FEL Bootstrap Experiments for the Ramp-Up of LCLS-II Superconducting Linac

S. Xiao, A. Rosenstrom, P. Heimann, S. MacDonald, S. Rokni

RadSynch 2025, June 24-27, 2025

CNPEM, Brazil

Outline

Introduction of LCLS-II superconducting (SC) linac

Bootstrap plan of LCLS-II superconducting (SC) linac

Current FEL performance

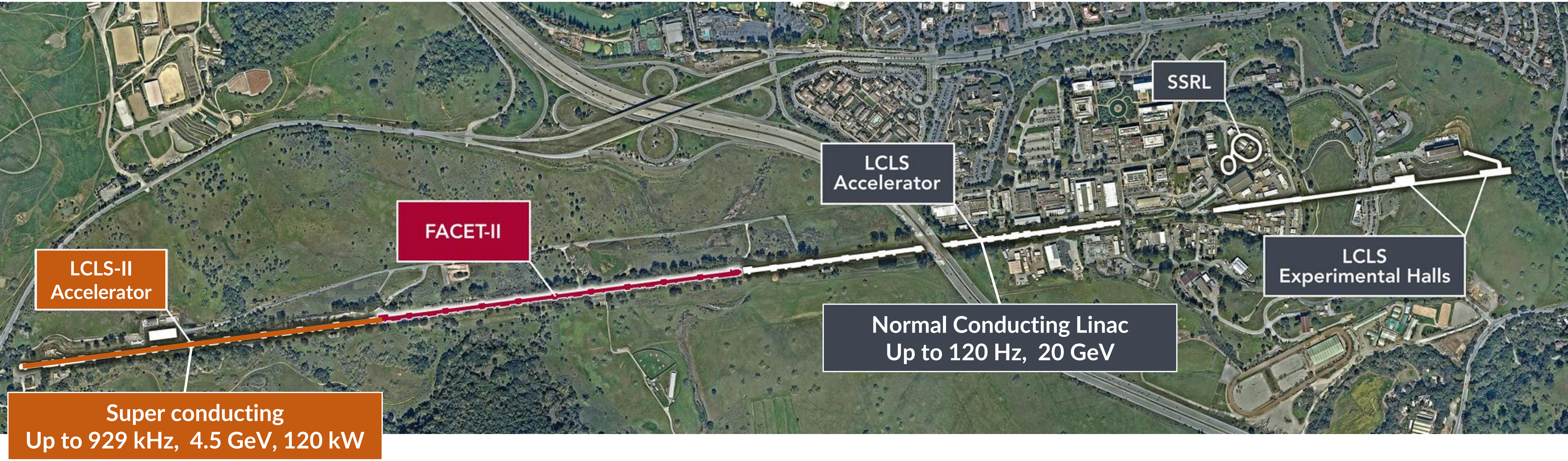
Experiments supporting the ramp-up:

- Material drilling
- Air attenuation

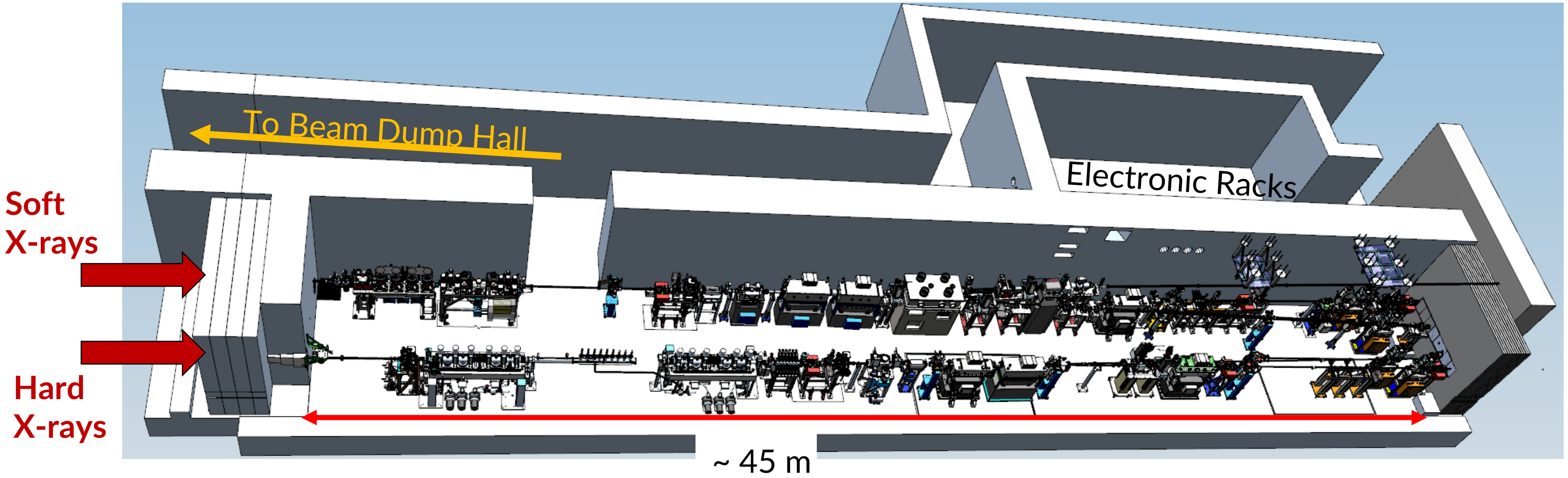
Summary

LCLS & LCLS-II at SLAC

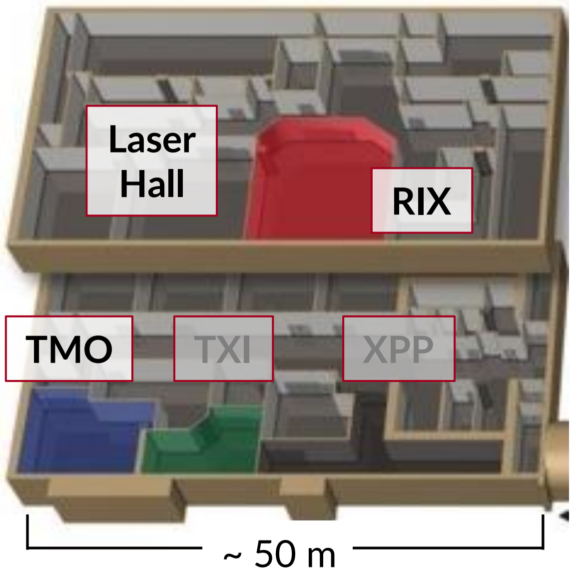
The 3-km long Linac at SLAC is separated to 3 facilities



LCLS-II FEL Beam Lines



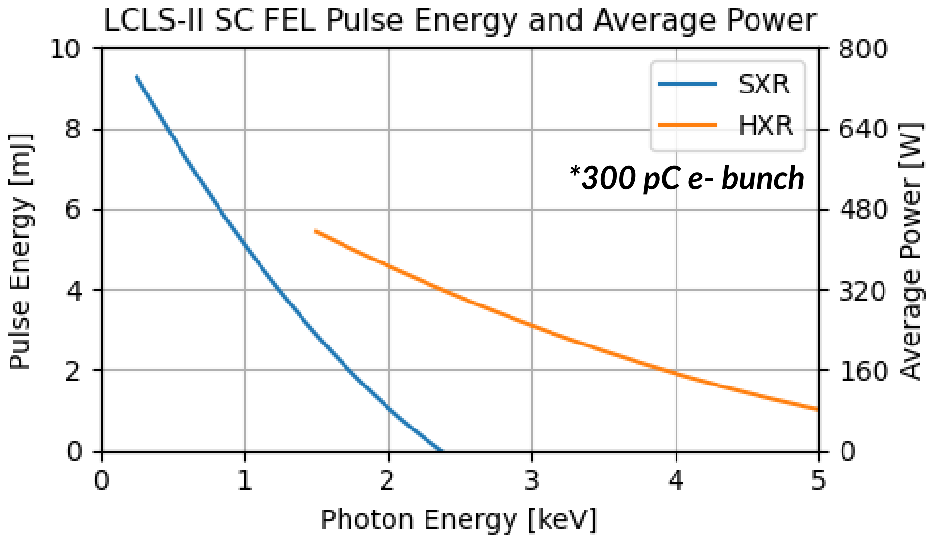
Front End Enclosure (FEE)



Near Experiment Hall (NEH)

Electron beam: 2-4.5 GeV, up to 929 kHz, 120 kW

Undulator	SXR	HXR	Unit
Period length	39	26	mm
Number of periods	87	130	
Segment length	3.4	3.4	m
Number of segments	21	32	
K_{eff} at min. gap	>5.48	>2.44	



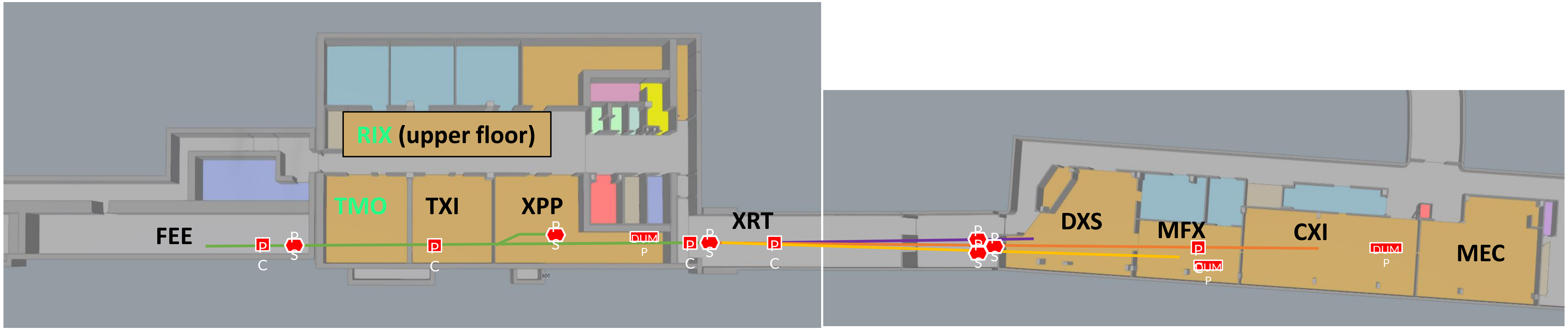
<1 W FEL from normal conduction Linac

LCLS-II FEL Beam Lines

Currently FEL from LCLS-II superconducting linac can only be sent to TMO and RIX

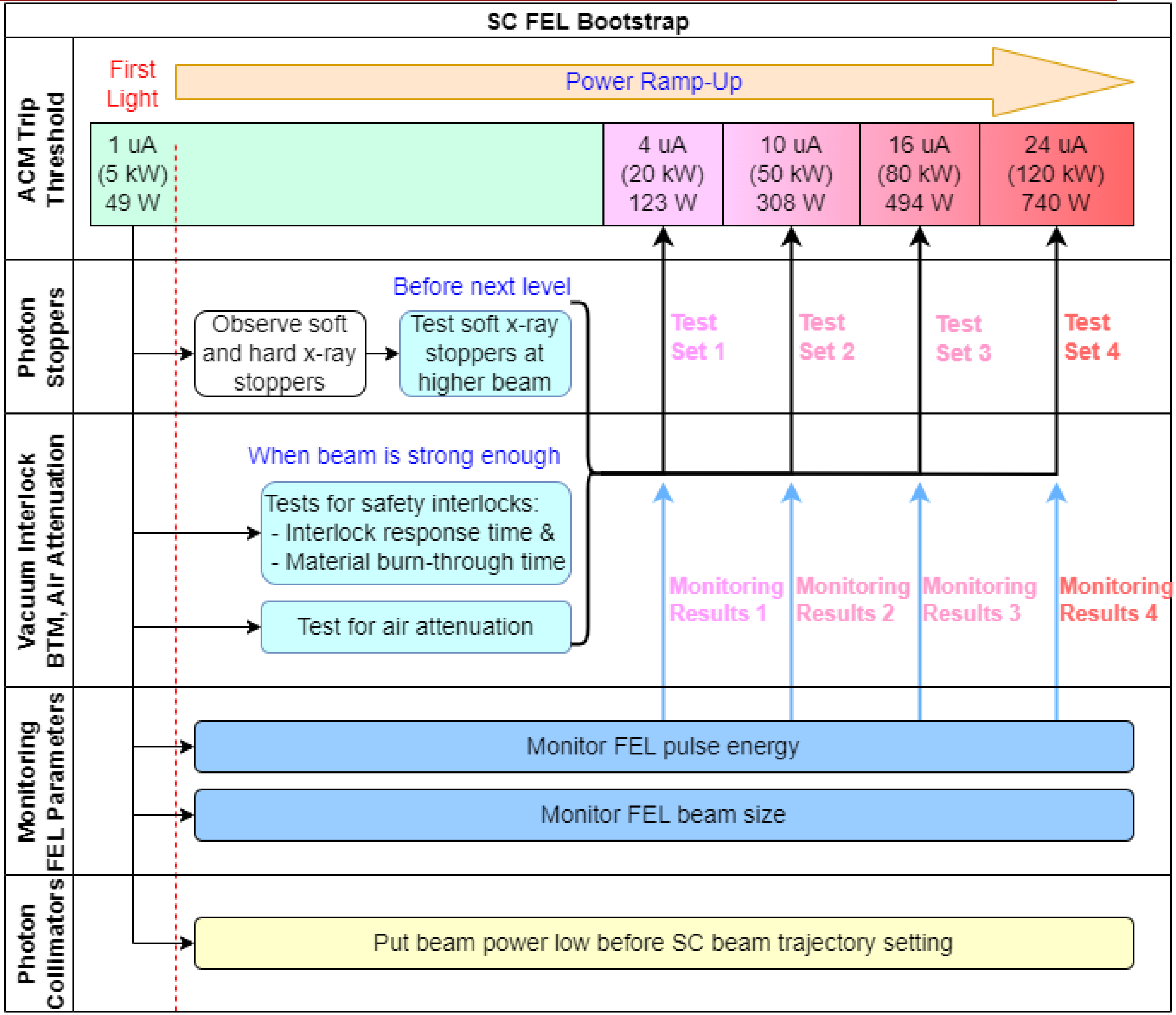
Other beamlines can still only take FEL from the normal conducting linac

- They will be upgraded in the LCLS-II HE project and beyond



Bootstrap Plan of LCLS-II SC Linac

1. Start from low power beam (by limiting electron beam current)
2. Monitor FEL beam parameters and perform necessary tests
   - Stopper performance
   - Material drilling
   - Air attenuation
3. Determine if beam power can be increased by evaluating the monitor and test results

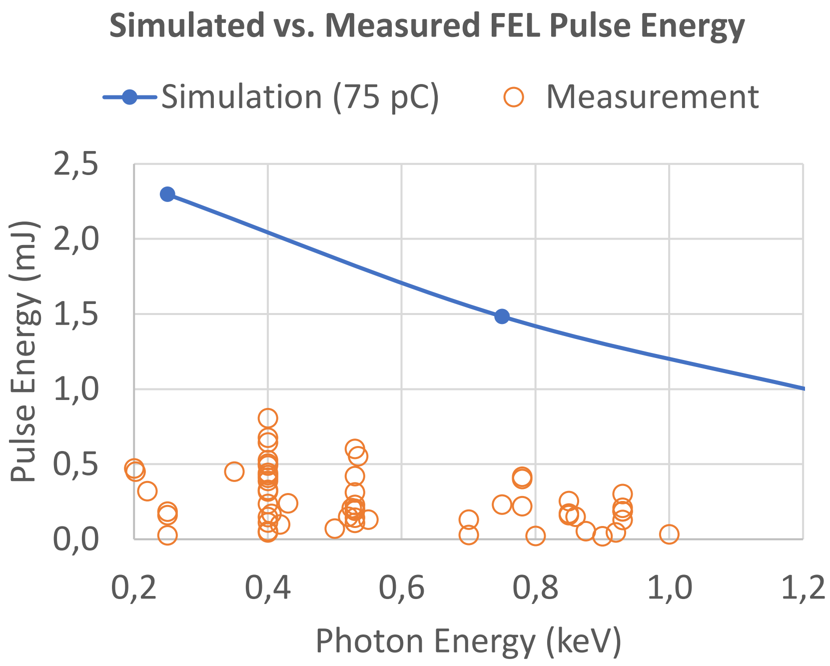


Current Status of LCLS-II SC FEL Beams

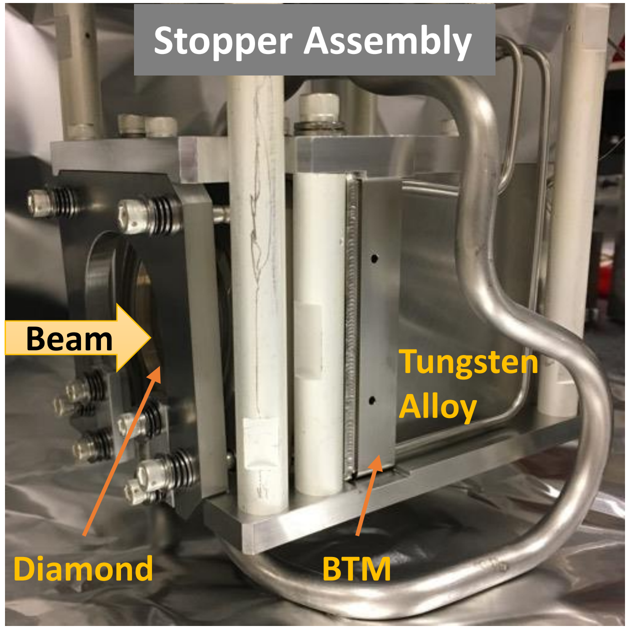
FEL tuning efforts were **focused on the soft x-ray line** so far:

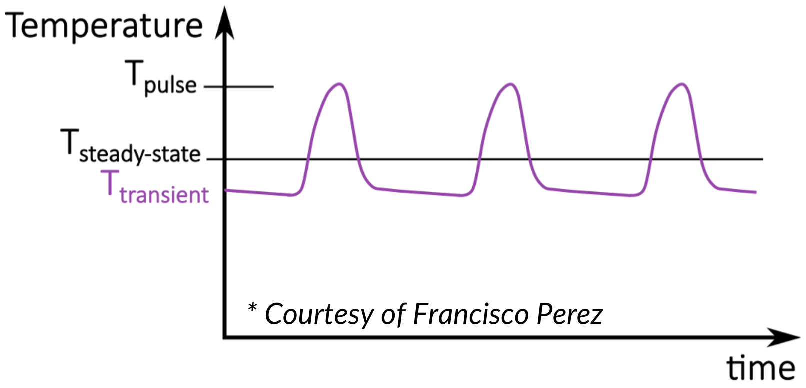
- Start from ≤1 kHz beam in August 2023
- Ramp-up to 8.3 kHz (mid-2024), 16.6 kHz, and **now 33.2 kHz** (since Jan. 2025)
- Current operation mainly at 70-80 pC, 33.2 kHz, 3.75 GeV (~9 kW) electron beam
  - LCLS-II design nominal is 4 GeV, need some cryo works to increase the electron beam energy further
- **Generated 10–20 W soft x-ray FEL beams, up to ~800 uJ/pulse**
  - The FEL yield is up to 35% of simulation

Plan to ramp-up further by the end of 2025



Stopper Surface Monitor: Why





* *Courtesy of Francisco Perez*

Diamond-based stopper may suffer slow sublimation around the Carbon K-edge

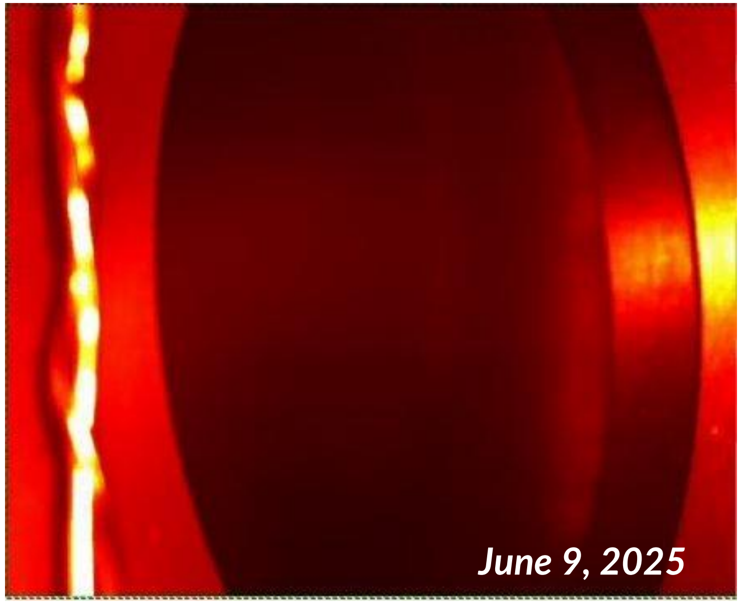
- Temperature on the stopper diamond depends on FEL average power **and** FEL pulse energy
  - Temperature from average power (steady state): 470 °C
  - Temperature from single pulses (transient): 1940 °C
- Diamond can transform to graphite, and graphite will sublimate slowly from 1500 °C
- The sublimation will be slow since the high temperature will be transient

Monitor stopper surface along operation and test at key powers

Stopper Surface Monitor: How and What

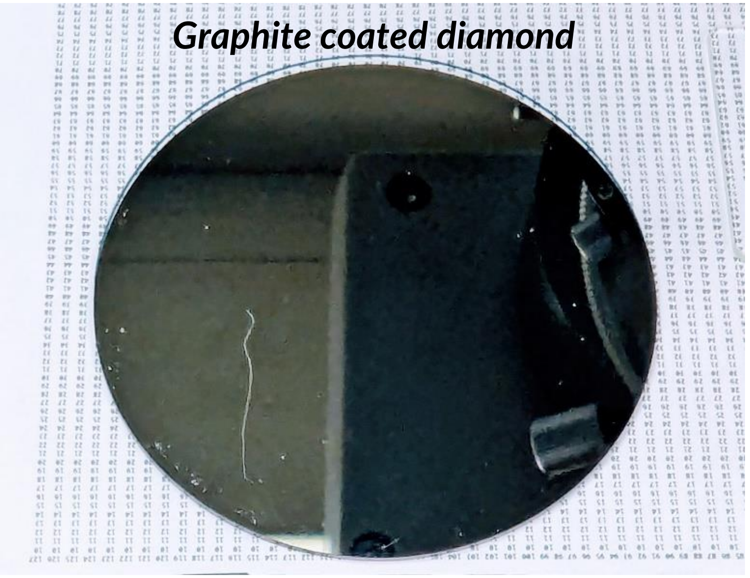
Deployed a dedicated "test stopper" upstream of the safety stopper

- Machine protection will insert the "test stopper" together with the safety stopper
- **Check the surface via a camera every 2 weeks**
- No visible issues



Annually or after major high-power operations, **take it out for further checks**

- Last microscopy check in summer 2024 downtime
- There is a scratch (possibly from disassembly)
- No hint of damages from beams



* *Courtesy of* Willem Langeveld

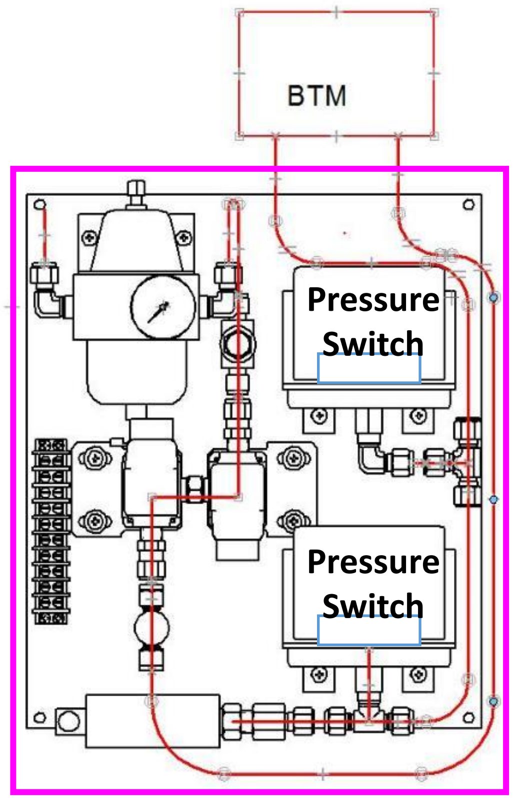
Material Drilling Experiment: Why

1. LCLS-II burn-through monitor (BTM) on FEL stoppers, collimators and dumps is based on a pressured gas chamber

   → **The size of holes** drilled by FEL determines the shut-off speed of BTM: assumed hole diameter = beam FWHM

2. There shall be materials to absorb beams during the BTM response time

   → **The speed of material drilling** is important: must not fully drilled through before the beam is shut-off by a BTM (estimated as in the range of a few seconds)



BTM Control Box

Goals of material drilling experiment:

1. The size of holes
2. The speed of material drilling

Material Drilling Experiment: How (1/2)

Designed a sample holder

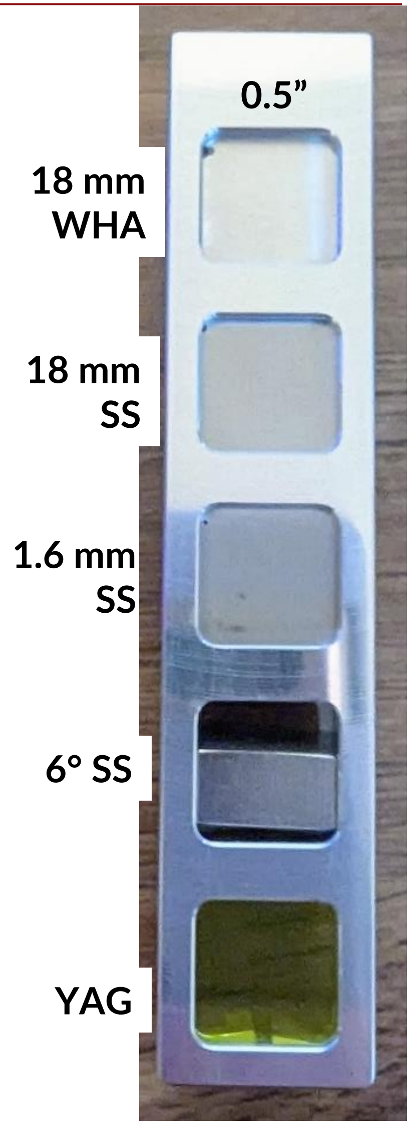
- Multiple samples on a holder
- YAG is used to measure beam size at the sample location

First tested with unfocused beam (in June 2024), at a position much closer to undulator compared to stoppers

→No damage observed due to low FEL beam power

Then tried to use focused beam (in December 2024 and May 2025)

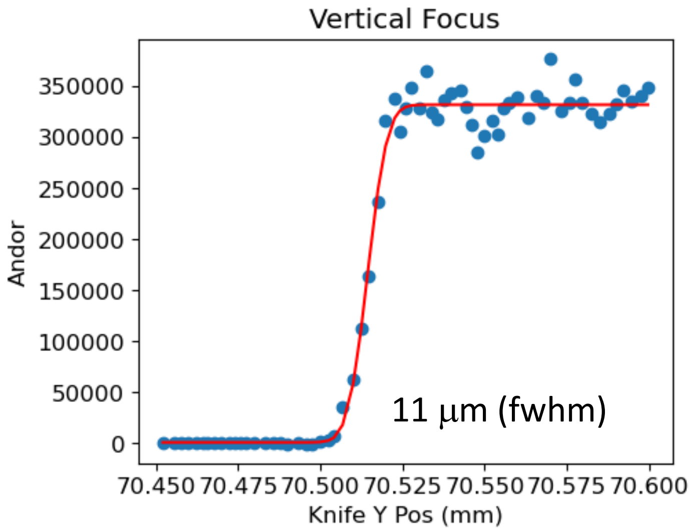
- Both used **focused mono beam** to the RIX beamline (more in the next slide)
    - Studied but couldn't use focused pink beam (some device damage concerns)

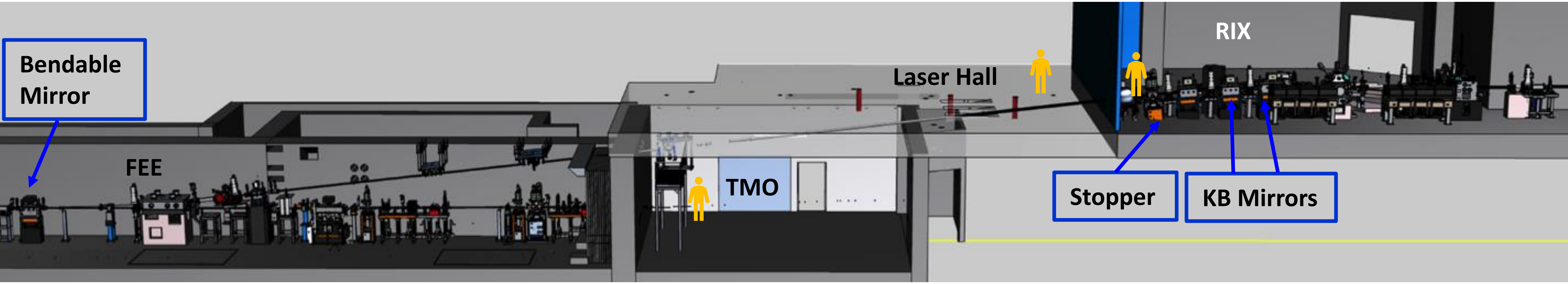


Material Drilling Experiment: How (2/2)

RIX beamline has a monochromator in the front end enclosure (FEE)

- Beams will be focused by K-B mirrors in the hutch
- Deployed a power meter after the sample holder to measure the beam on samples
- Use knife scan to measure the beam size





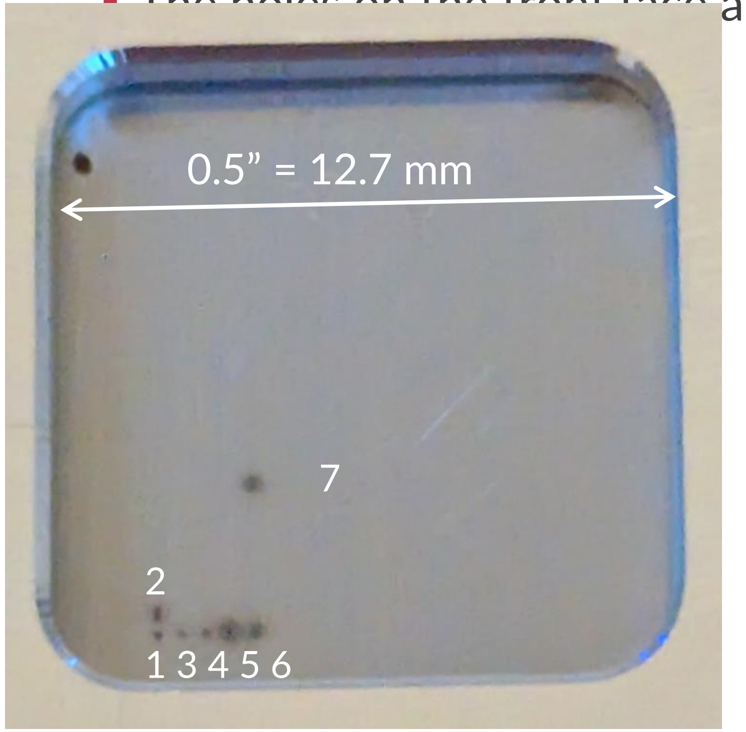
Material Drilling Experiment: What (1/4)

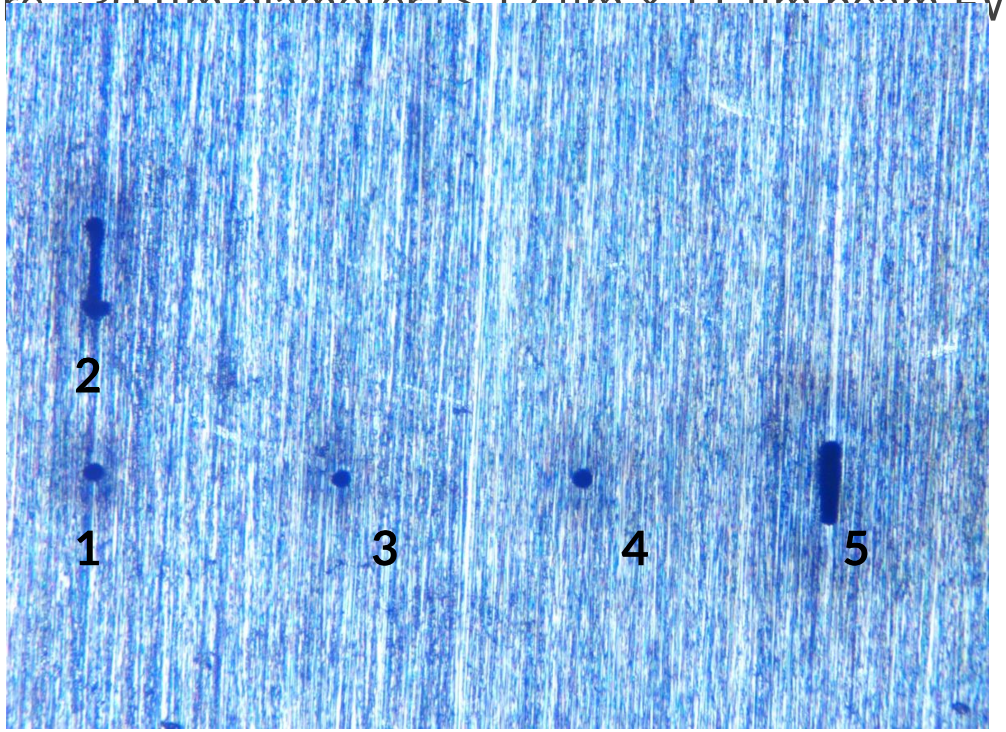
FEL parameters in the December 2024 experiment

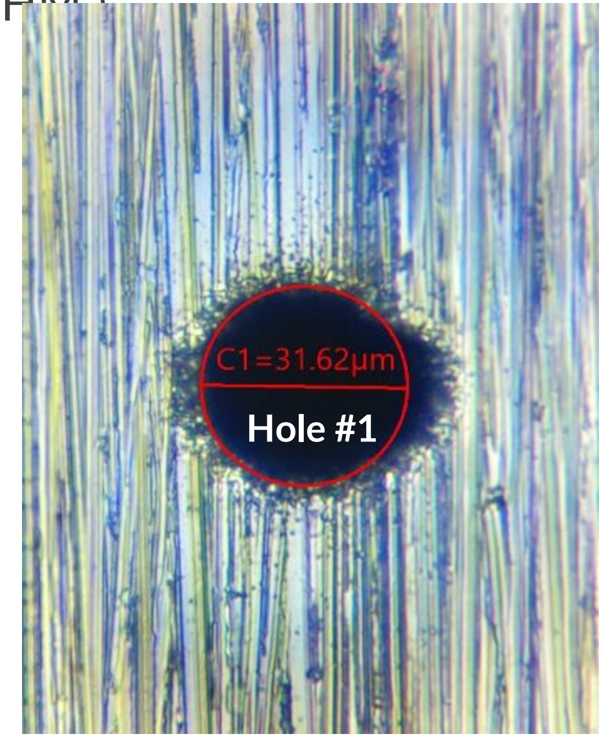
- 400 eV, 8.3 kHz, 1.5 uJ/pulse *(lower than expected)*, 17 μm × 11 μm FWHM → 3.6 eV/atom

Surface damages on 1.6 mm thick stainless steel, **but no drill through** after a few minutes (up to ~15 min.)

- The holes on the front face are ~30 μm diameter (> 17 μm × 11 μm beam FWHM)



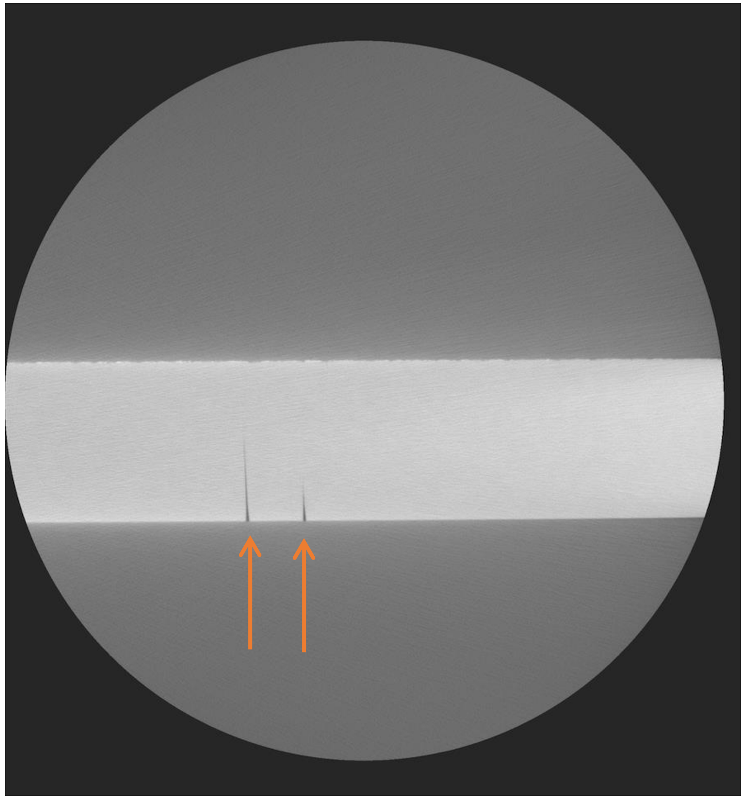




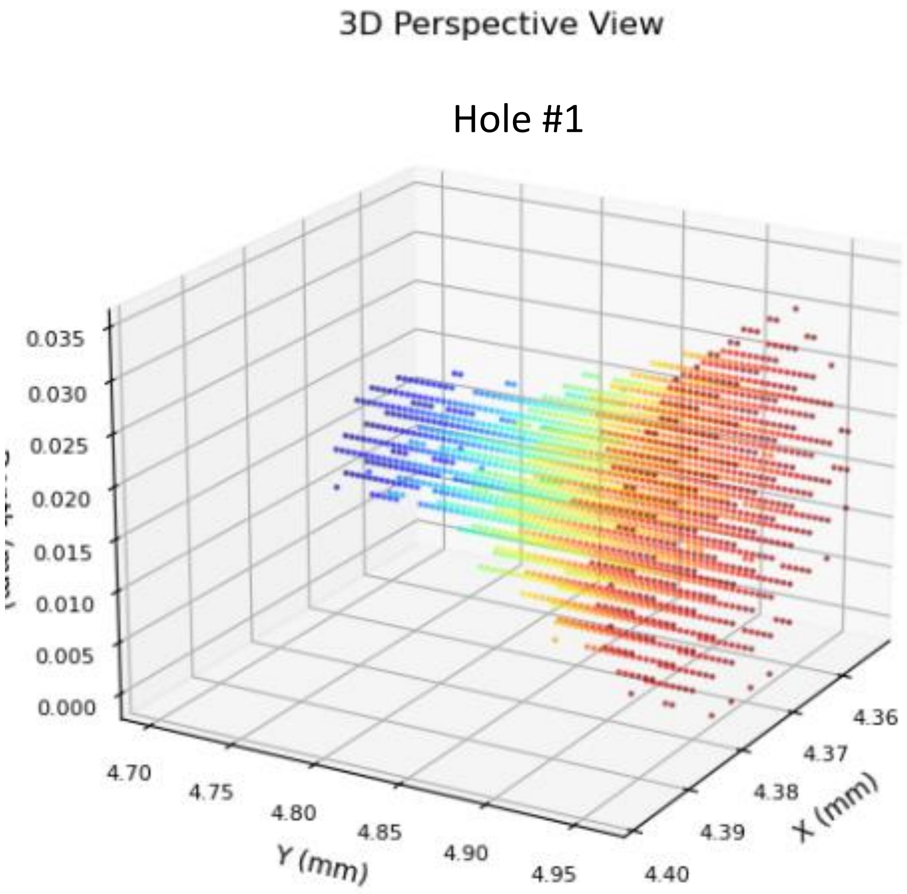
Material Drilling Experiment: What (2/4)

Use x-ray tomography to analyze the hole profile

- Cone shape holes
- Drilled up to half of the 1.6 mm thick stainless steel



Hole #1



Material Drilling Experiment: What (3/4)

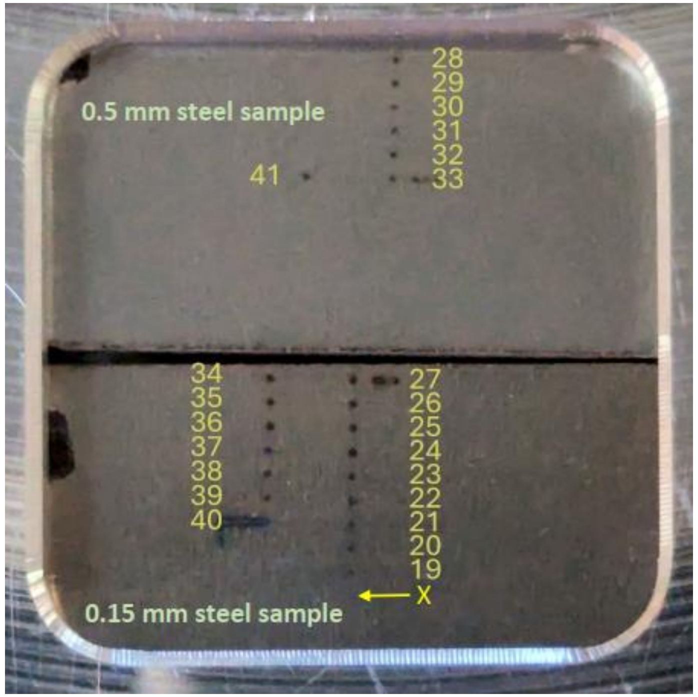
FEL parameters in the May 2025 experiment

- 750 eV, 33.2 kHz, **0.2 uJ/pulse** *(much lower than expected)*, 9 μm × 10 μm FWHM → 2.0 eV/atom

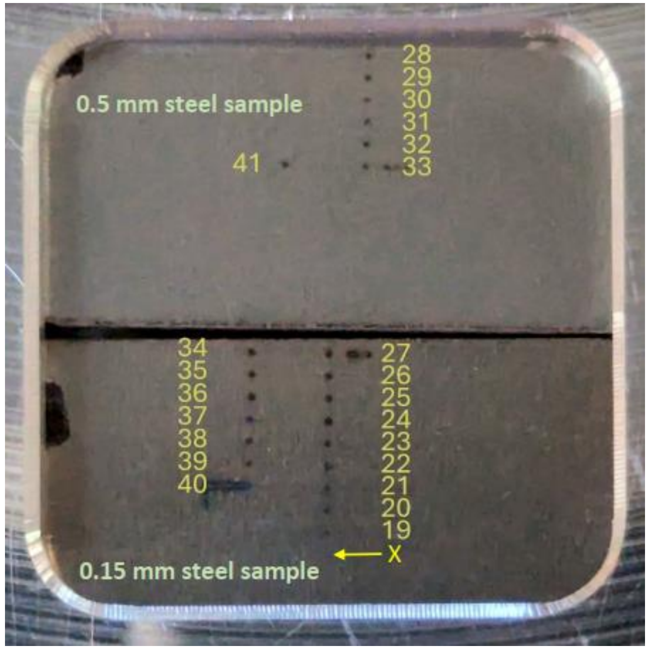
Thin samples are tested in this experiment:

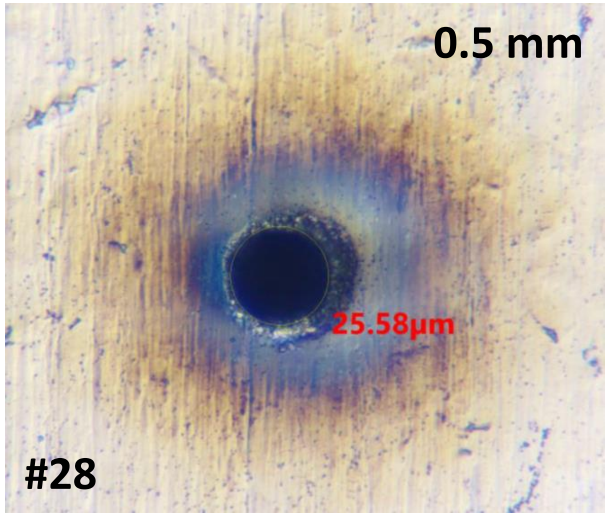
- Drilled through 0.15 mm thick stainless steel in ~2 minutes
- Couldn't drill through 0.5 mm thick stainless steel in 20+ minutes
- Front face holes are 20-25 μm diameter (> 9 μm × 10 μm beam FWHM)

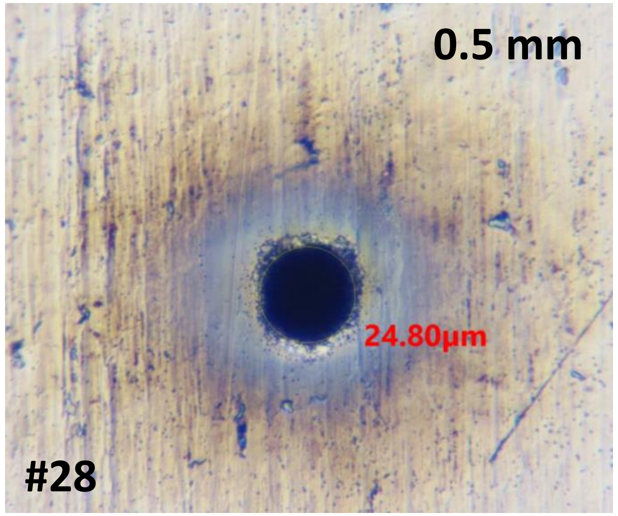
X-ray tomograph analysis ongoing

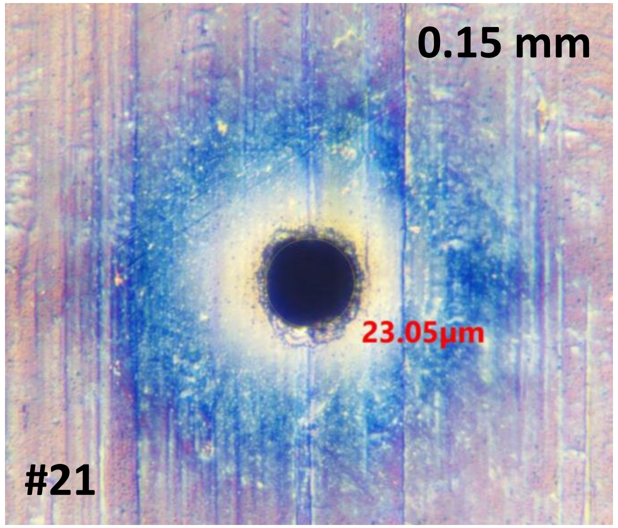


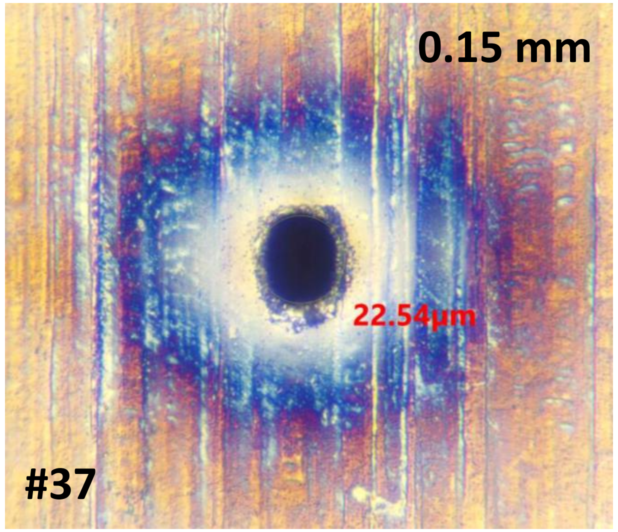
Material Drilling Experiment: What (4/4)









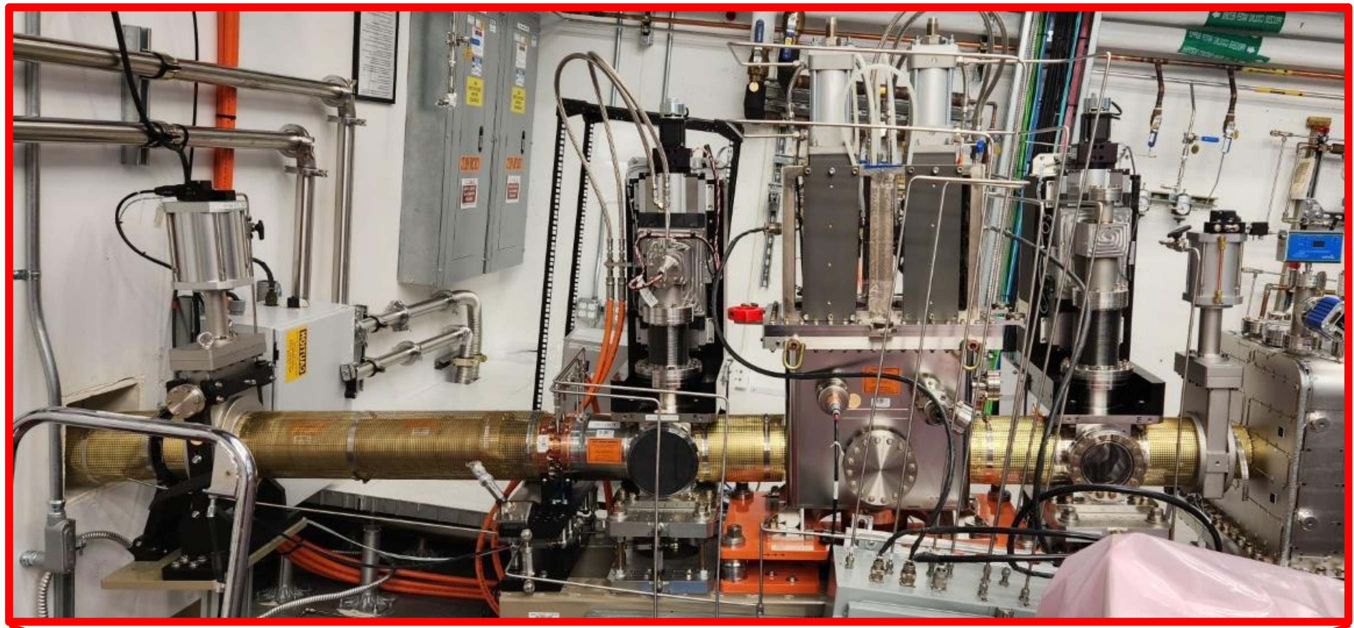


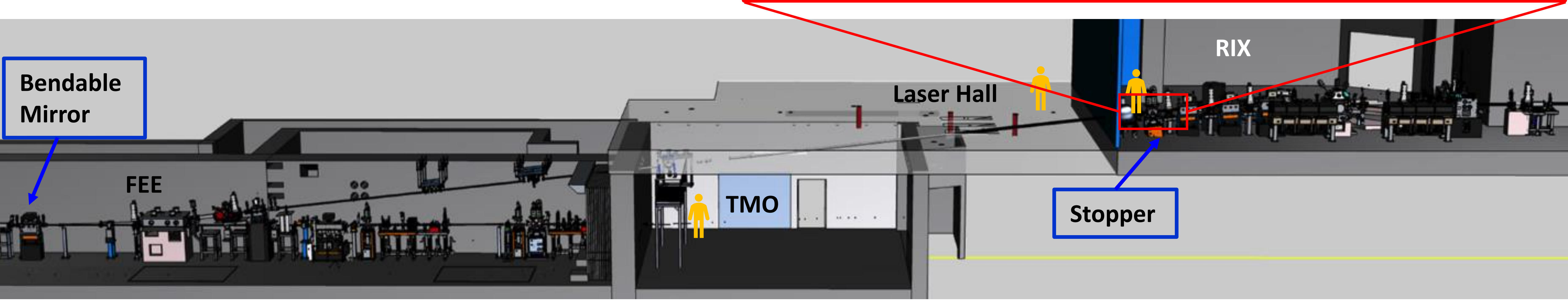
Air Attenuation Experiment: Why

Air is used to contain beams leaking out of vacuum, especially for the RIX beamline

- People can stay beside the beam pipe while beam is running
- Add “air exclusion zones” along the beamline in accessible area

LCLS developed a conservative estimates: need to verify it is really conservative



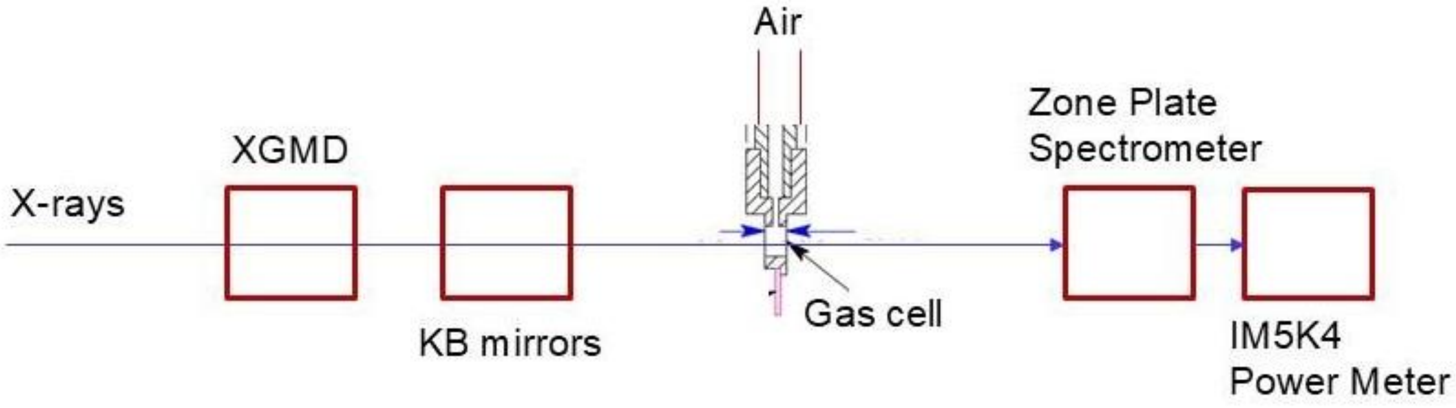


Air Attenuation Experiment: How

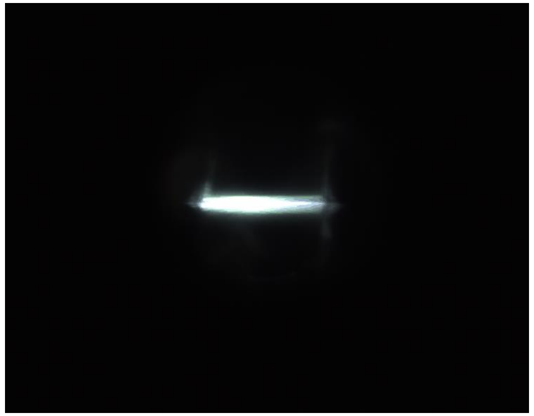
Burn a gas cell (in vacuum) and measure the air transmission

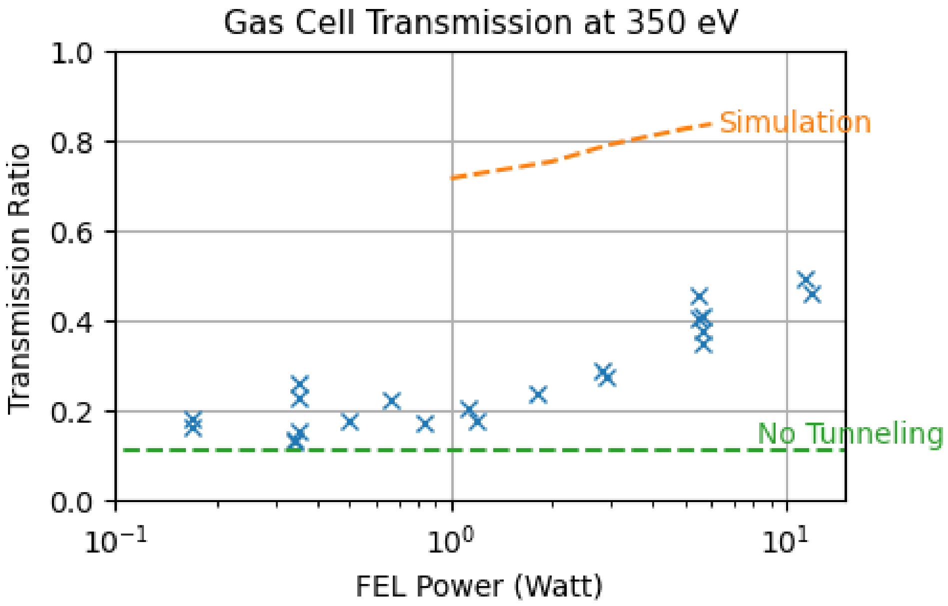
- 6.6 mm air path from the gas cell
- YAG screen to measure beam size
- Run at different powers with the combination of attenuations and repetition rates (2 or 3 runs for each set of parameters)

Photon energy	316, **346**, 446, 611 eV
Pulse energy at XGMD	~340 μJ
Pulse energy at cell	~250 μJ
Repetition rates	100 - 33.2 kHz
Attenuation	0.07 - 1
Power at cell	0.02 – 8.6 W
Focus	2 - 10 μm FWHM



Air Attenuation Experiment: What





Air transmission increased significantly with FEL beam power

- Changing separation rate and changing pulse energy *(by changing attenuation)* have similar results
- Haven't saturate at 10 W

Compare measurements and calculations

- Measured transmission is less than calculated → the calculation is **conservative at the current power level**

Summary

LCLS-II FEL beam operation was ramped up from 1 kHz to 33.2 kHz since August 2023

Bootstrap monitoring and experiments are conducted as plan:

- Monitor FEL yield: Up to 20 W beams, ~800 uJ/pulse
- Verified the integrity of stopper
- The material drilling experiments used focused mono beam (due to practice constrains)
  - Observed drilling was slow (but the mono beam power was also low)
  - Front face hole diameter > FEL beam FWHM (but the back face need more studies)
- The air attenuation experiment confirms the estimation method is conservative at the current power level

Will continue following the bootstrap process for upcoming ramp-up by the end of 2025

- The superconducting lianc will be shutdown in the whole 2026 for the LCLS-II HE upgrade

Thank You!