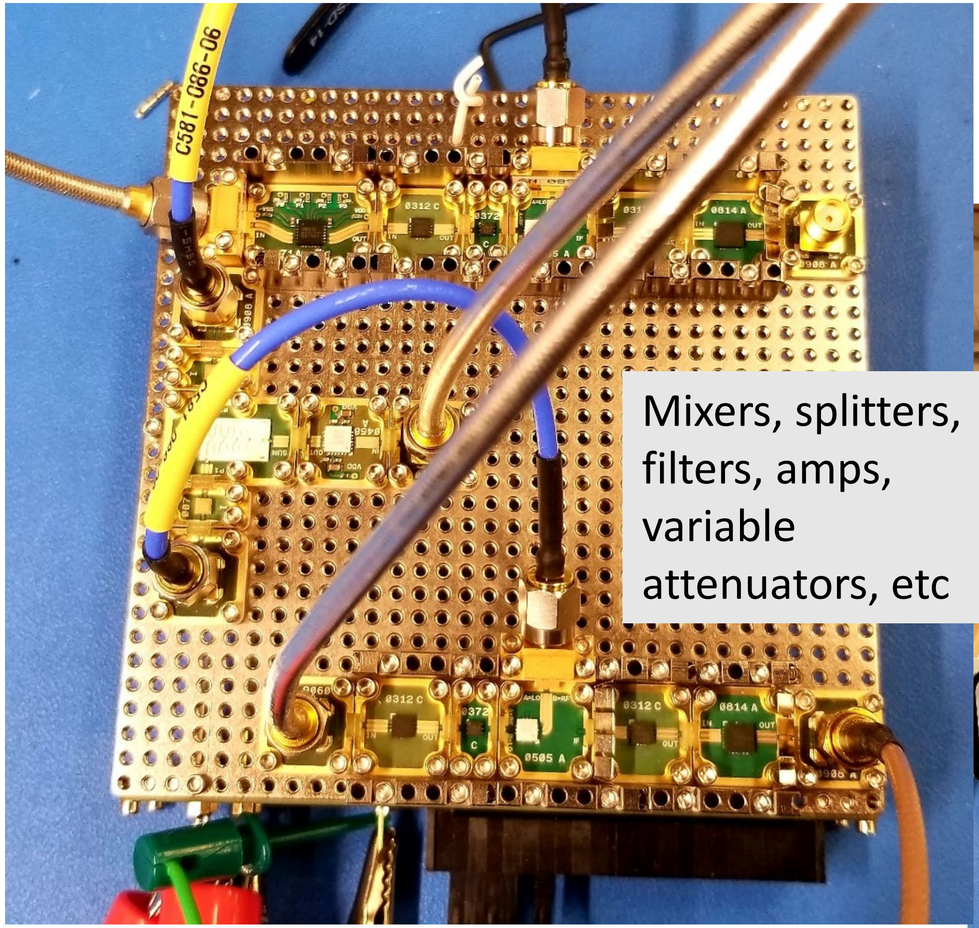
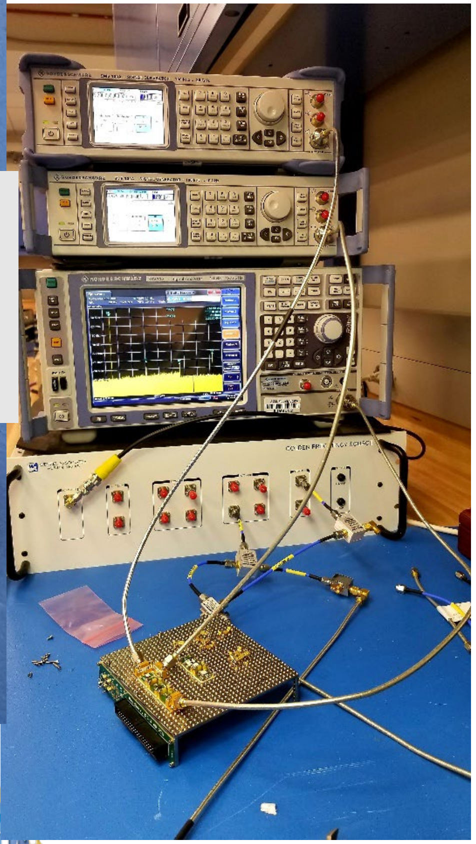
Low Level RF

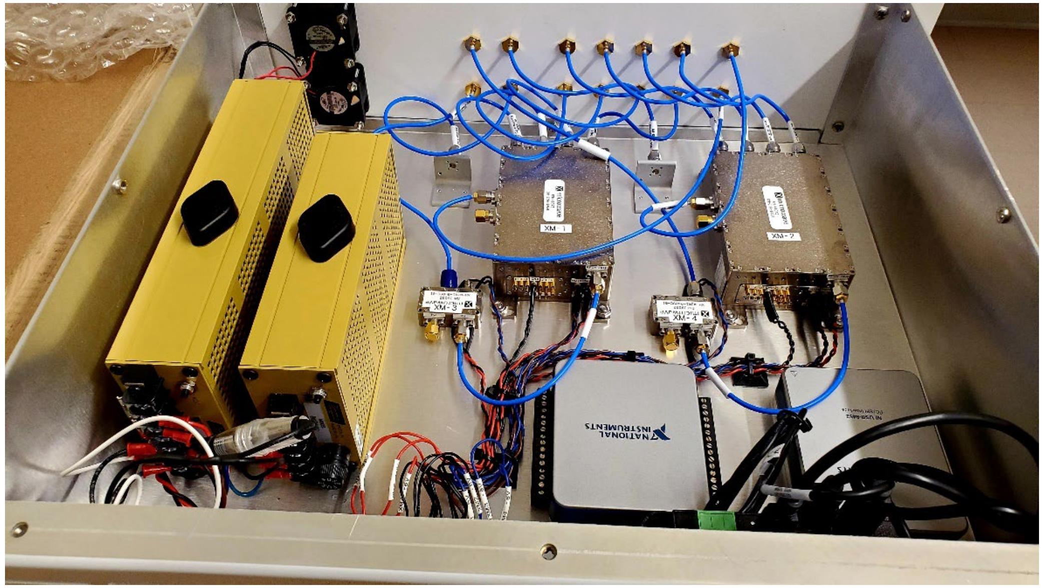
Rapid and inexpensive prototyping of microwave circuits using modular waveguide components from **X-Microwave**. Much student involvement in design, test, commission.



Mixers, splitters, filters, amps, variable attenuators, etc



Complete IQ Modulator. Similar boxes for downconverter, IQ demod, and machine protection



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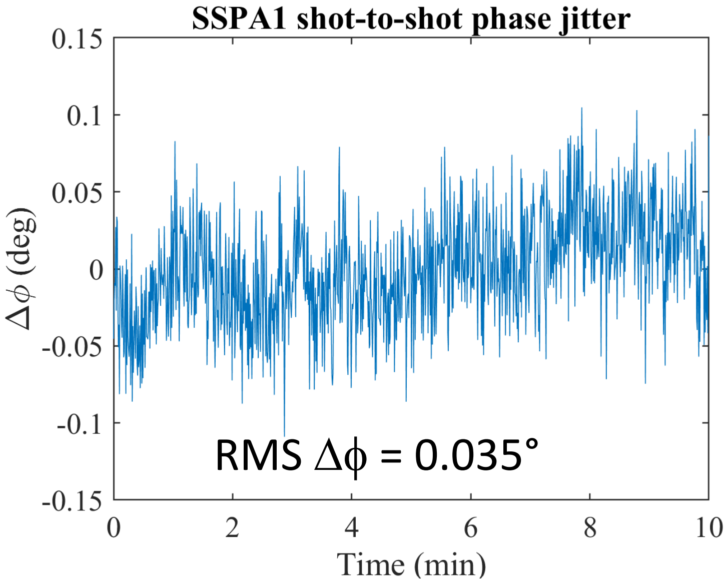
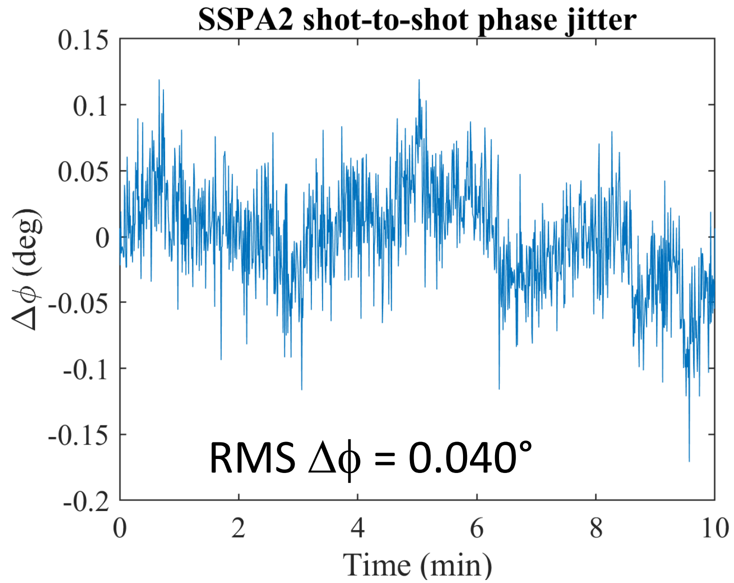
LLRF performance to Klystron input

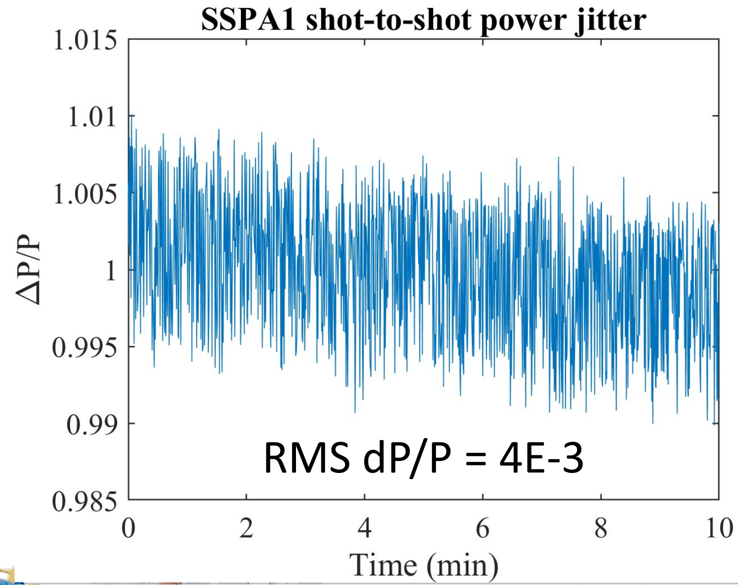
Microwave Amps Ltd
AM73-9.3S-50-50R
9.3 GHz, 100 W, 1 us, 1 kHz

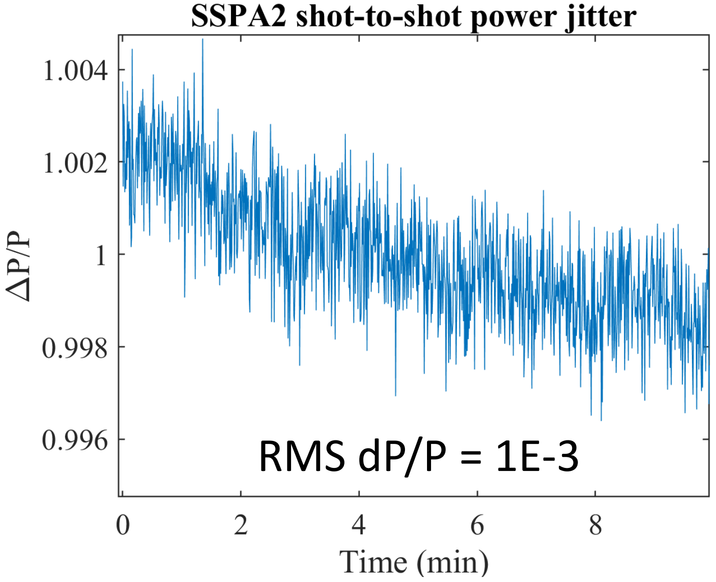
25 W to saturate klystron output

Fast RMS jitter $\Delta\phi$ = 0.02° (6 fs)

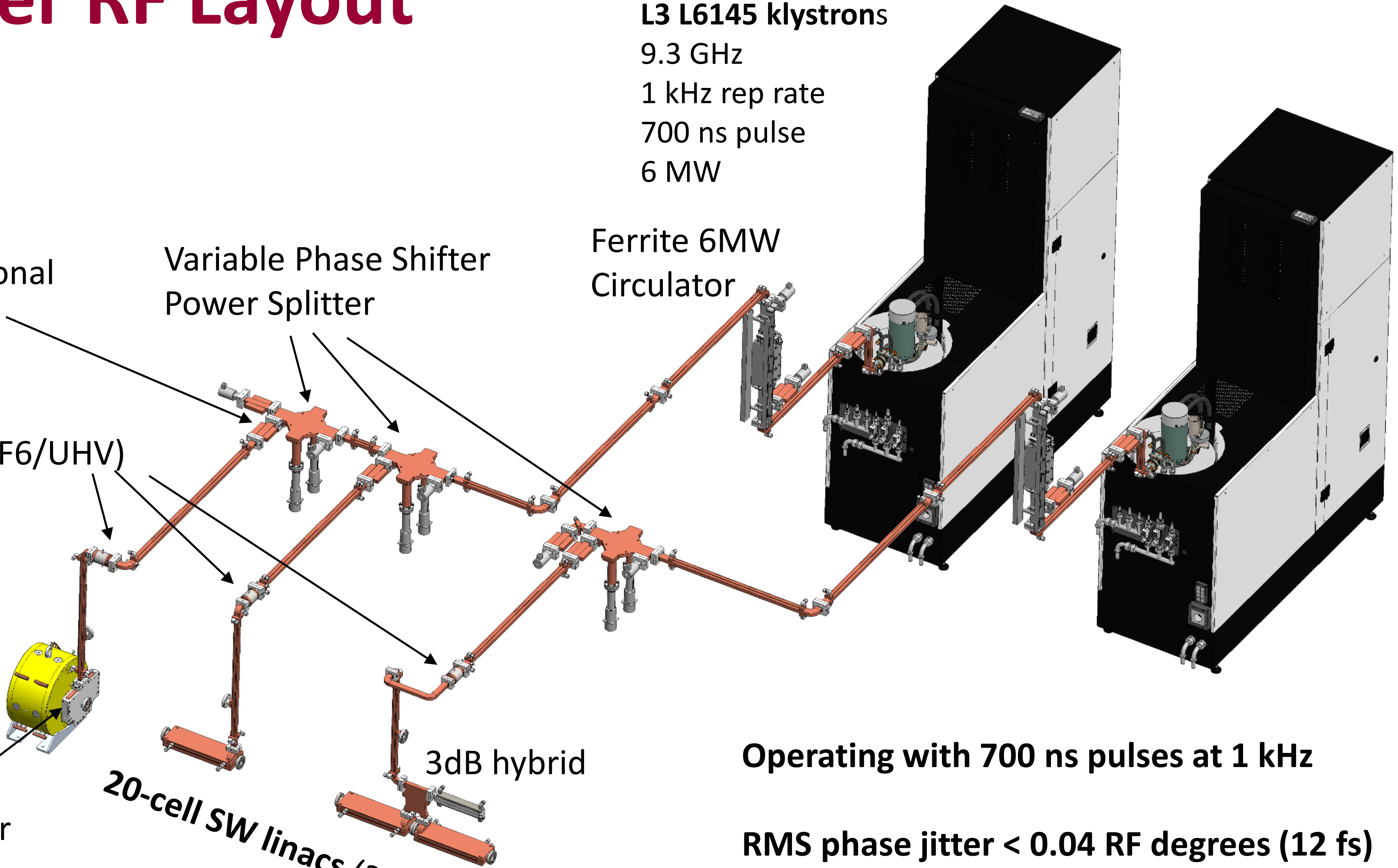








High Power RF Layout



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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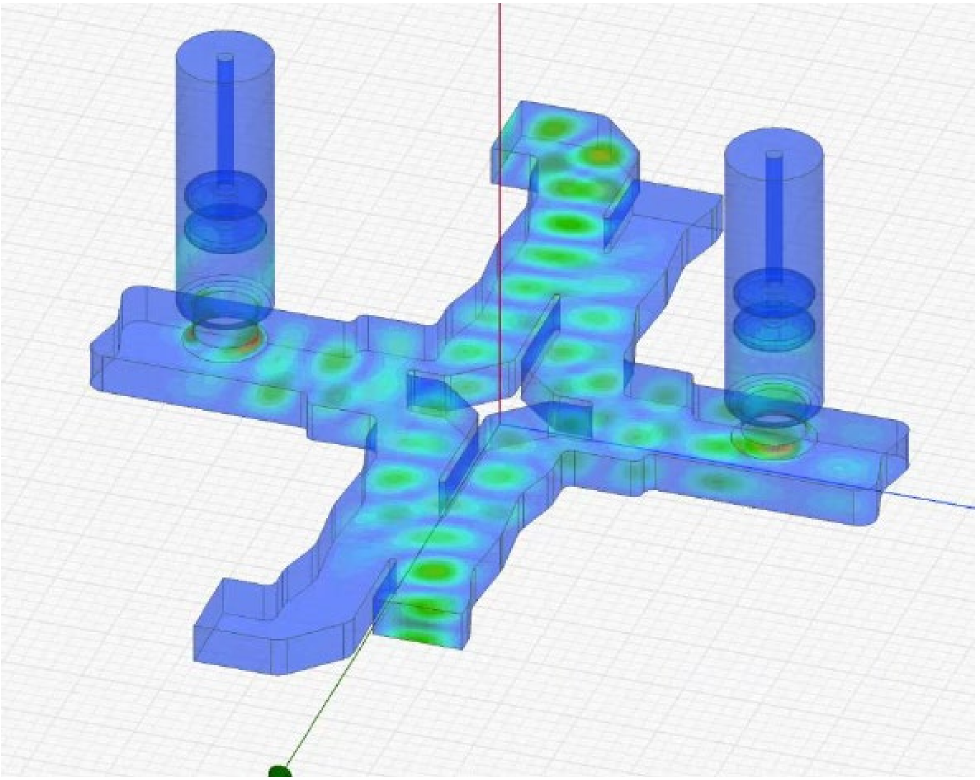
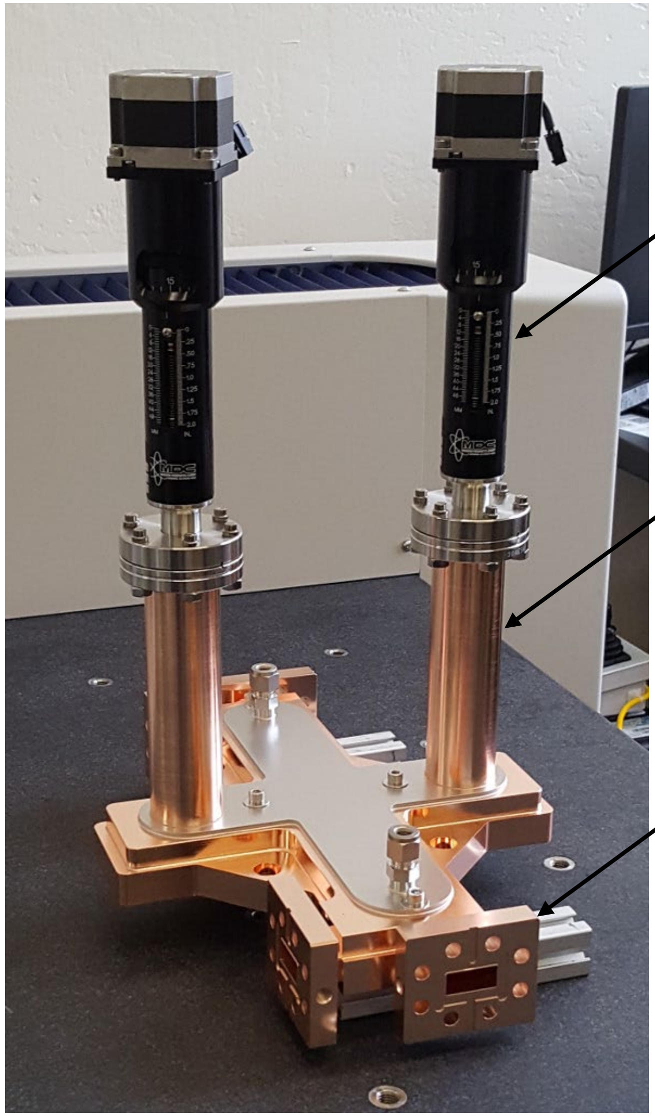
Variable Phase Shifter Power Divider (VPSPD)

- Divide or combine high power
- Move plungers together for phase shift
- Move plungers separately for power shift among output ports



Tibaray



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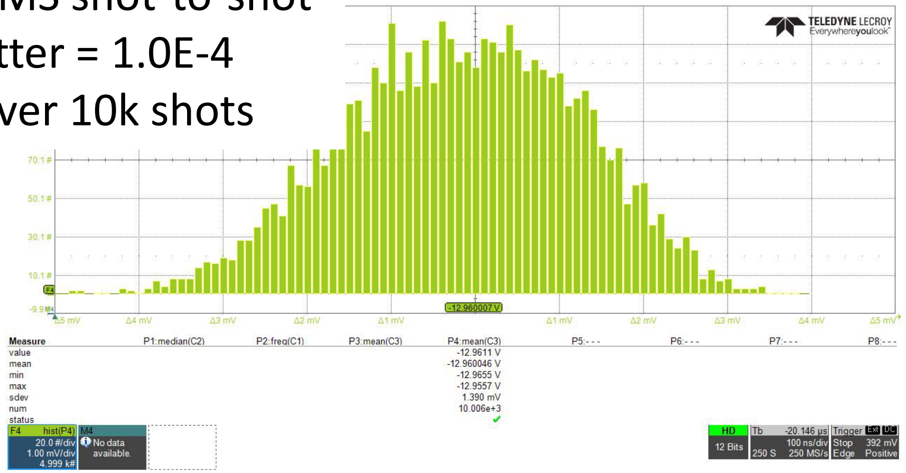
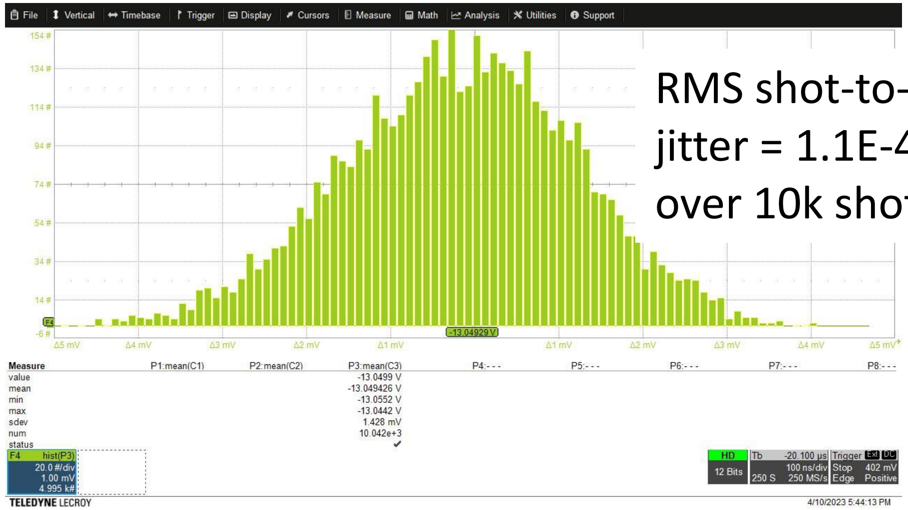
Modulator Performance

Scandinova
K1
130 kV
98 A
2.5 us
1 kHz

RMS shot-to-shot
jitter = 1.0E-4
over 10k shots





RMS shot-to-shot
jitter = 1.1E-4
over 10k shots

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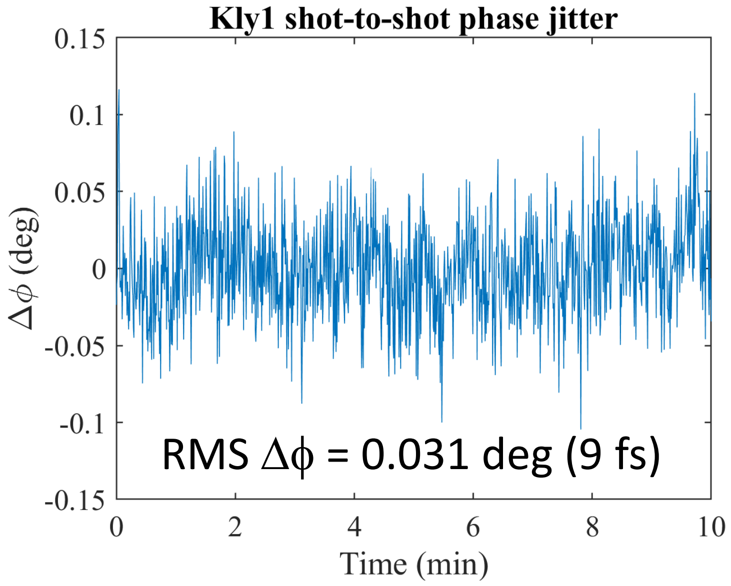
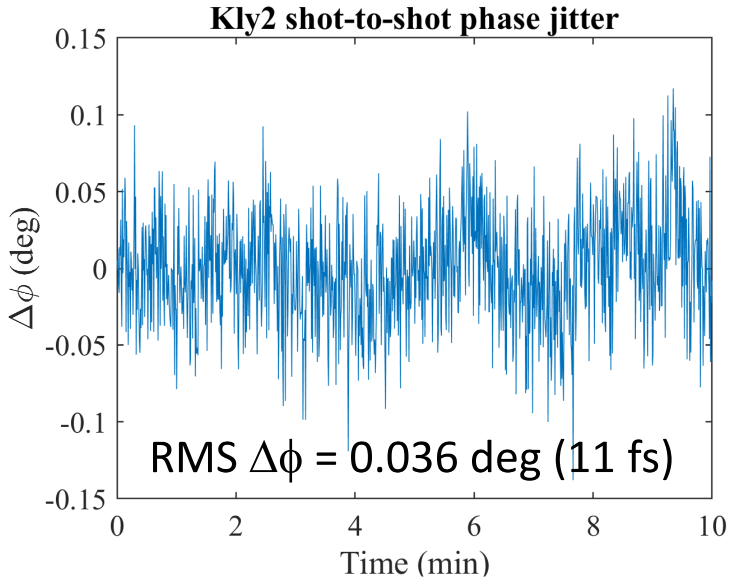
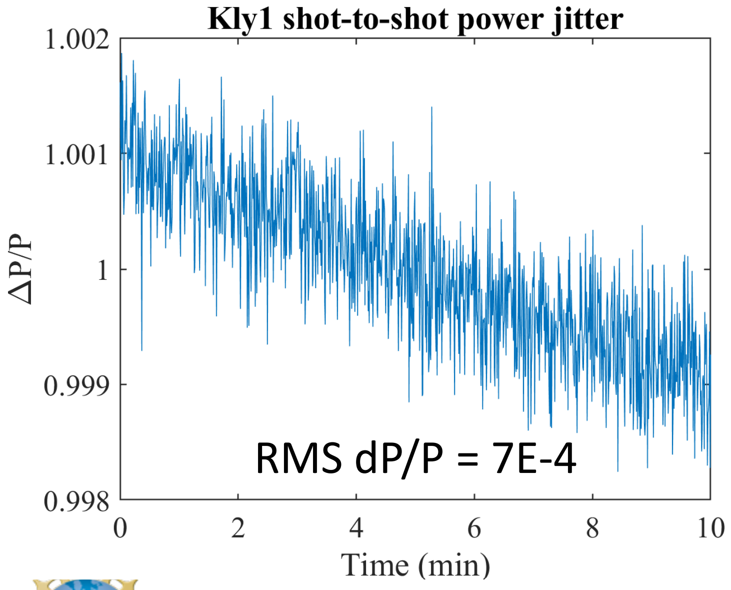
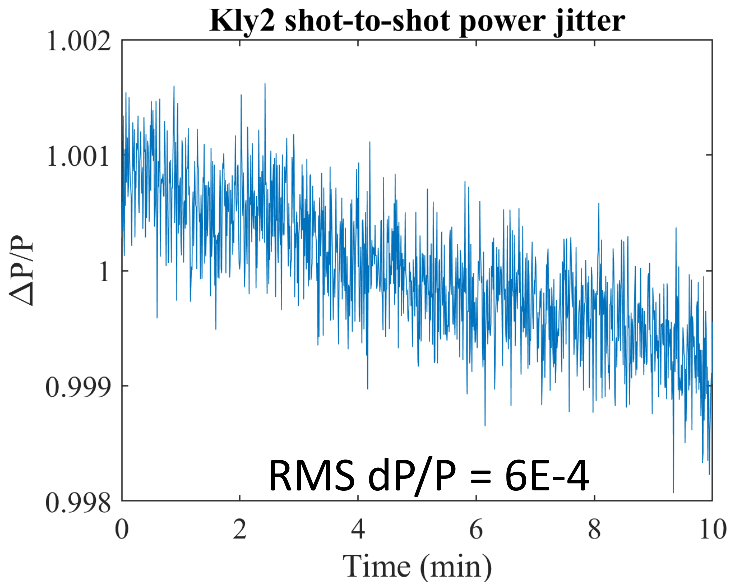
Klystron Performance

Stellant (ex L-3)
L-6145
6 MW, 1 us, 1 kHz
59 dB small signal gain









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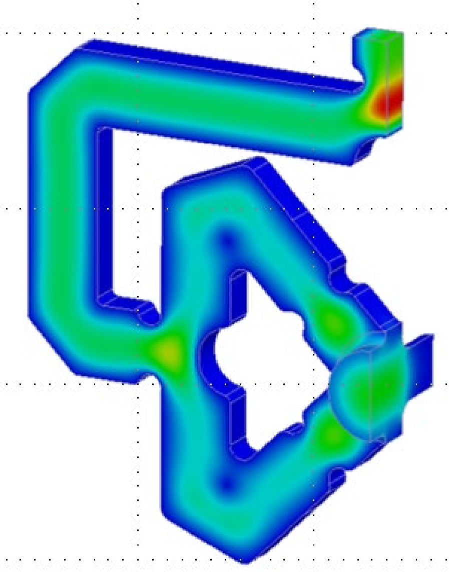
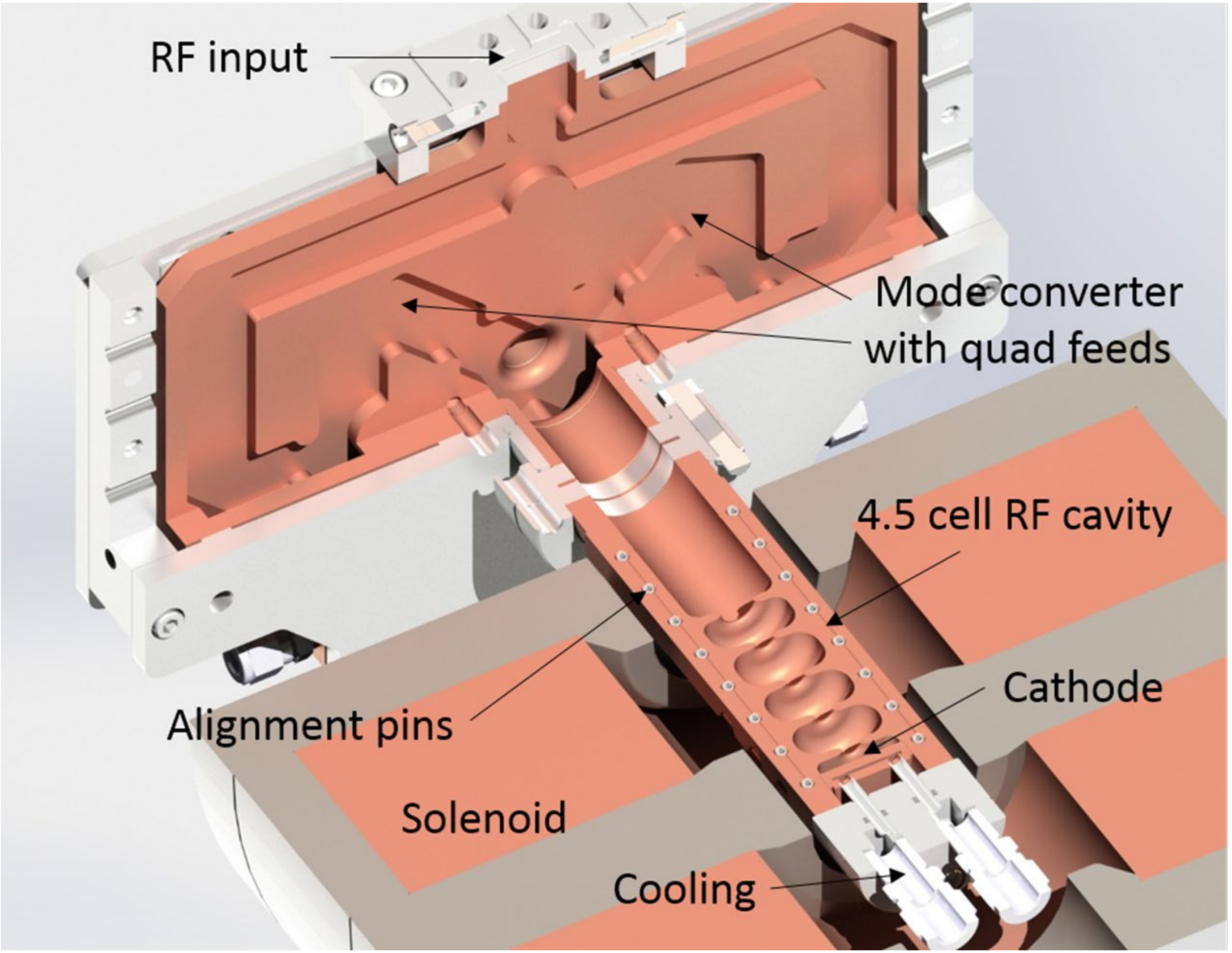
kHz X-band Photoinjector



- 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
2.4 MW
3.6 MeV
105 MV/m

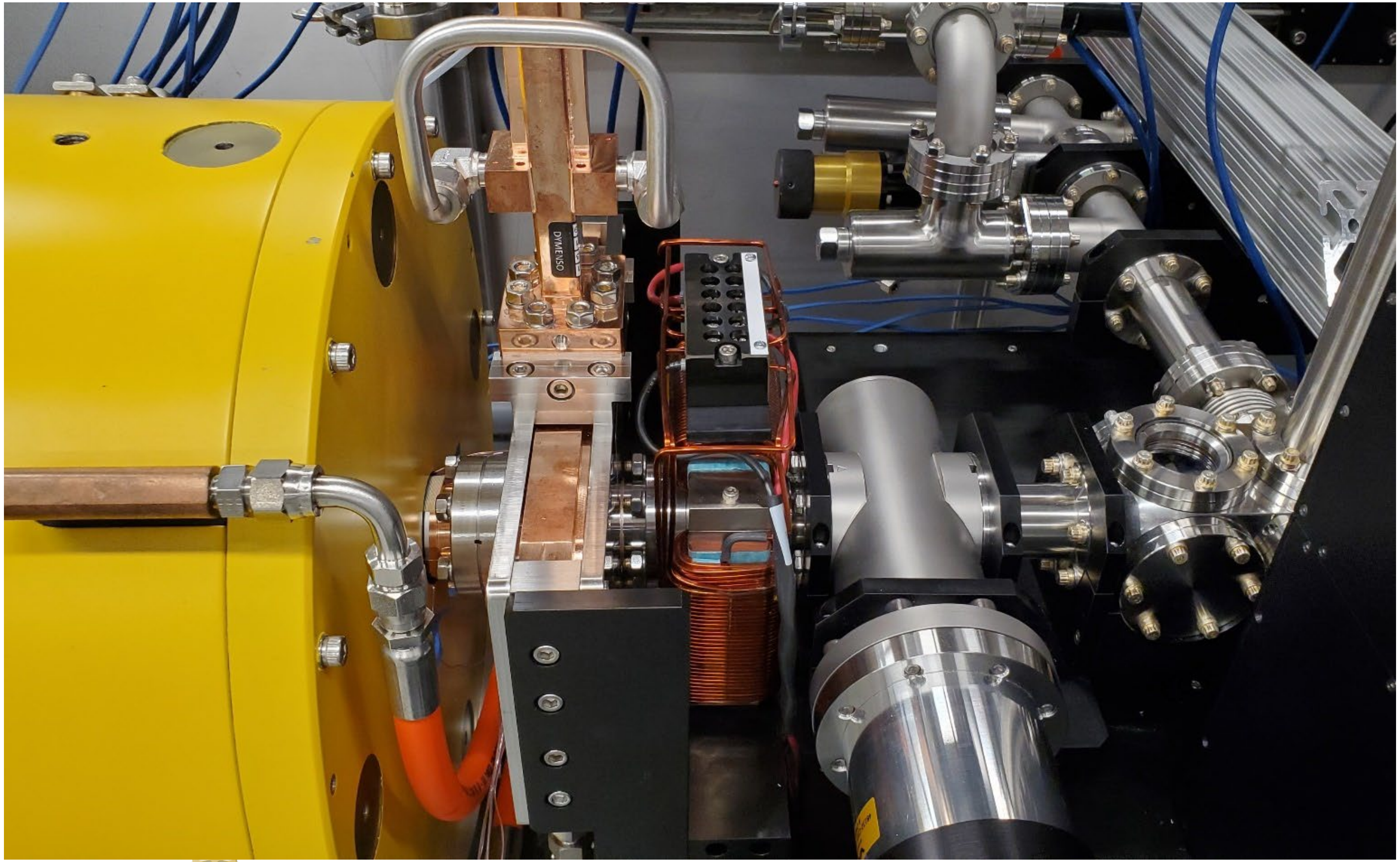


Photoinjector Performance

Commissioned to

- 2.8 MW delivered
- 117 MV/m gradient
- 3.8 MeV energy
- 1000 Hz rep rate
- 700 ns pulses
- Conditioning time ~3 days
- Zero breakdowns/day

- 20 pC (limited by UV optics)
- ~0.3 um emittance
- Few hundred fs pulse



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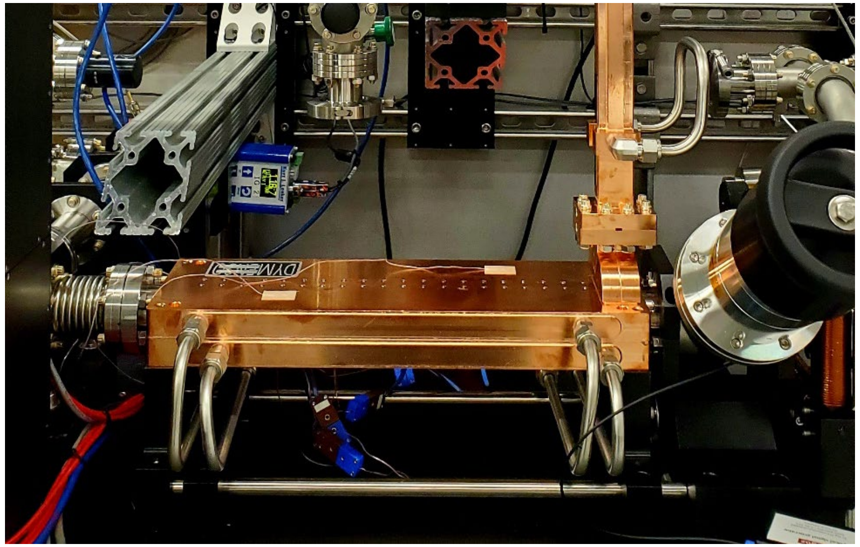
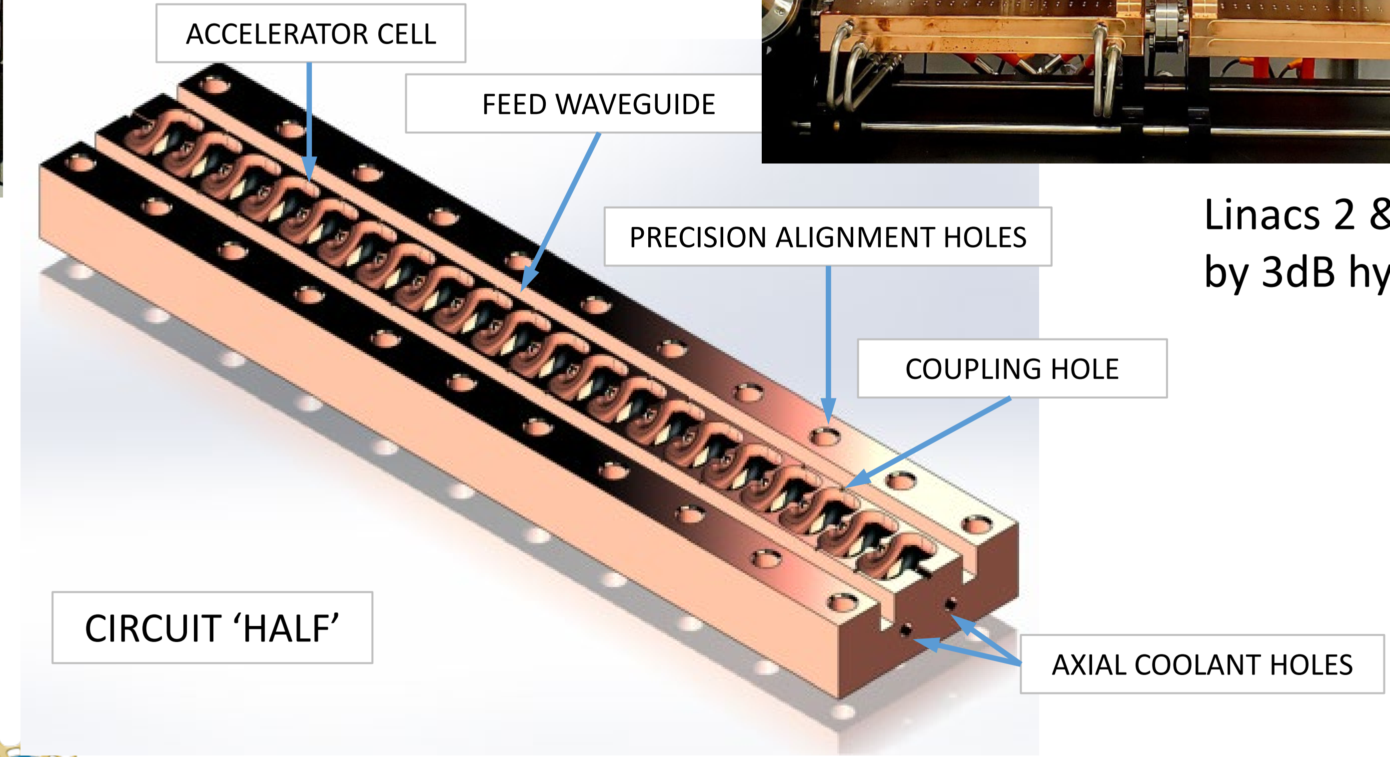
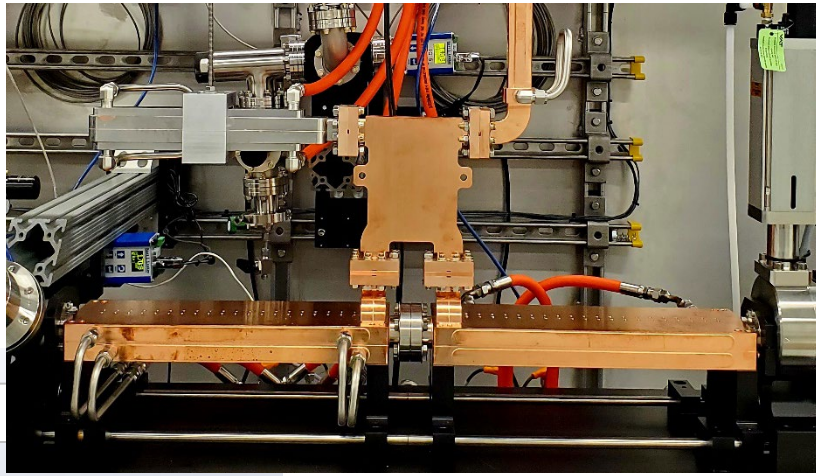
9.3 GHz Distributed-Coupling SW Linac

Tantawi and Li (SLAC and Tibaray)



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





Linacs 2 & 3 fed by 3dB hybrid

- 20-cell structure 35 cm long
- 9.3 GHz
- 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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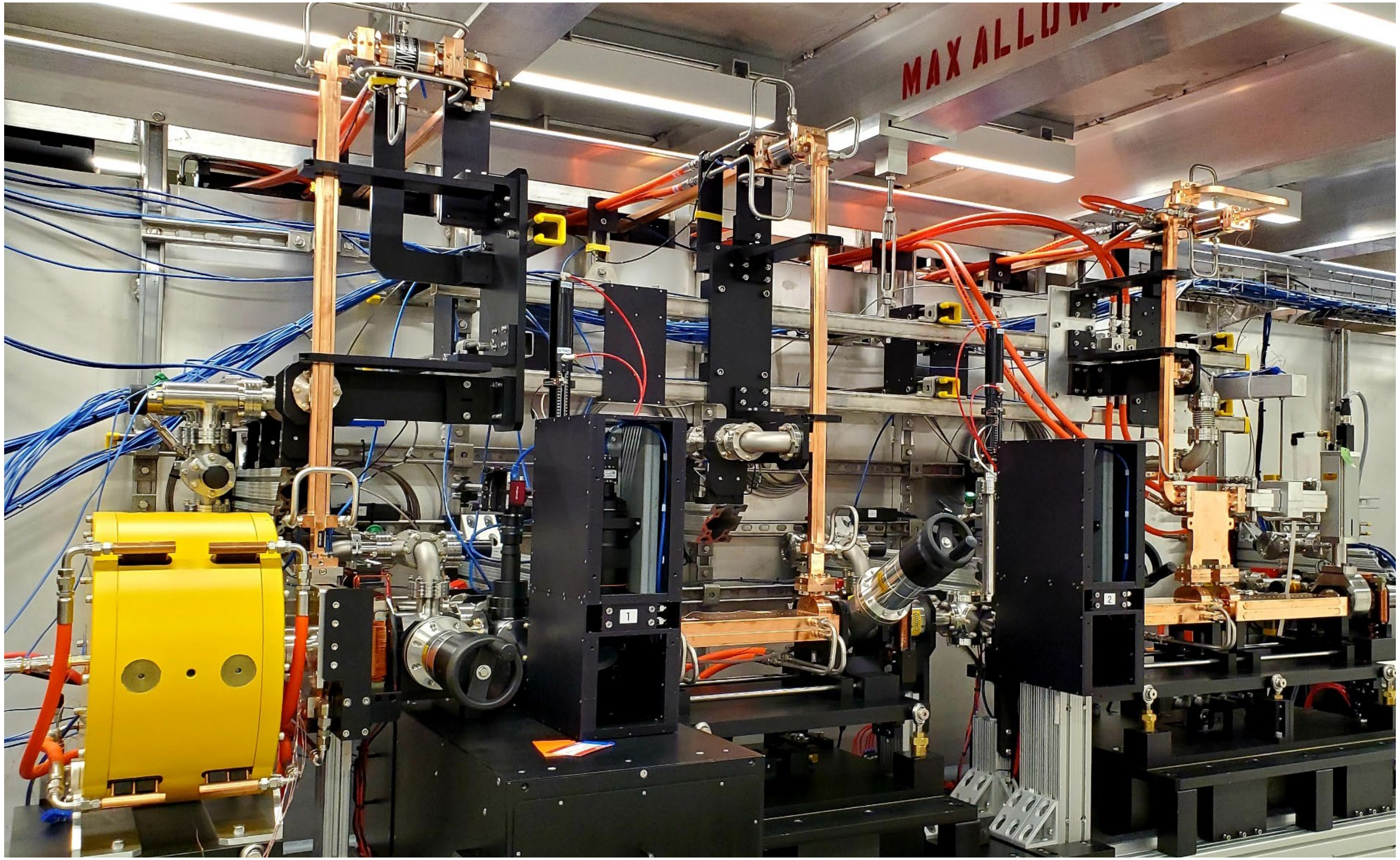
Linac Performance

Commissioned to

- 27 MV/m gradient
- 108 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
- 29 MeV final beam energy (still tuning)
- RMS dE/E = 50-200 ppm



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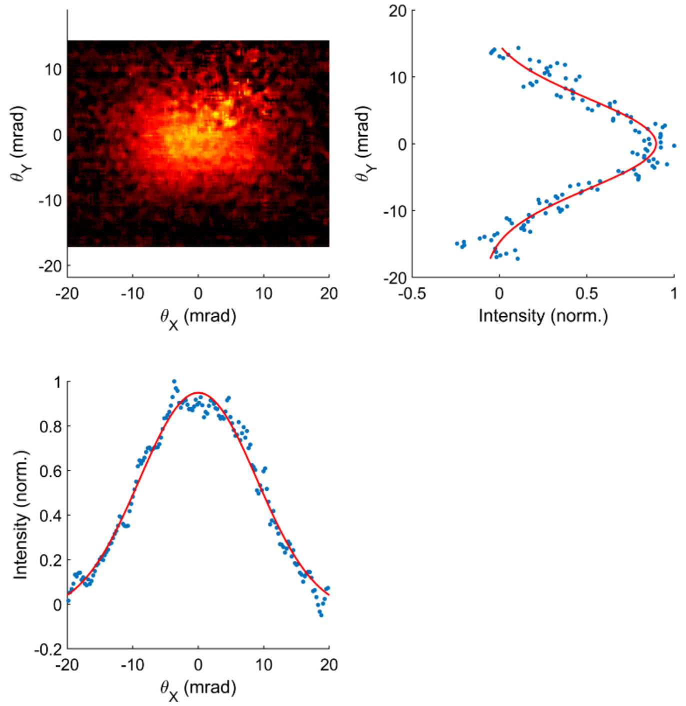
CXLS Hard X-ray Design Parameters

Parameter	**0.1% Bandwidth**	**5% Bandwidth**	**Units**
Photon energy range	2 – 20	2 – 20	keV
Average flux	5×10^{9}	1×10^{11}	photons/s
Average brilliance	2×10^{12}	5×10^{12}	photons/(s .1% mm^2mrad^2)
Peak brilliance	3×10^{19}	9×10^{18}	photons/(s .1% mm^2mrad^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	5×10^{6}	1×10^{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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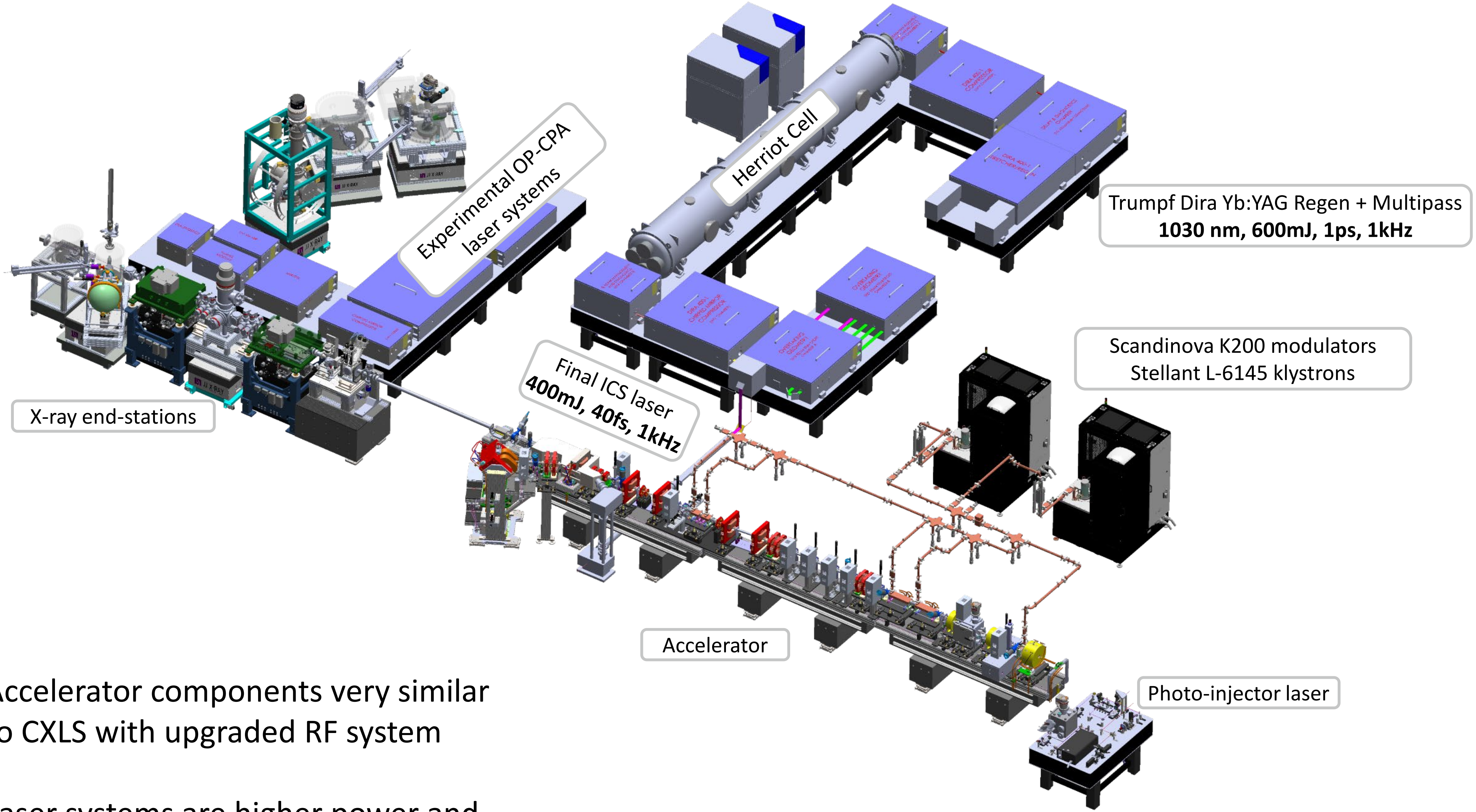
CXFEL Layout – Construction over next 4.5 years



Accelerator components very similar to CXLS with upgraded RF system

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

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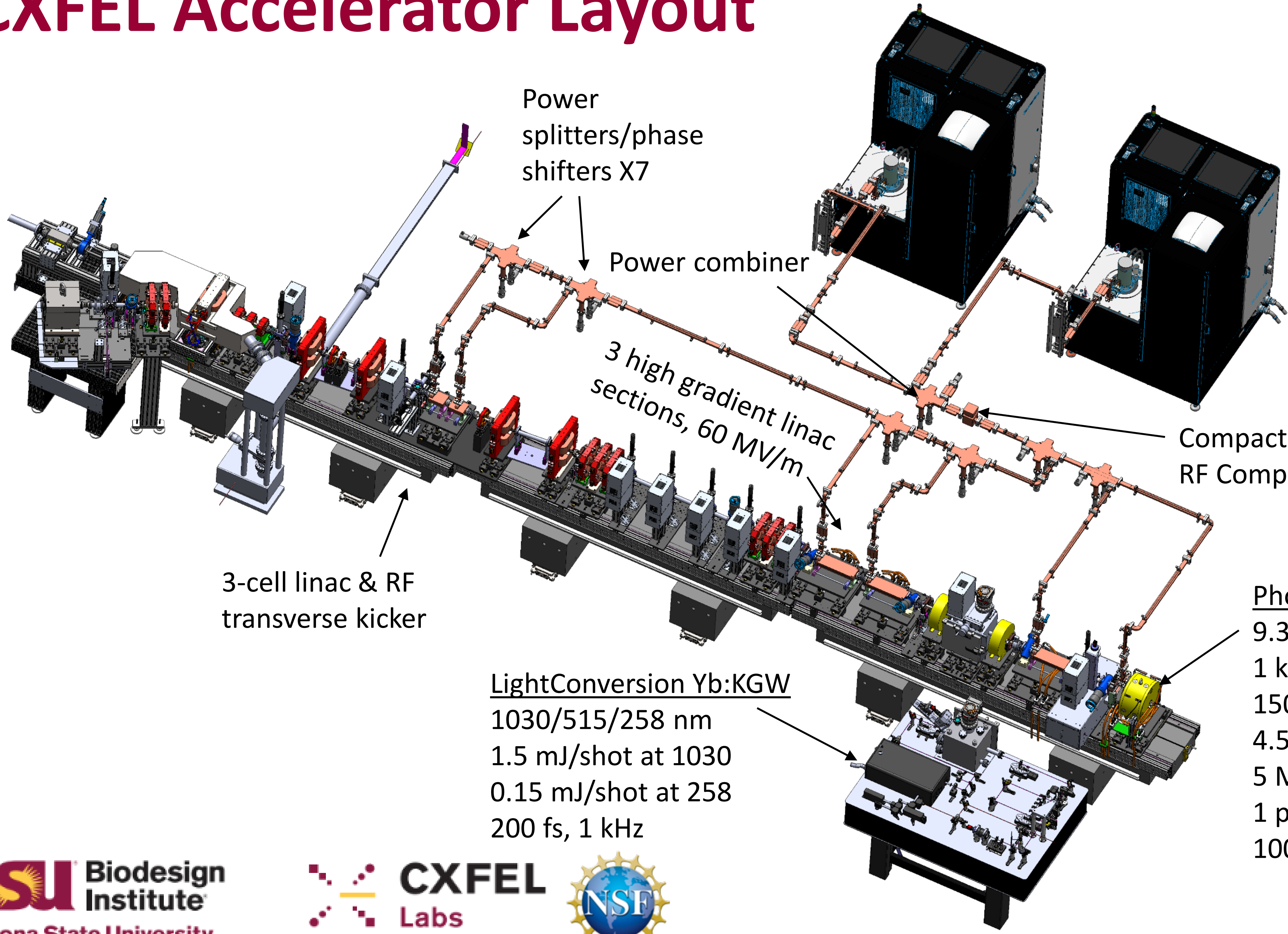
CXFEL Accelerator Layout



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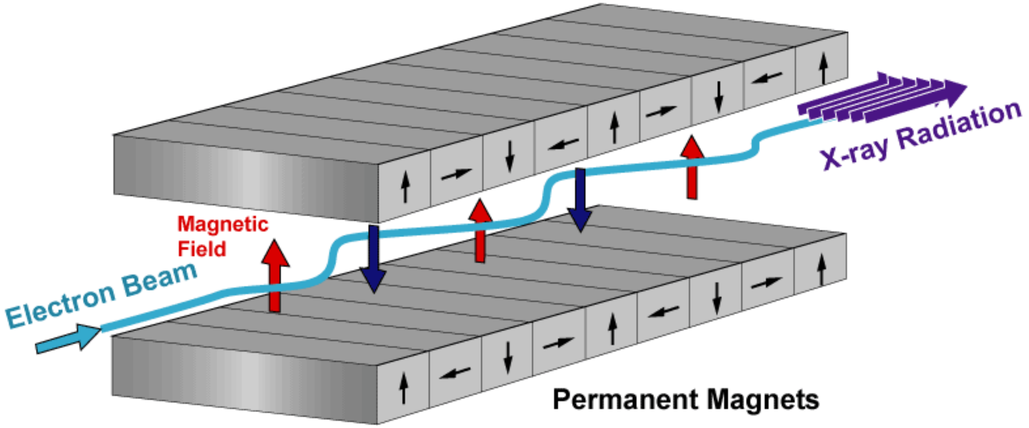
Additional Slides

ICS: replace undulator with a laser

Undulator Radiation



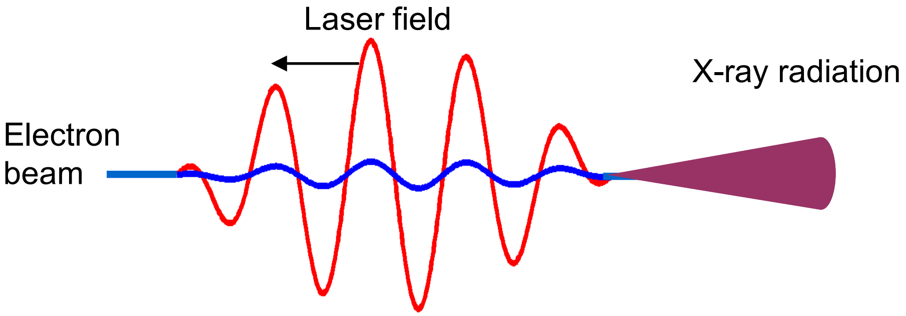
$$\lambda_x = \frac{\lambda_u}{2\gamma^2}$$

$$\lambda_u \approx 3cm$$

$$E = \gamma mc^2 \approx 10 \text{ GeV}$$

1000 m long accelerator

Inverse Compton Scattering



$$\lambda_x = \frac{\lambda_{laser}}{4\gamma^2}$$ X-ray wavelength

$$\lambda_{laser} \approx 1\mu m$$ Undulator/laser wavelength

$$E \approx 20 \text{ MeV}$$ E-beam energy required

1 m long accelerator

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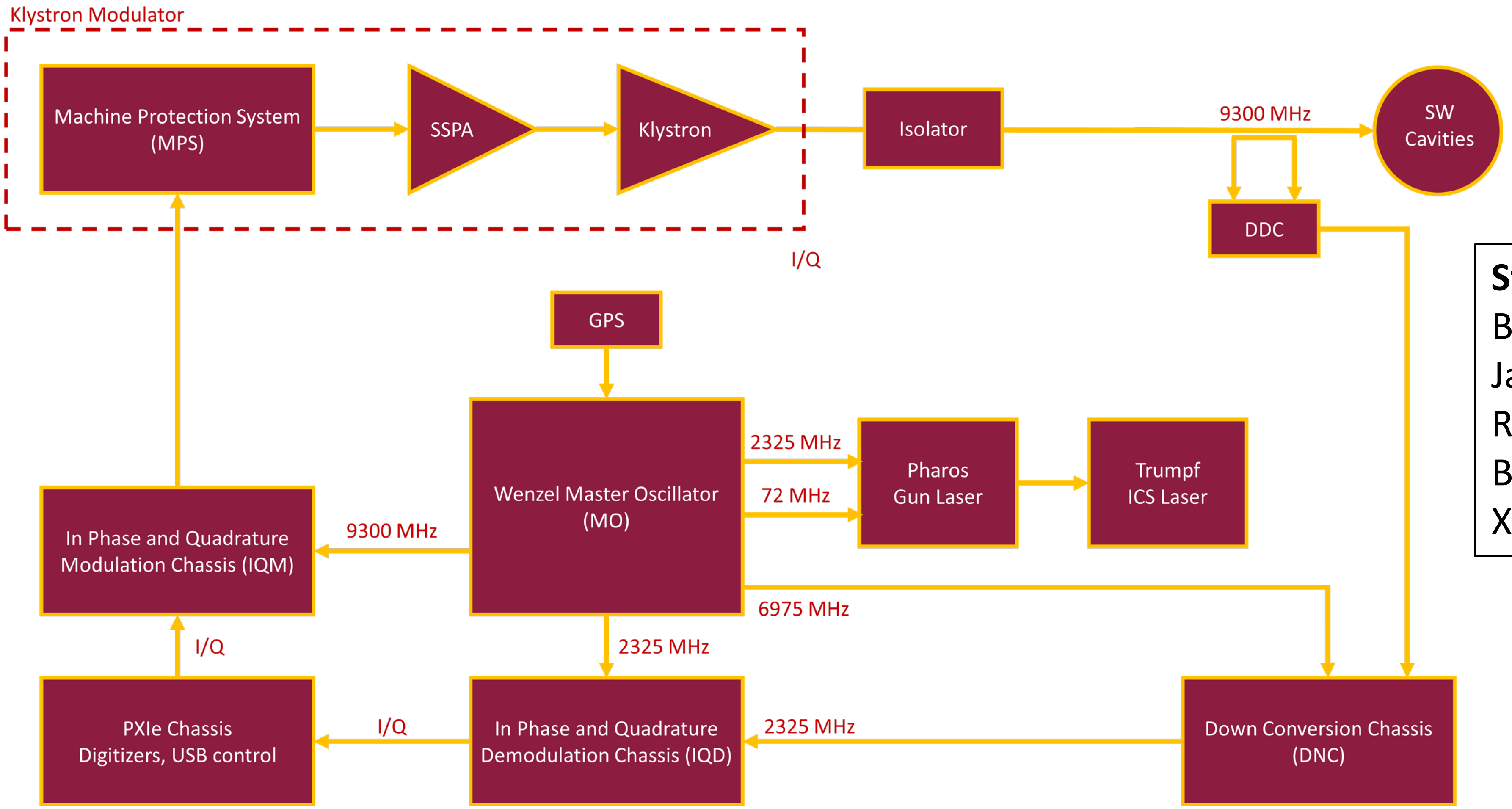
RF and Timing Systems



Steven Jachim (Senior RF Engineer)
Brandon Cook
Jasmin Falconer
Rae Larsen
Brett Liebich
Xinyi Ma

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