Radiation Safety Analyses and Tests for the FEL from LCLS-II Superconducting Linac

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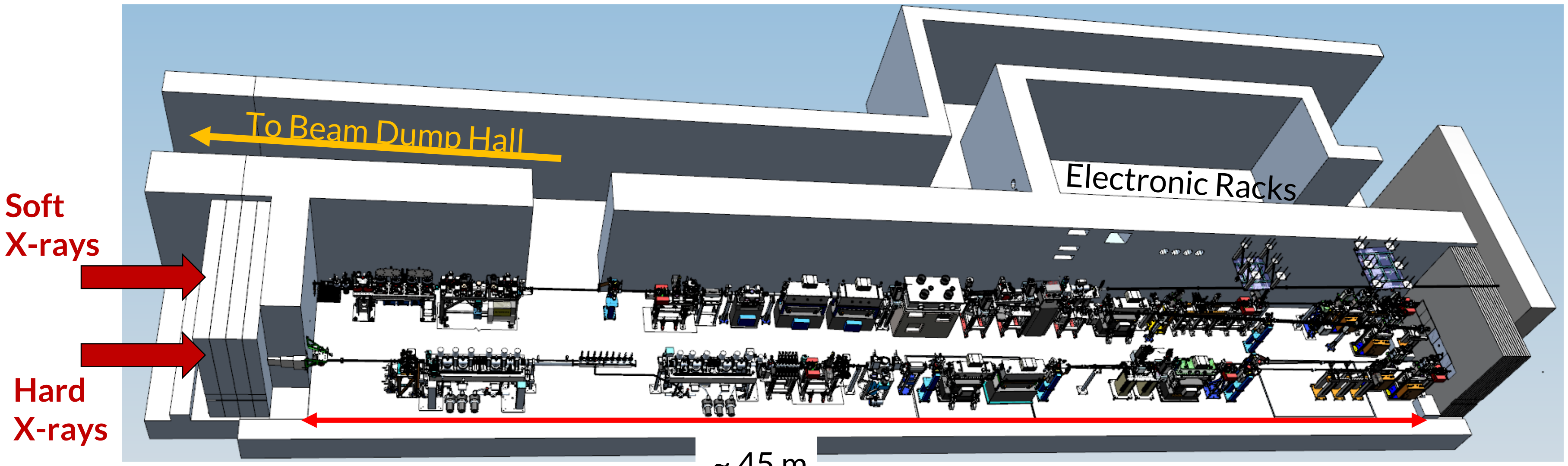
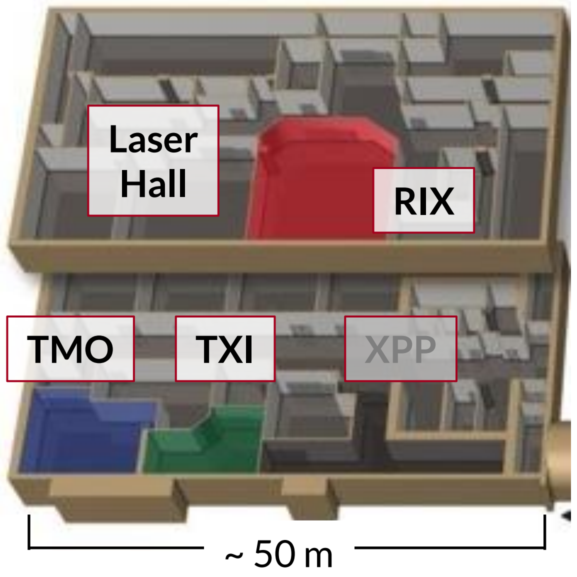
Outline

1. Introduction of LCLS-II FEL beam lines and FEL parameters
2. Beam containment systems FEL from superconducting Linac
3. Tests for radiation safety devices with FEL from *normal conducting Linac*
4. Summary

LCLS-II FEL Beam Lines



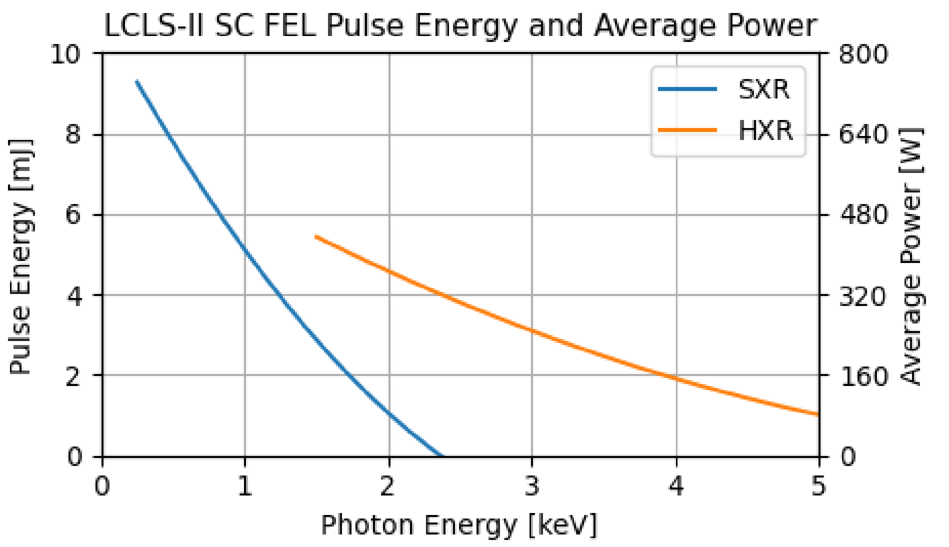
Front End Enclosure (FEE)



Near Experiment Hall (NEH)

Electron beam: 2-5 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

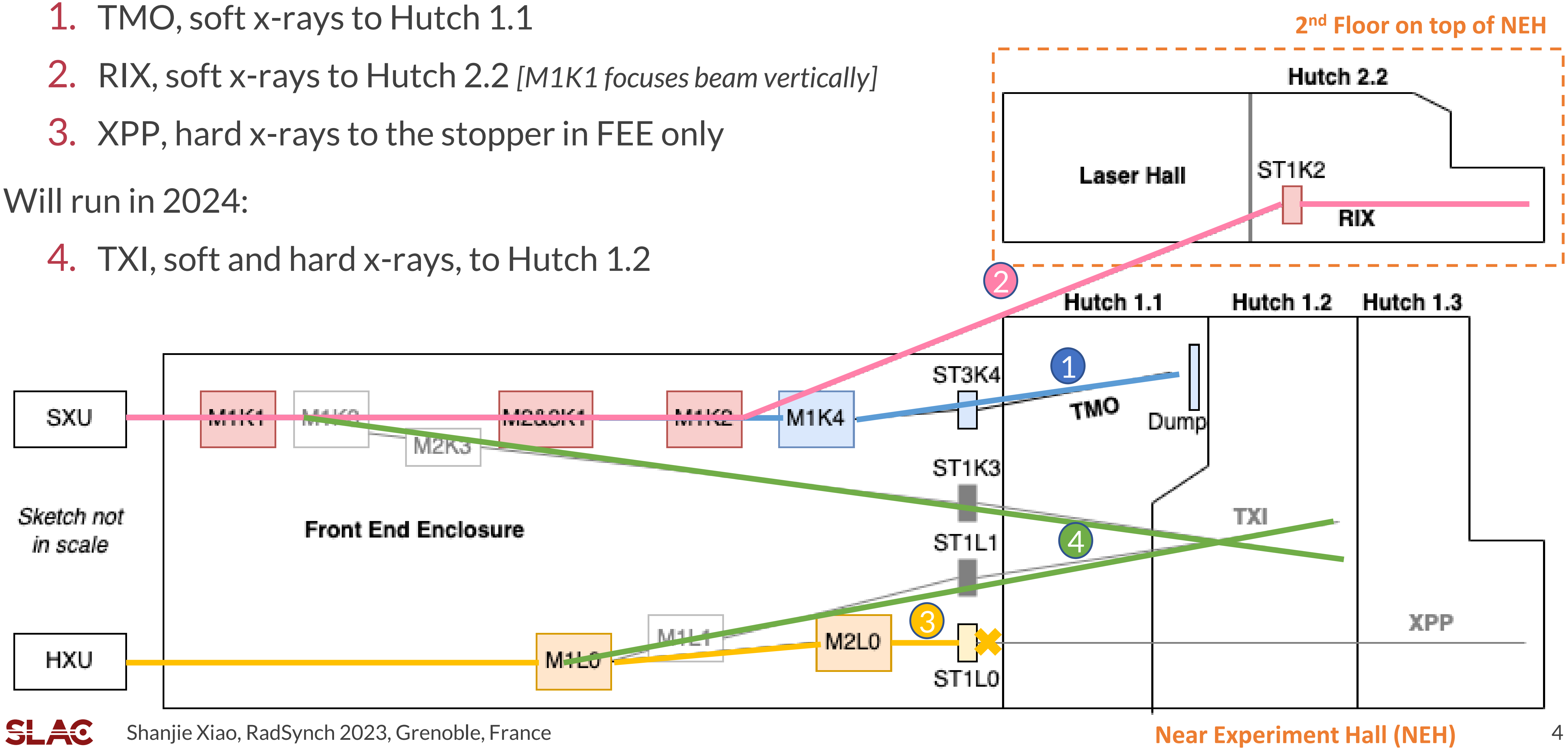
LCLS-II FEL Beam Lines Schedule

Plan to run in July 2023:

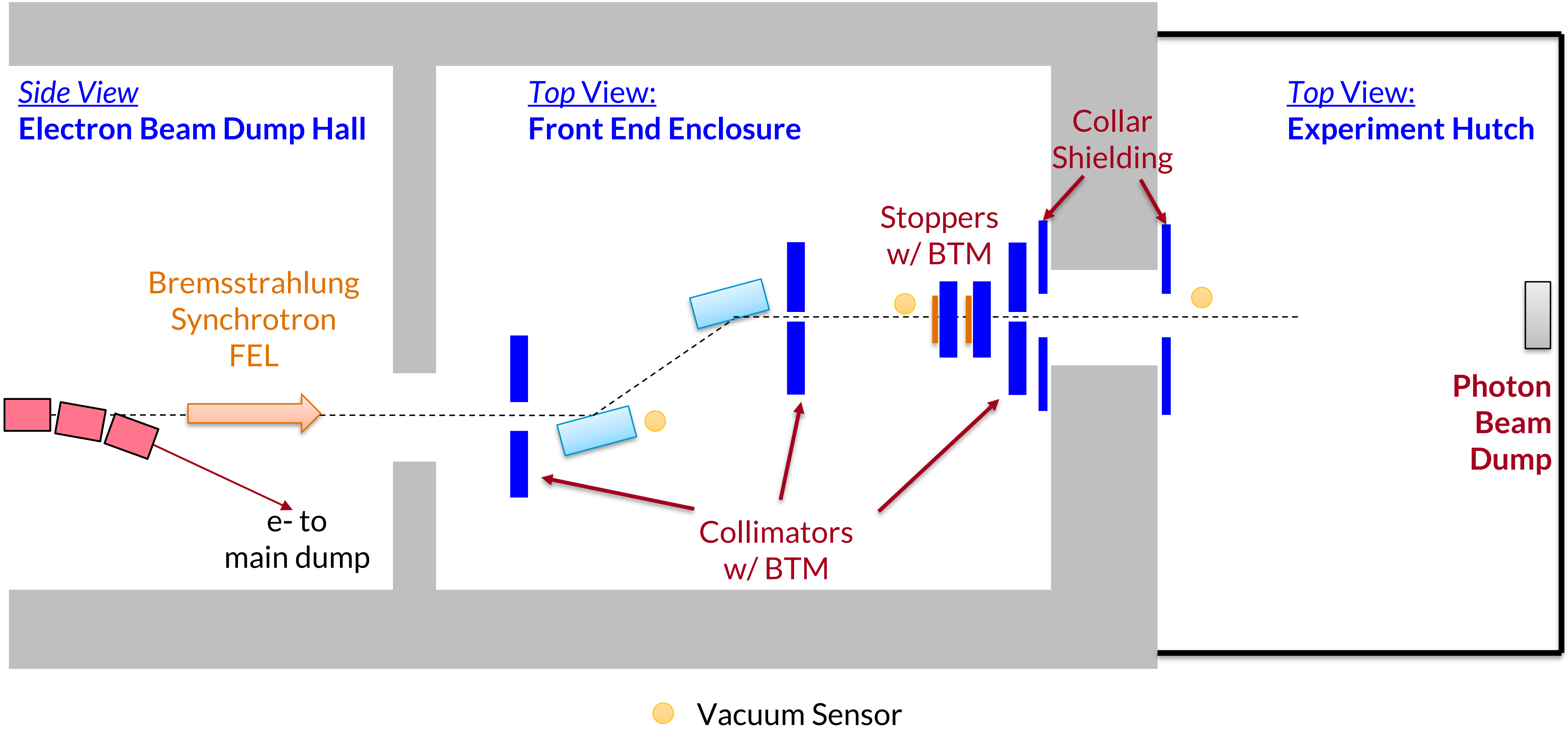
1. TMO, soft x-rays to Hutch 1.1
2. RIX, soft x-rays to Hutch 2.2 *[M1K1 focuses beam vertically]*
3. XPP, hard x-rays to the stopper in FEE only

Will run in 2024:

4. TXI, soft and hard x-rays, to Hutch 1.2



General Principles of FEL Beam Containment



Outline

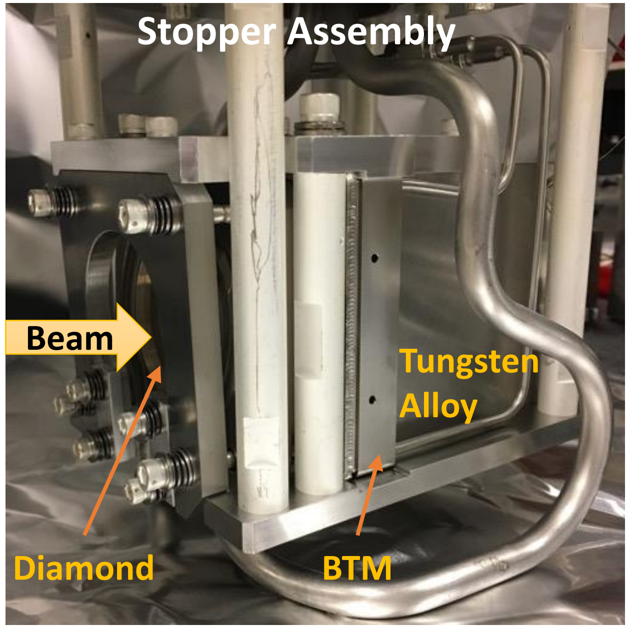
1. Introduction of LCLS-II FEL beam lines and FEL parameters
2. Beam containment systems for the FEL from superconducting Linac
   - FEL stopper, collimator and beam dump
   - Vacuum interlocks and burn-through monitors (BTMs)
   - Air attenuation for high repetition rate FEL beams
   - Bootstrap plan
3. Tests for radiation safety devices with FEL from *normal conducting Linac*
4. Summary

FEL Stopper (1/2)

Diamond photon stoppers: 750 μm thick diamond coated with graphite

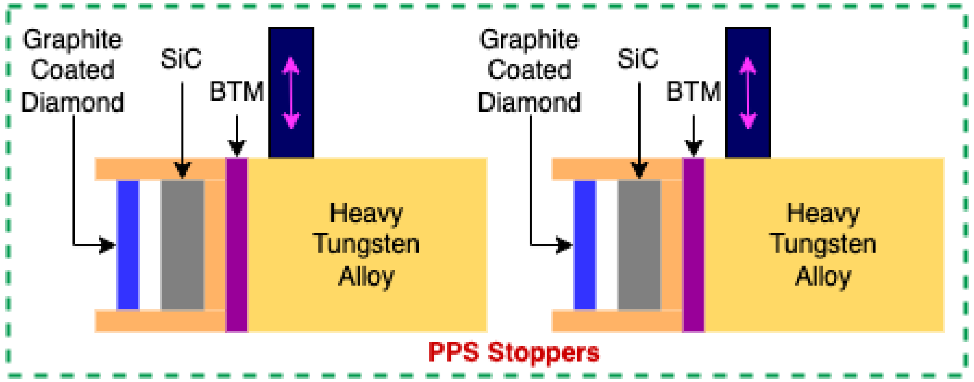
Following the absorber:

- SiC *(10 mm)*: absorb high energy x-rays from FEL harmonics and synchrotron radiation
- Burn-through monitor (BTM): trip off beams when the front layers are damaged *(e.g., cooling water failure)*
- Heavy tungsten alloy block *(10 cm)*: (1) block high energy radiation such as bremsstrahlung and secondary radiation from electron beam accident (2)



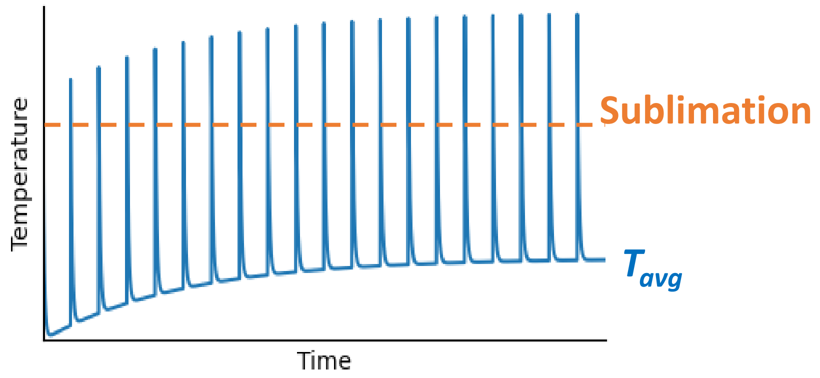
The stopper can take the maximum ***hard x-ray*** beam

But the temperature from ***soft x-ray*** beam can be very high (>2400 °C) around the carbon K-edge



FEL Stopper (2/2)

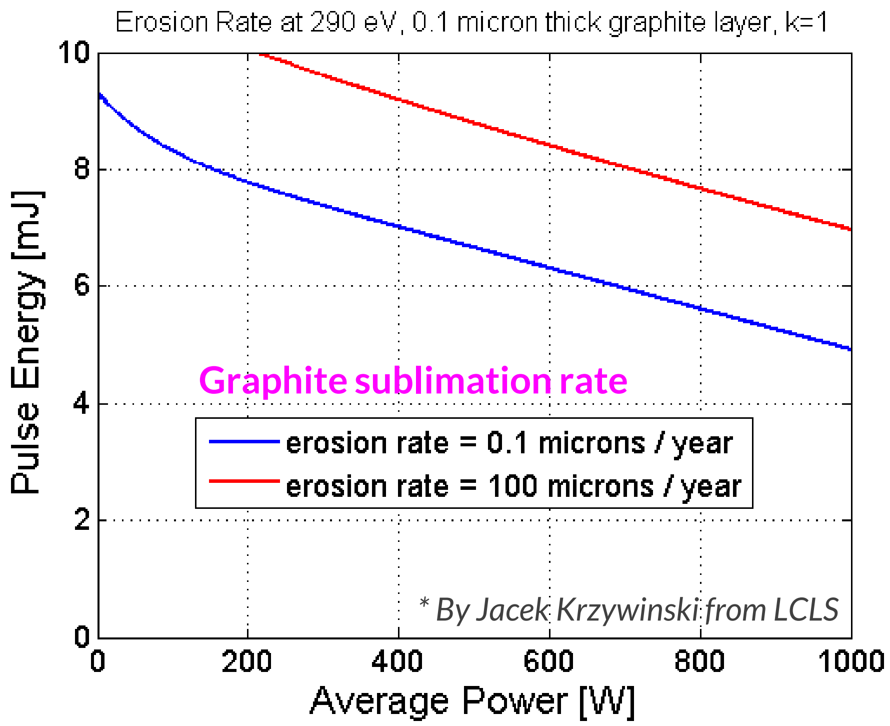
$$T(t) = T_{avg} + T_{pulse}$$



1. Temperature from <u>average power</u> (steady state): 470 °C
2. Temperature from <u>single pulses</u> (transient): 1940 °C, **dominate**

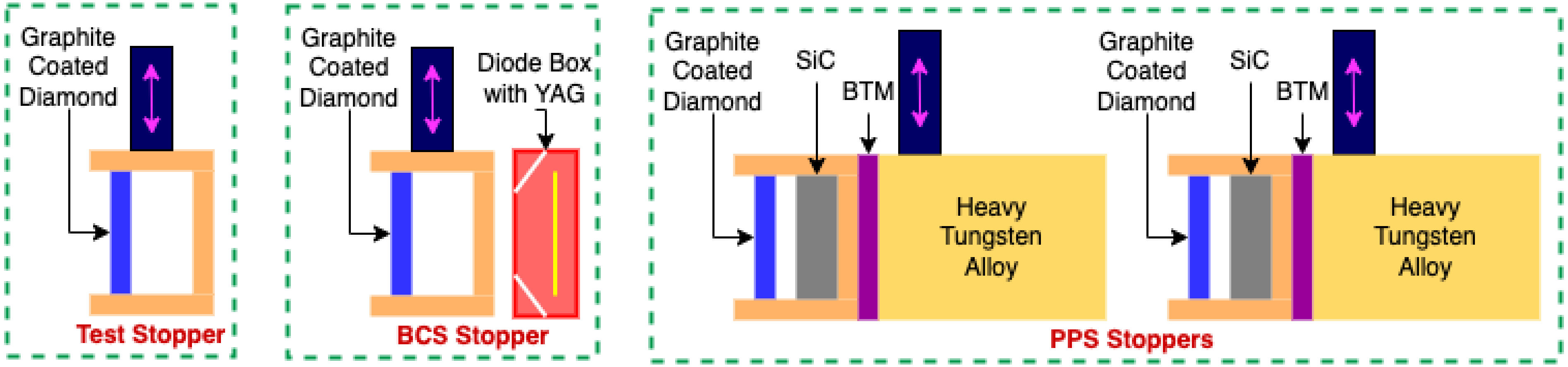
With such high temperatures:

- Diamond can transform to graphite, and graphite may sublimate slowly
- Max. sublimation rate ~1,000 μm/year *(750 μm thick diamond)*
  - Big uncertainty: T + 100-200°C → ~10x sublimation rate



Mitigations for Soft X-ray FEL Stoppers *(slow sublimation)*

1. For soft x-ray beam line, add an extra stopper (*"BCS stopper"*)
   - The BCS stopper is equipped with a photodiode BTM, which can trip beam fast



2. Will run from low power at the beginning and gradually increase the power after certain verifications (*bootstrap, details in later slides*)

FEL Collimator

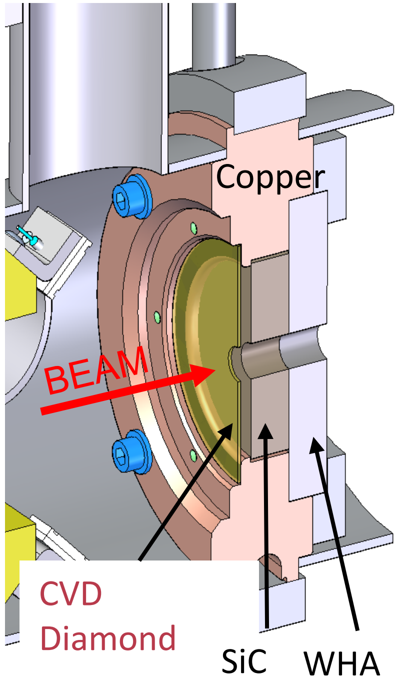
Photon collimators with a diamond layer (TMO and XPP) and without (RIX and TXI)

- Both designs can take less power than stoppers
- May be damaged by the max. FEL beams

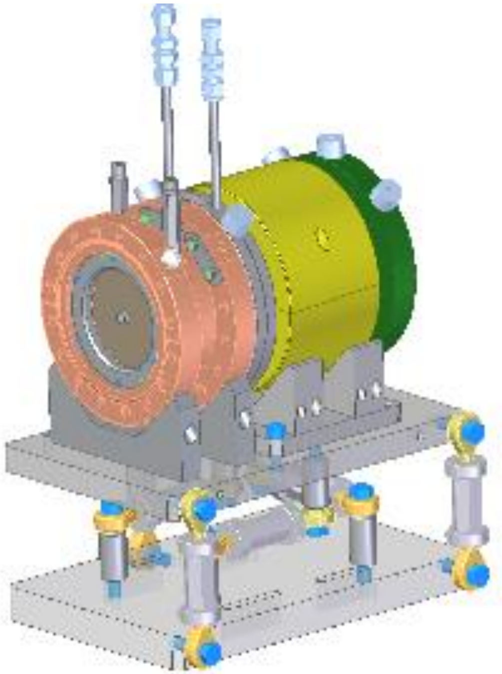
Radiation safety system need to consider cases that FEL collimators are damaged

→ Safety interlocks:

- Burn-through monitors
- Vacuum interlocks



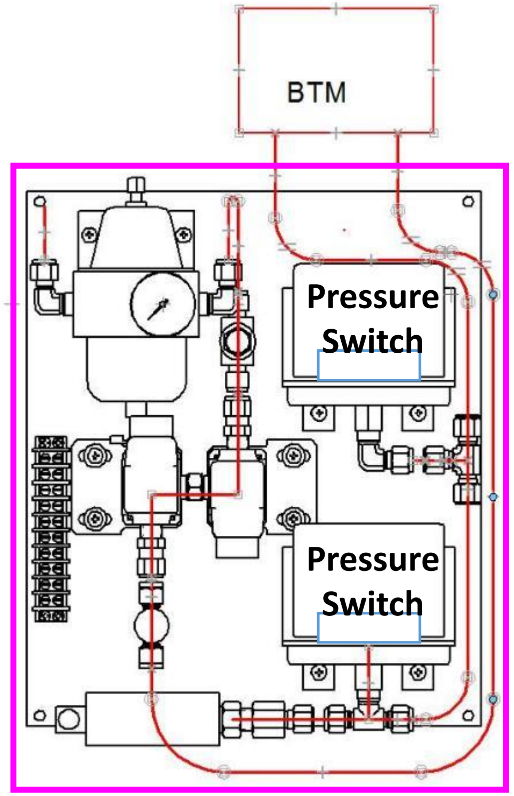
Design with diamond layer



Design without diamond layer

Burn-Through Monitor (BTM): Traditional Design

A **traditional BTM** consists of a pressured gas chamber connected to a control box

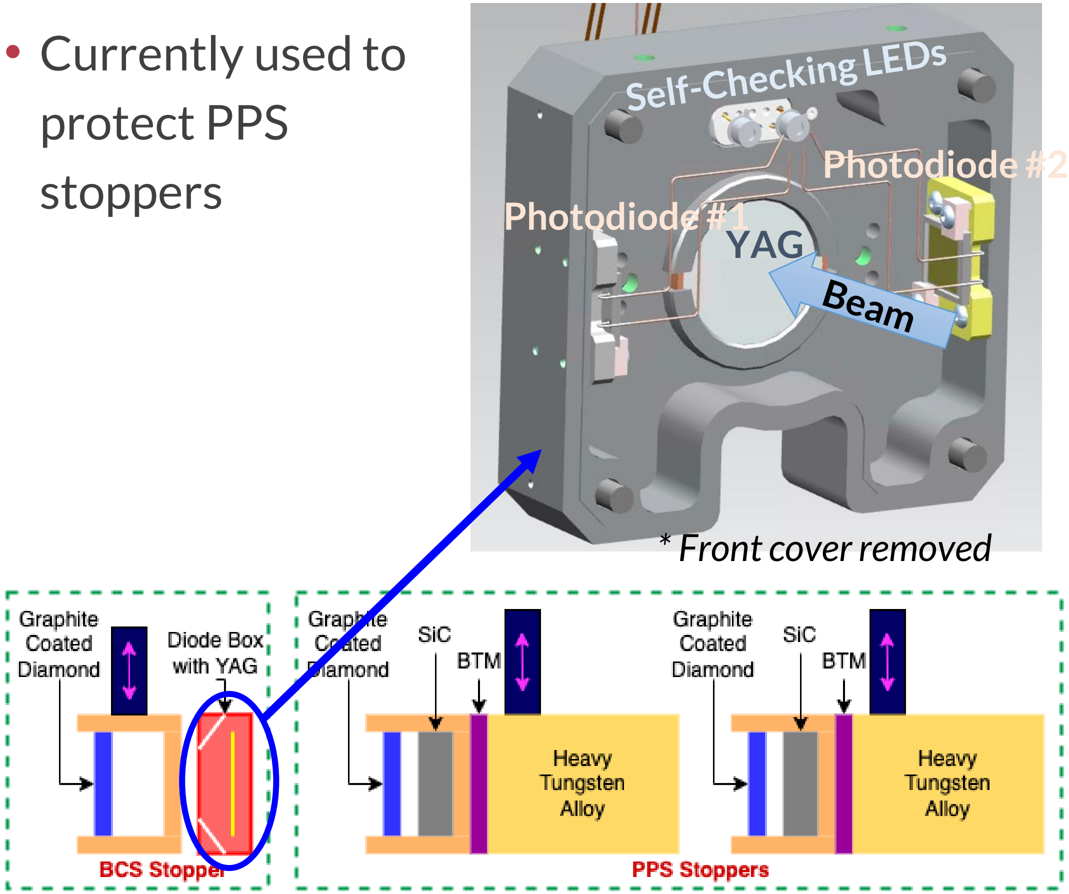


BTM Control Box

BTM Control Box (as built)

New fast-response BTM:

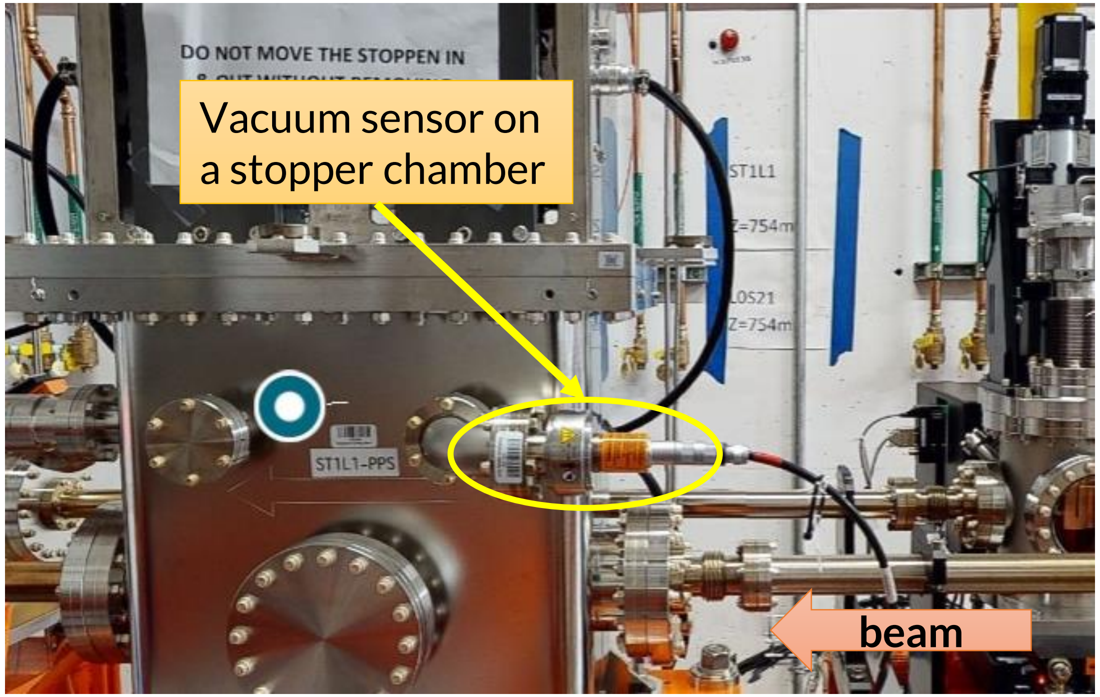
- Dark box with a YAG screen, 2x photodiodes and 2x self-checking LEDs
- Currently used to protect PPS stoppers

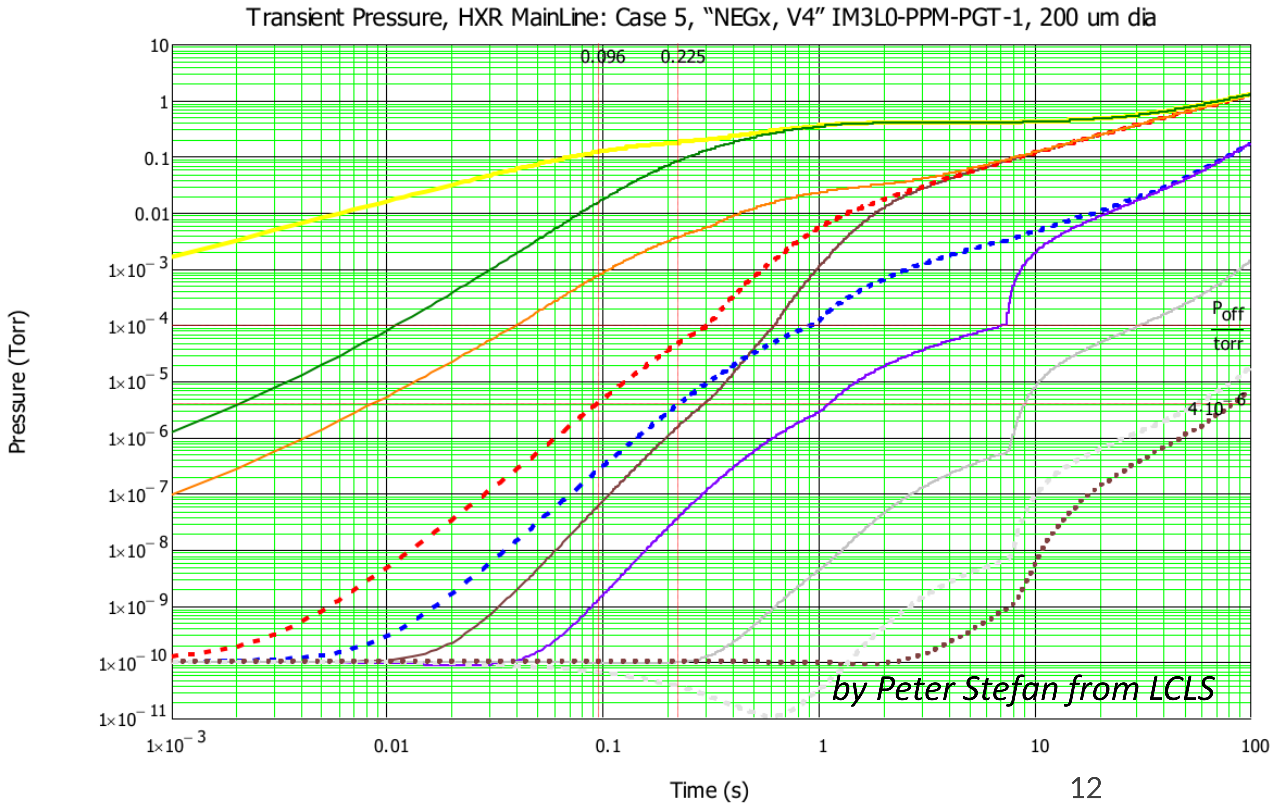


Vacuum Interlock

Add vacuum sensors *(cold cathode vacuum gauge, VAT 770SH-99NN)* along beam lines, such that a leak at any location along the line can be detected within 1 second

- 3-4 sensors per beam line
- Transient pressure calculation *(Finite Time Increment Model, FTIM)* for the interlock response time

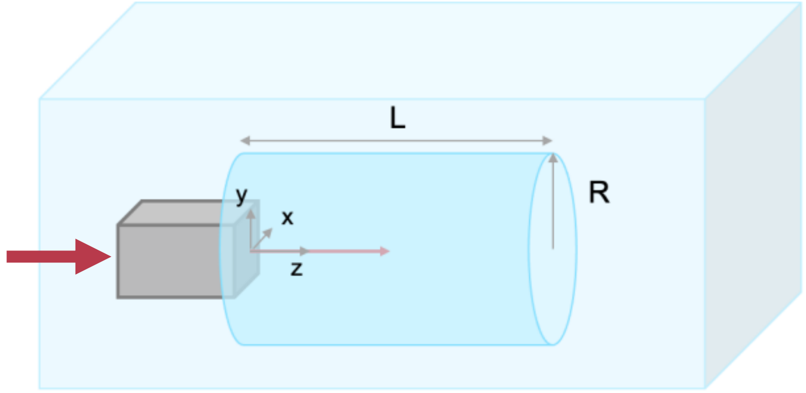


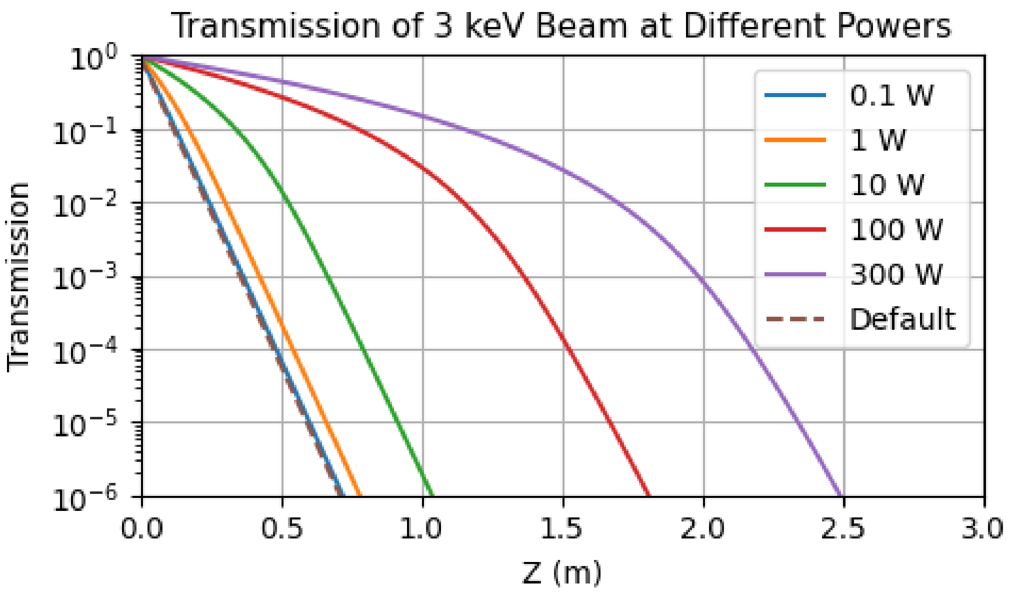


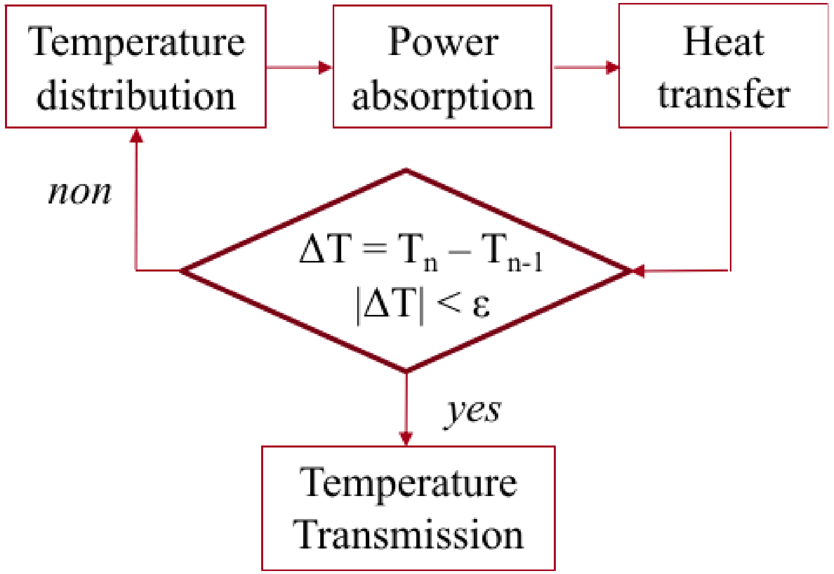
Air Attenuation for LCLS-II SC FEL

Conservative model *(by Lin Zhang from LCLS)* for “tunneling effect”

- Heat convection boundaries
- Thermal conduction only, no air convection
- Use ANSYS for FEA calculation







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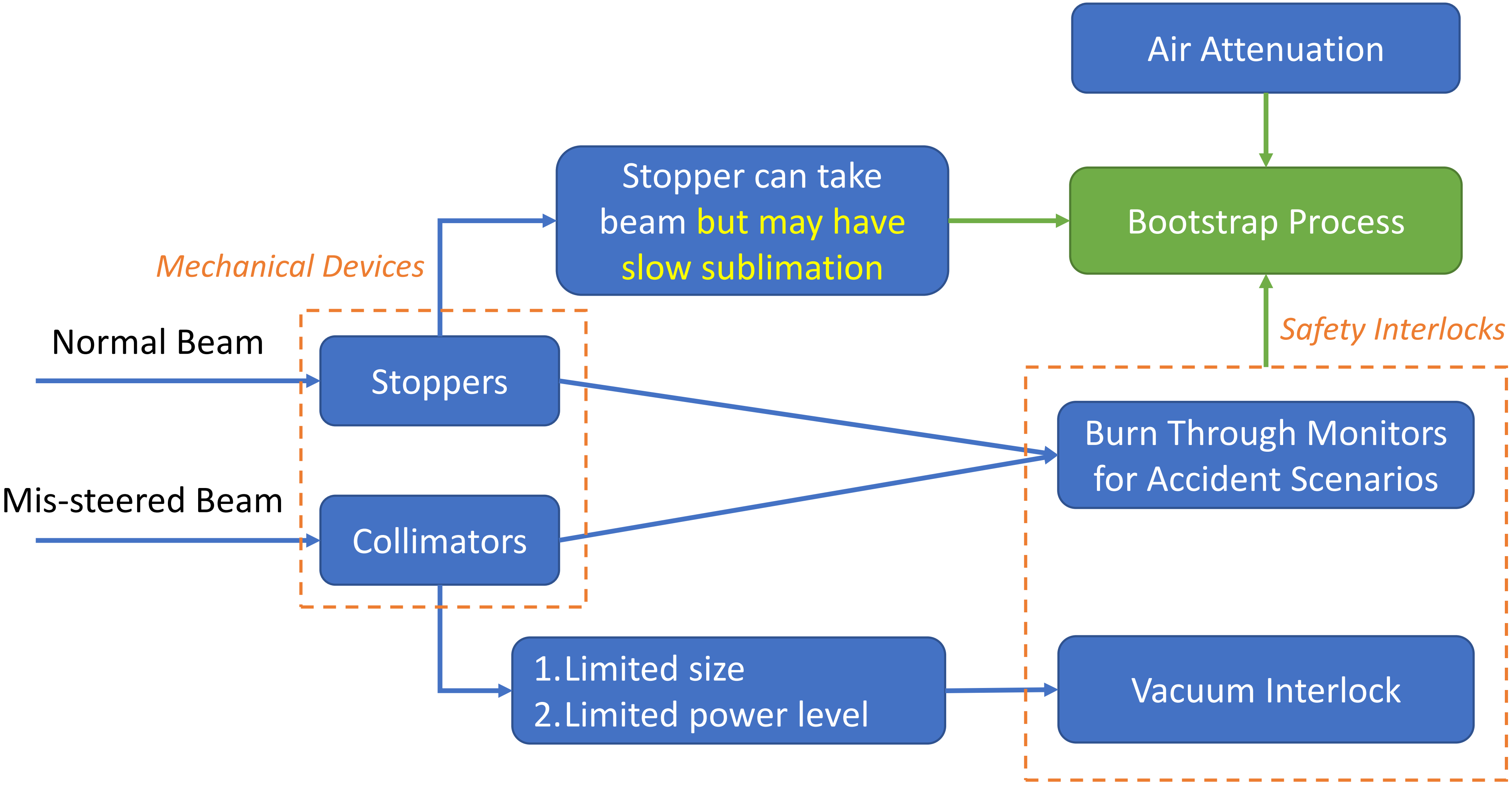
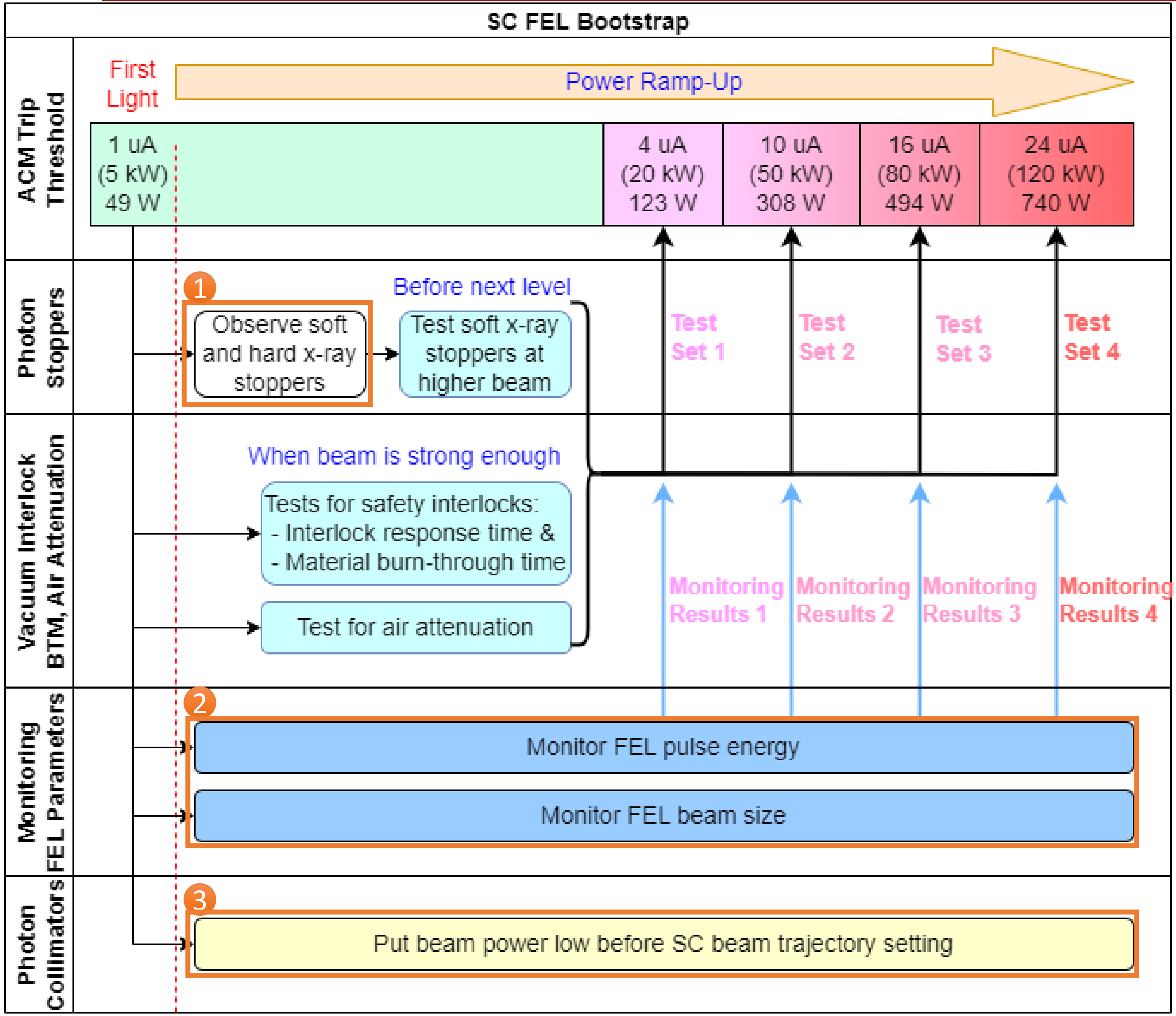


Bootstrap Plan: Monitoring from First Light



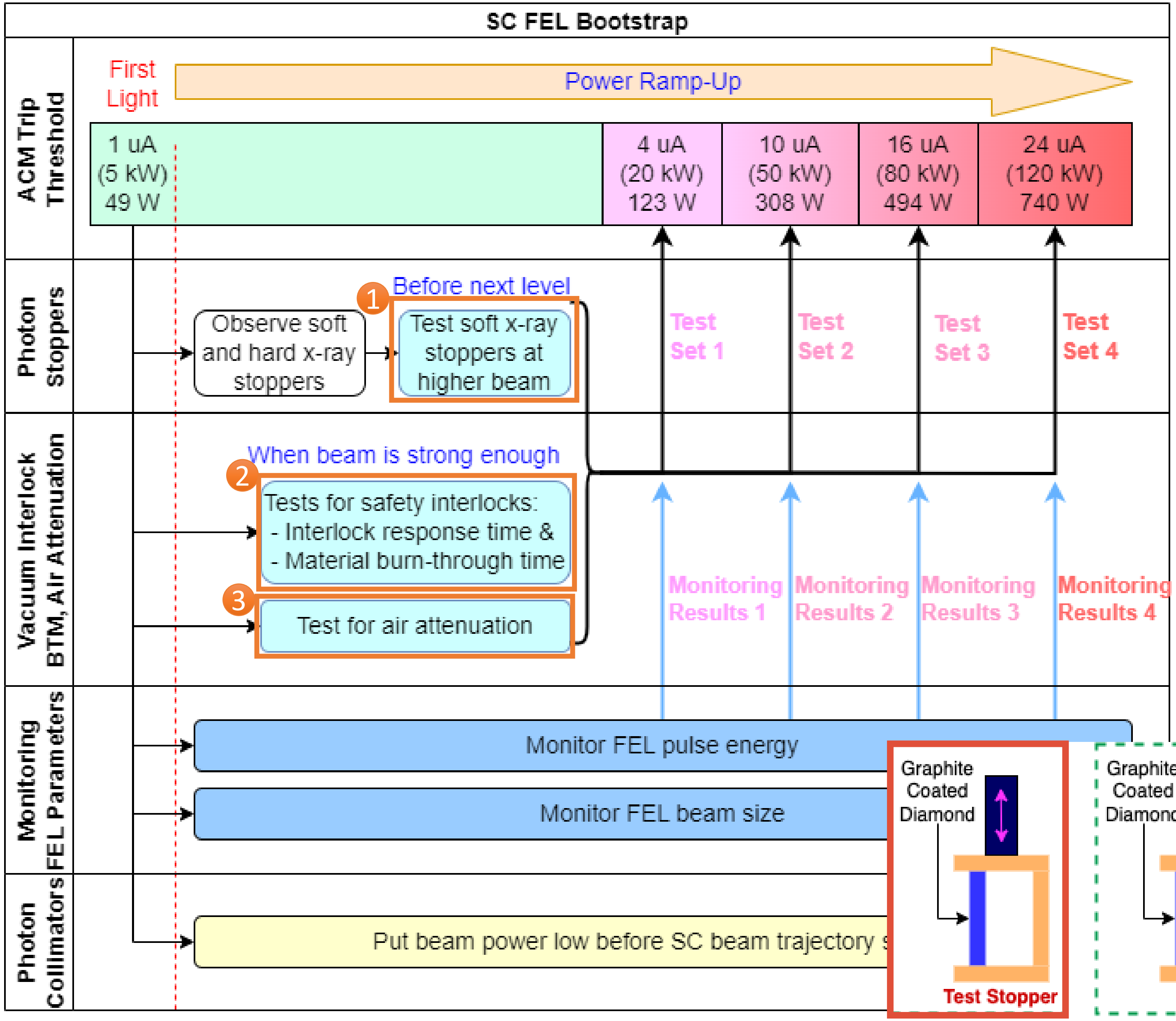
No safety device to directly limit FEL beam power → Limit electron beam current *(via Average Current Monitors, ACMs)* to indirectly limit FEL beam power

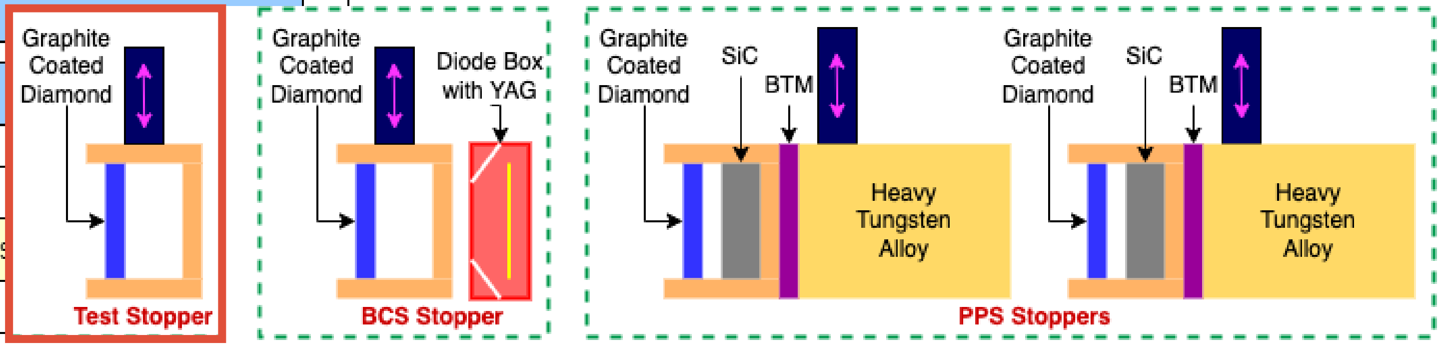
1. Observe stopper surfaces (*both SXR and HXR*) via cameras
   - Verify the integrity of diamond layer

2. Monitor actual FEL pulse energy and beam size
   - Compare measured and simulated values

3. Reduce beam power before trajectory setting
   - Beam has more chances to hit collimators during trajectory setting

Bootstrap Plan: Tests before Ramp Up





1. Verify if **stoppers** will be sufficient for the next power level
   - Temporarily increase the beam power
2. **Material drilling tests** *(steel & WHA)*: Verify *interlock response time* (*BTMs & vacuum interlocks*) will be shorter than *material burn-through time*
   a) Size of holes drilled by FEL beams
   b) Material drill through time
3. Verify the **air attenuation** for SC FEL beams

Outline

1. Introduction of LCLS-II FEL beam lines and FEL parameters
2. Challenges to containment FEL from superconducting Linac
3. Tests for radiation safety devices with FEL from *normal conducting Linac*
   - Photodiode BTM test
   - Material damage tests
4. Summary

Tests with LCLS Normal Conducting Beams

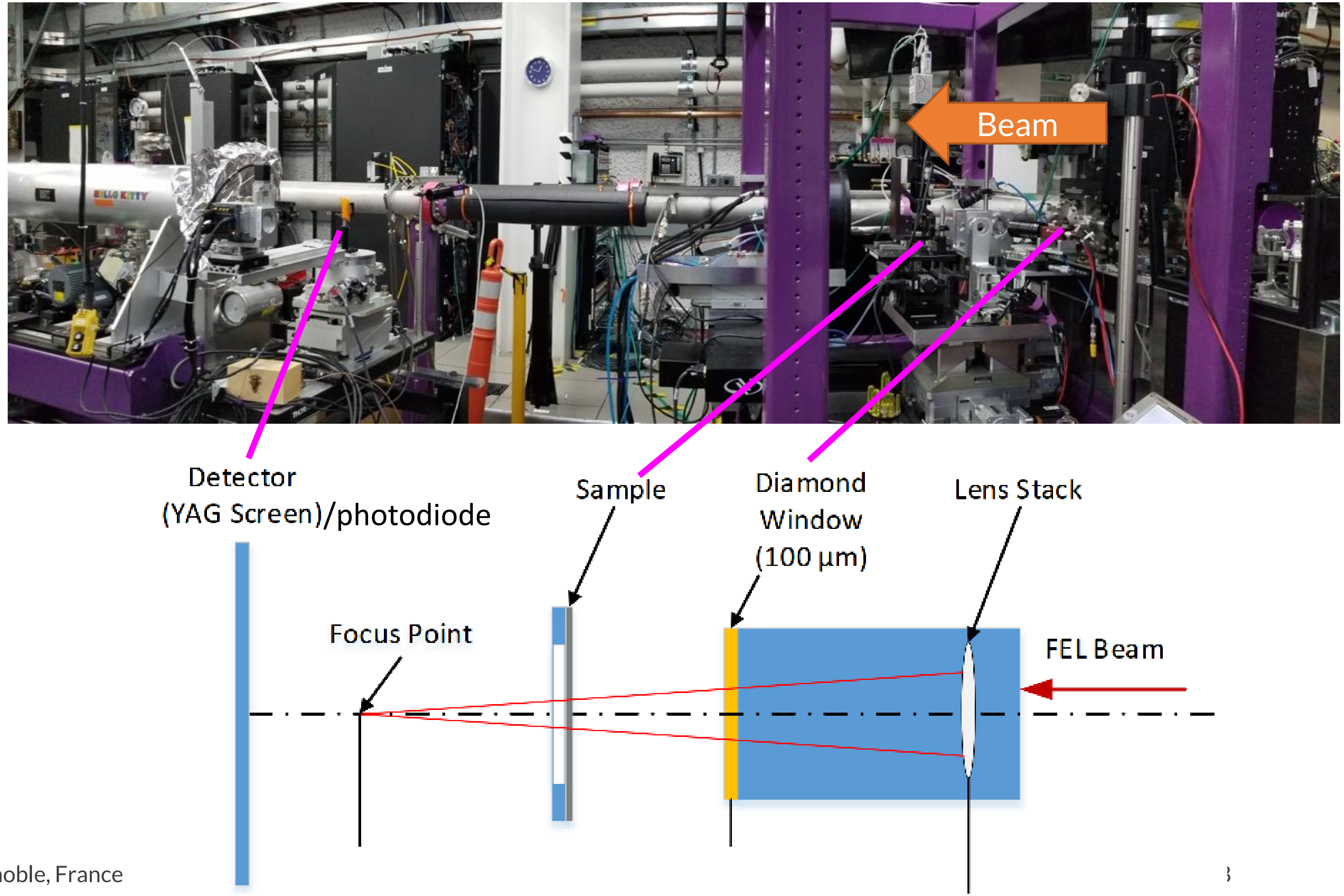
At LCLS in 2020 and 2021

Adjust beam sizes at the sample location to get different beam intensity

120 Hz beam

9.27 keV in 2020 test

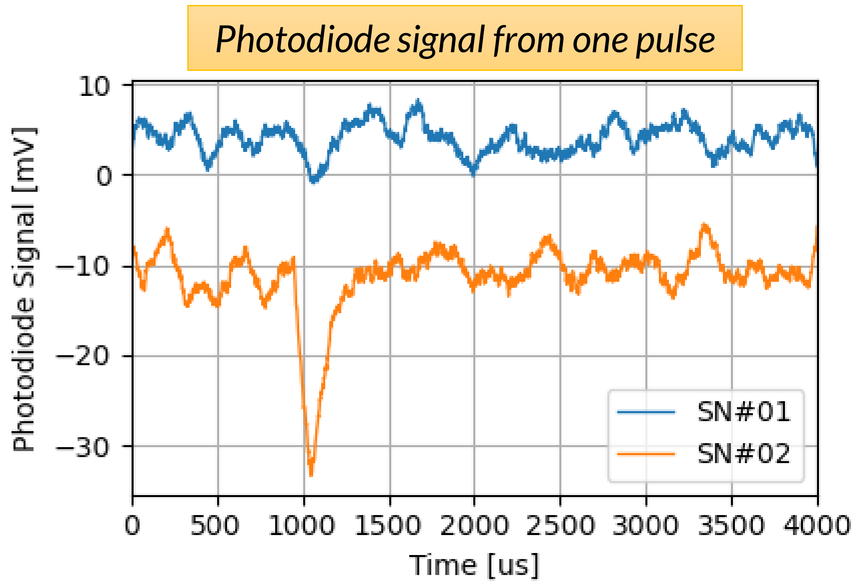
9.09 keV in 2021 test

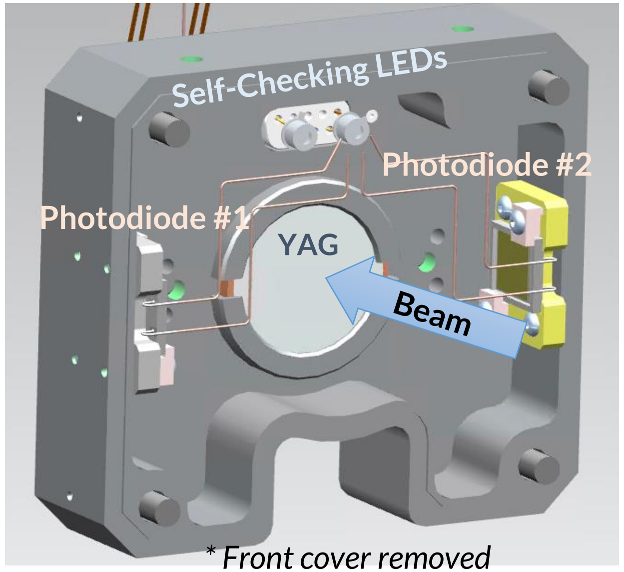


Test for Photodiode BTM

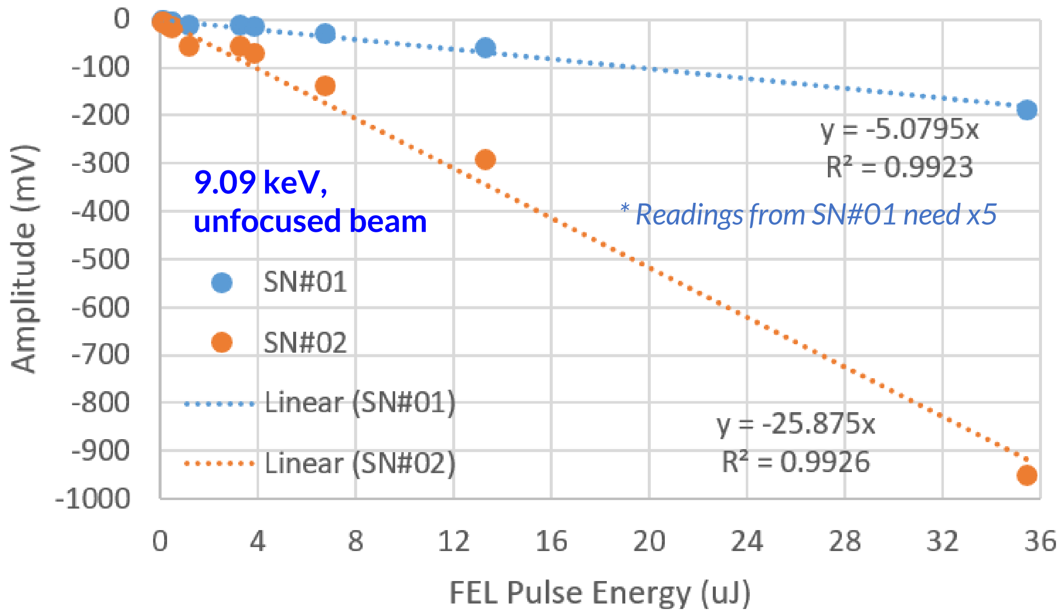
Dark box with 2x photodiodes and 2 self-checking LEDs

- YAG to produce strong signal
- Sensitive & fast: tripped by a single 1 μJ pulse, <100 μs
  - ~half signal after YAG drill through
  - Noticeable signal without YAG
- Good linearity





** Front cover removed*



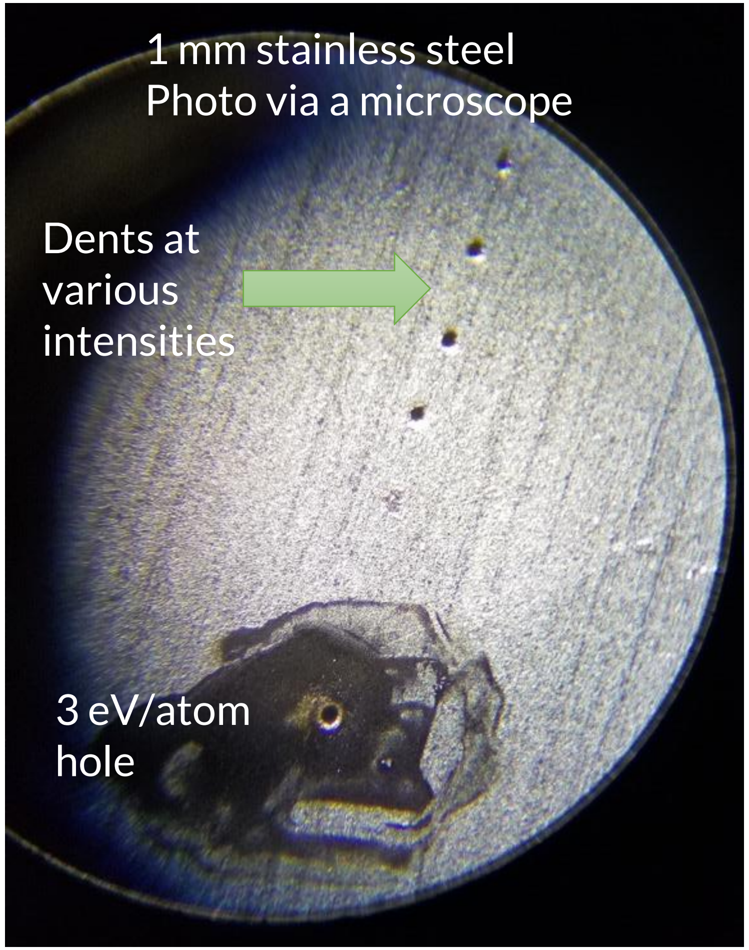
Material Damage Test: Damage Threshold

No obvious surface change on **SiC** under 1.1 eV/atom for 500,000 pulses

Visible damages on **stainless steel** from 0.7-4.2 eV/atom beam

1 mm thick stainless steel

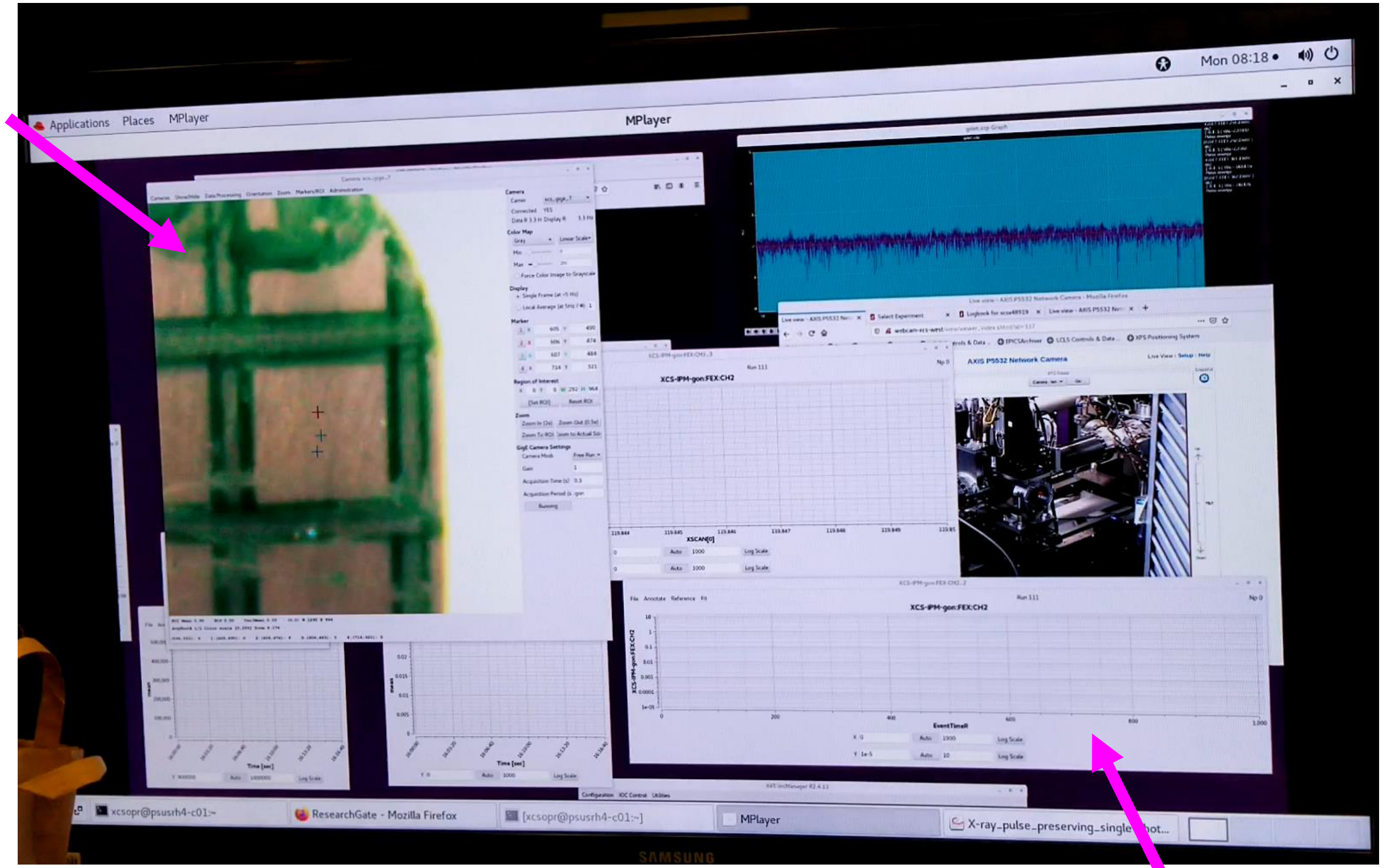
- Burn through immediately at 8 eV/atom
- No burn-through for 5 minutes (36,000 pulses) at 4.3 eV/atom
- Took 70 minutes (500,000 pulses) to burn-through at 3.0 eV/atom



Material Damage Test: Drill Time

1.27 mm thick stainless steel, 30 μm FWHM beam (4.5 eV/atom)

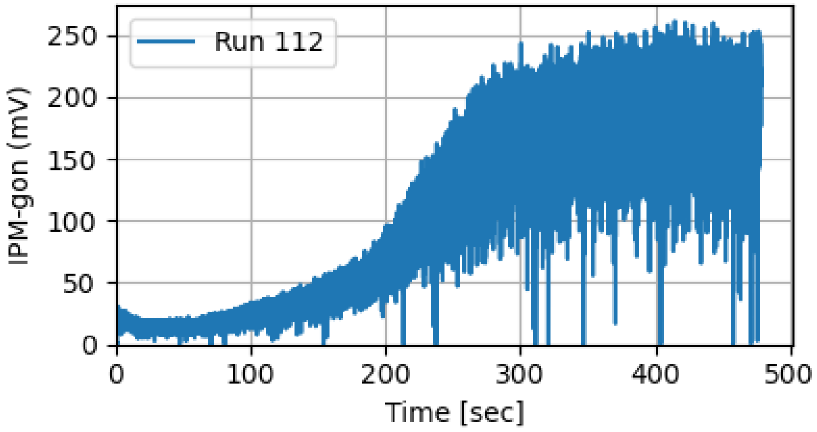
Target Surface



Photodiode behind target

Strong flare at the beginning, then dimmed

Special in this case: the photodiode behind the sample read increased signal over time

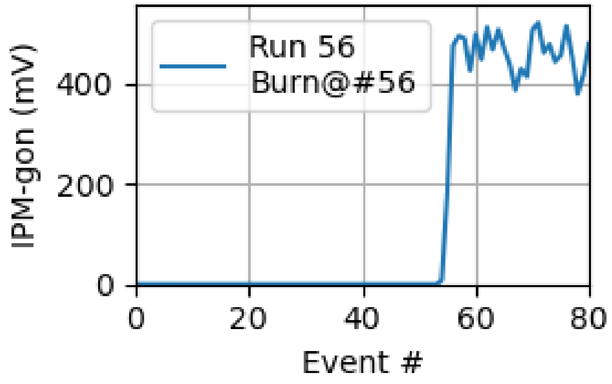


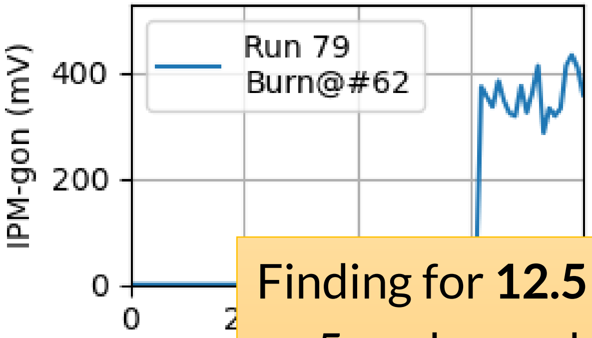
Material Damage Test: Drill Time

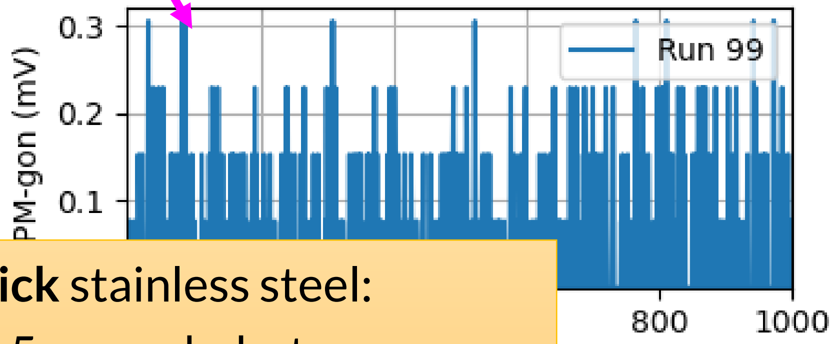
9.09 keV, 0.36 mJ (on target), 120 Hz, 0.043 W

	Stainless Steel						Al
Thickness (mm)	1.27						14
FWHM (μm)	2.25	5	10	20	30	40	2.25
Dose (eV/atom)	650	160	40	10	4.5	2.5	50
Pulses to Drill Through	57±2.2	58±1.2	60±0.4	76±1.3	117±0.4	No for 1000	83±1

* Repeat 10 times for each beam size on steel (raster the sample), but only twice on aluminum







Finding for **12.5 mm thick** stainless steel:

- 5 μm beam drilled in 5 seconds, but
- 2.25 and 10 μm beam didn't for a few minutes

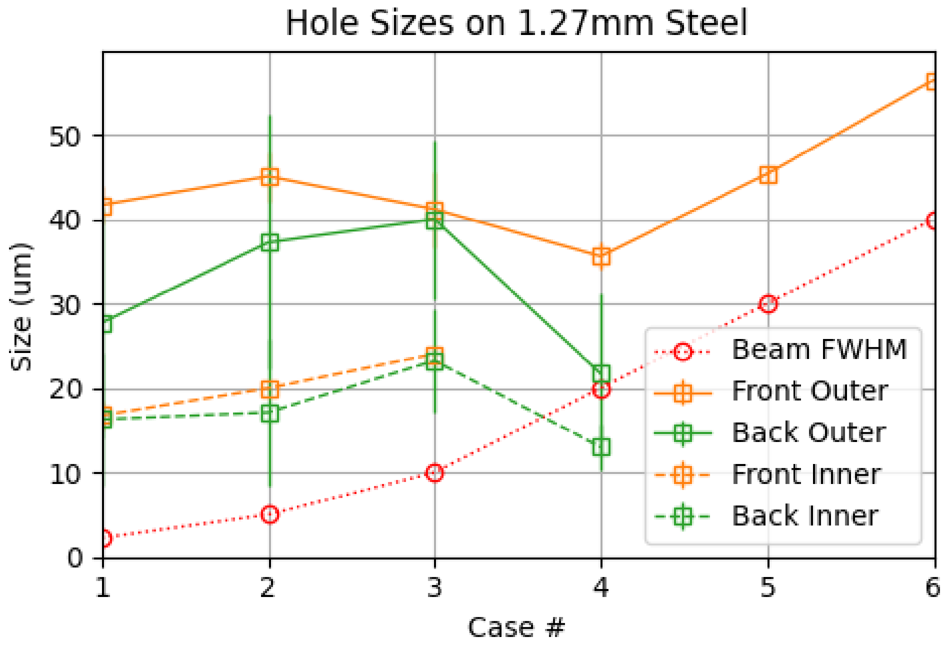
Material Damage Test: Hole Size

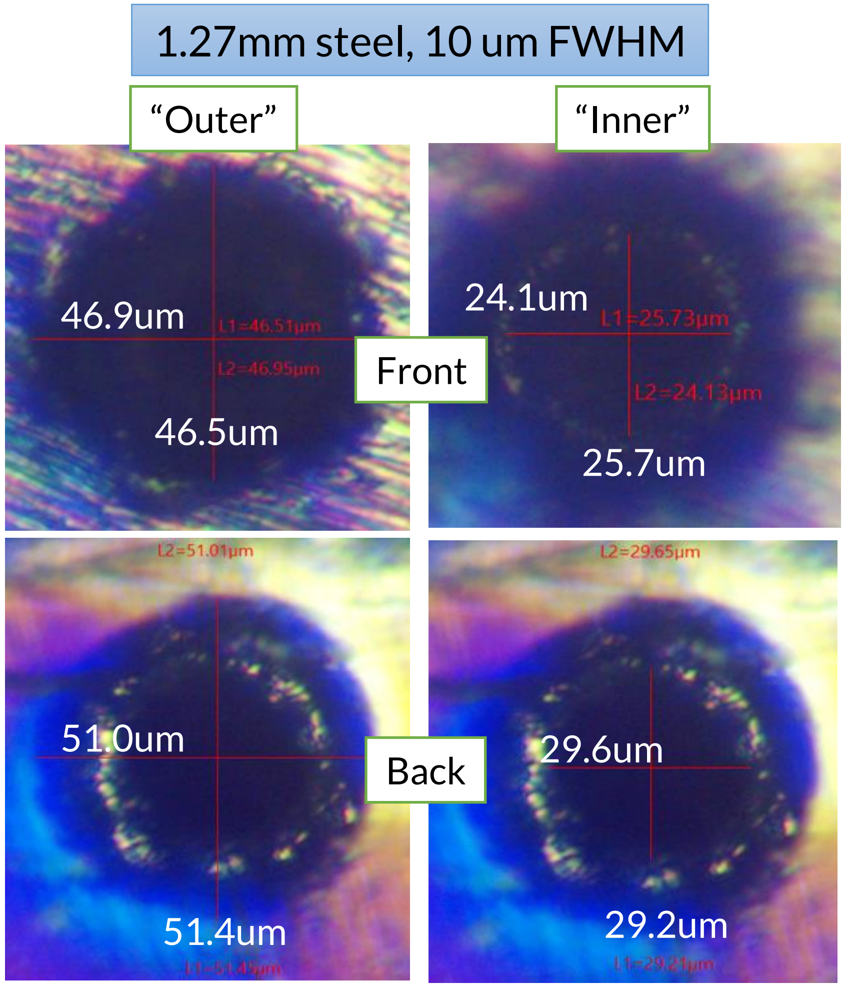
In the estimates of the response time of vacuum interlock and BTMs

- ***Assume hole diameter = beam FWHM***

The assumption is conservative in most cases but not conclusive

- Hard to determine which part are the holes via microscope
- No "Inners" and no Back holes for 30 and 40 um beams





Summary

Containment of FEL beams is the main challenge of FEL instrument

Radiation safety design must consider the combination of high pulse energy *(mJ/pulse)* and high average power *(W)* in the full photon wavelength spectrum:

- New design of photon stoppers and collimators
- Burn-through monitors and vacuum sensors are safety interlocks to shut off beams
- Air will still be efficient to attenuate low energy x-rays
- Need to follow the bootstrap process to gradually ramp up beam power

Used FEL beams from the LCLS normal conducting Linac for various tests:

- New photodiode BTM is sensitive and can trip fast
- Material damage caused by FEL beams
- Need further experiments for FEL from superconducting Linac

Thank You!