Commissioning of Radiation Safety Systems for the LCLS-II Accelerator Facility

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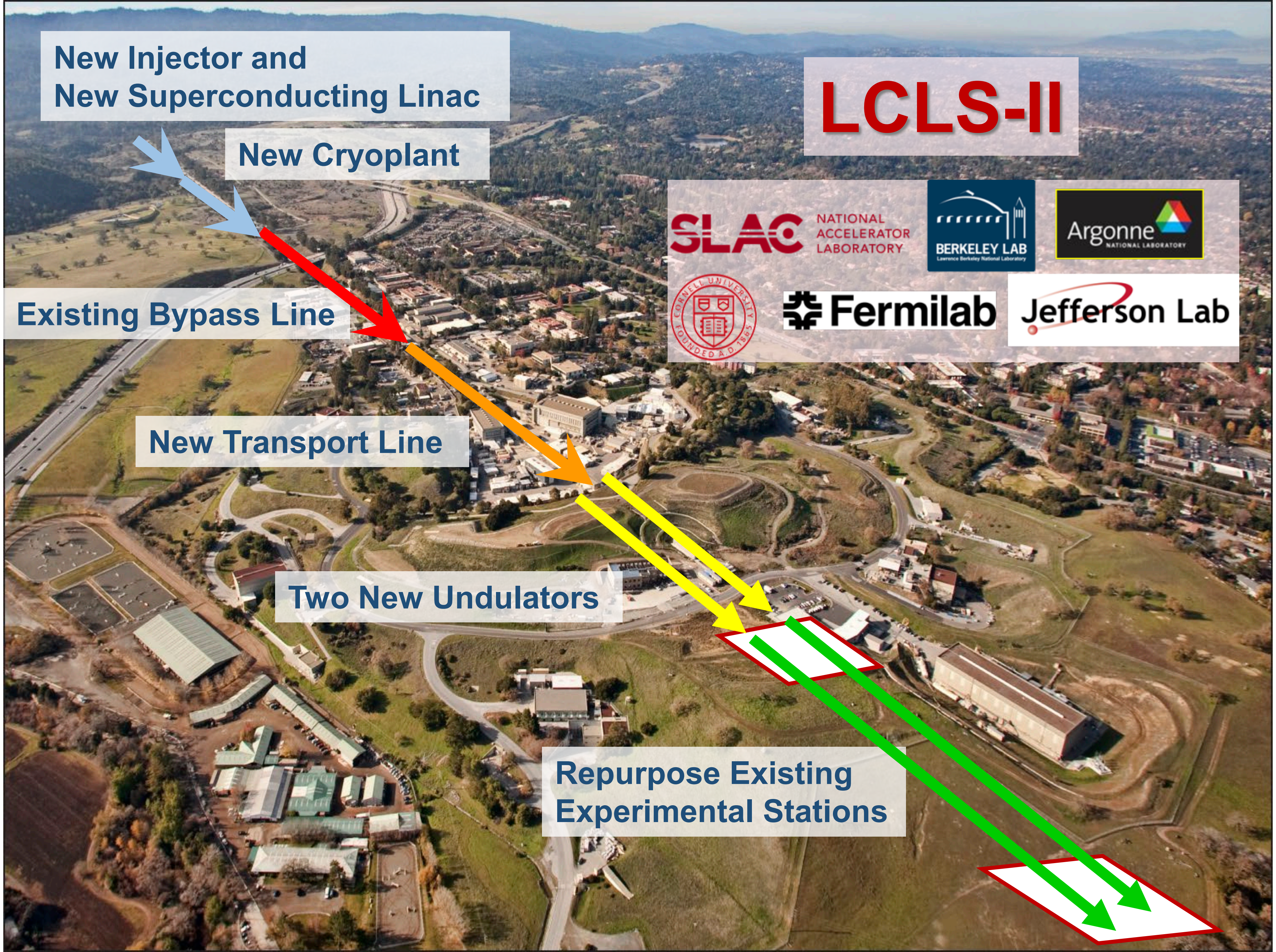
Outline

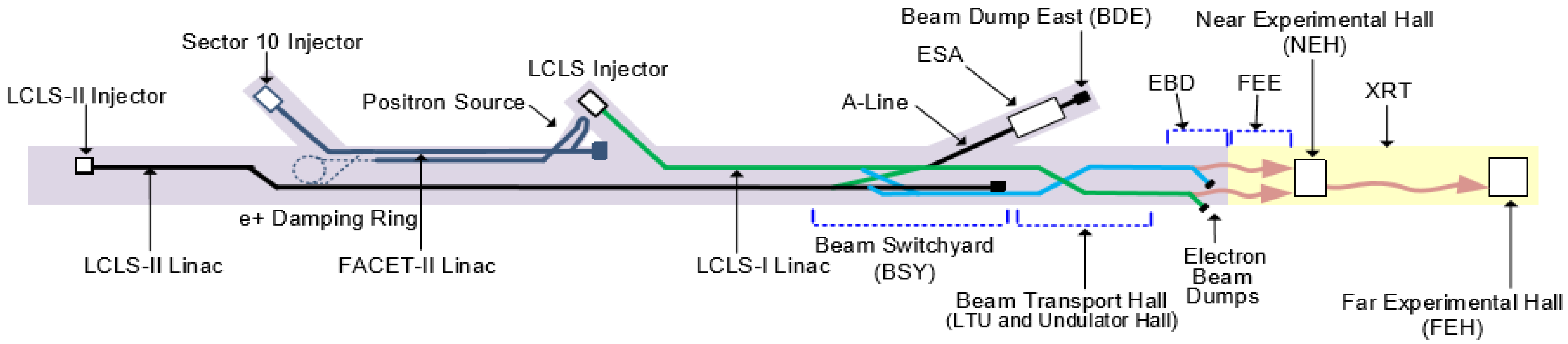
- LCLS-II Project at SLAC
- Radiation Safety Systems
  - Beam Containment System
- Commissioning plan
- Status of LCLS-II commissioning
- Summary

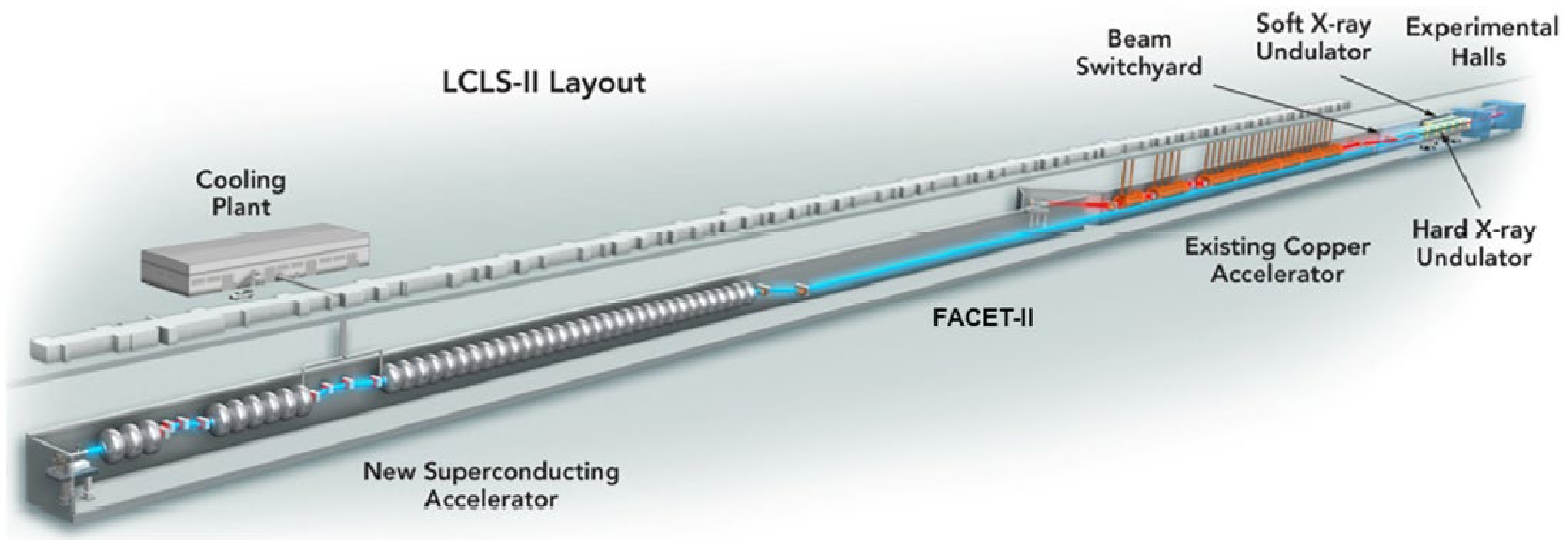

New Injector and
New Superconducting Linac
New Cryoplant
LCLS-II
SLAC NATIONAL ACCELERATOR LABORATORY
BERKELEY LAB
Argonne NATIONAL LABORATORY
Fermilab
Jefferson Lab
Existing Bypass Line
New Transport Line
Two New Undulators
Repurpose Existing
Experimental Stations

LCLS-II (SCRF) Baseline Parameters

Parameter	nominal	range	units
Electron Energy	4.0	2.0 - 4.14	GeV
Bunch Charge	100	10 - 300	pC
Bunch Repetition Rate in Linac	0.62	0 - 0.93	MHz
Avg. e^{-} beam power at linac end	0.25	0 - 1.2	MW
RF frequency	1.3	-	GHz
Avg. CW RF gradient (powered cavities)	16	-	MV/m
Photon energy range of SXR (**SCRF**)	-	0.2 - 1.3	keV
Photon energy range of HXR (**SCRF**)	-	1 - 5	keV
Photon energy range of HXR (Cu-RF)	-	1 - 25	keV

LCLS-II (SC and Cu Linacs)





Cryo Modules and Solid-State Amplifiers

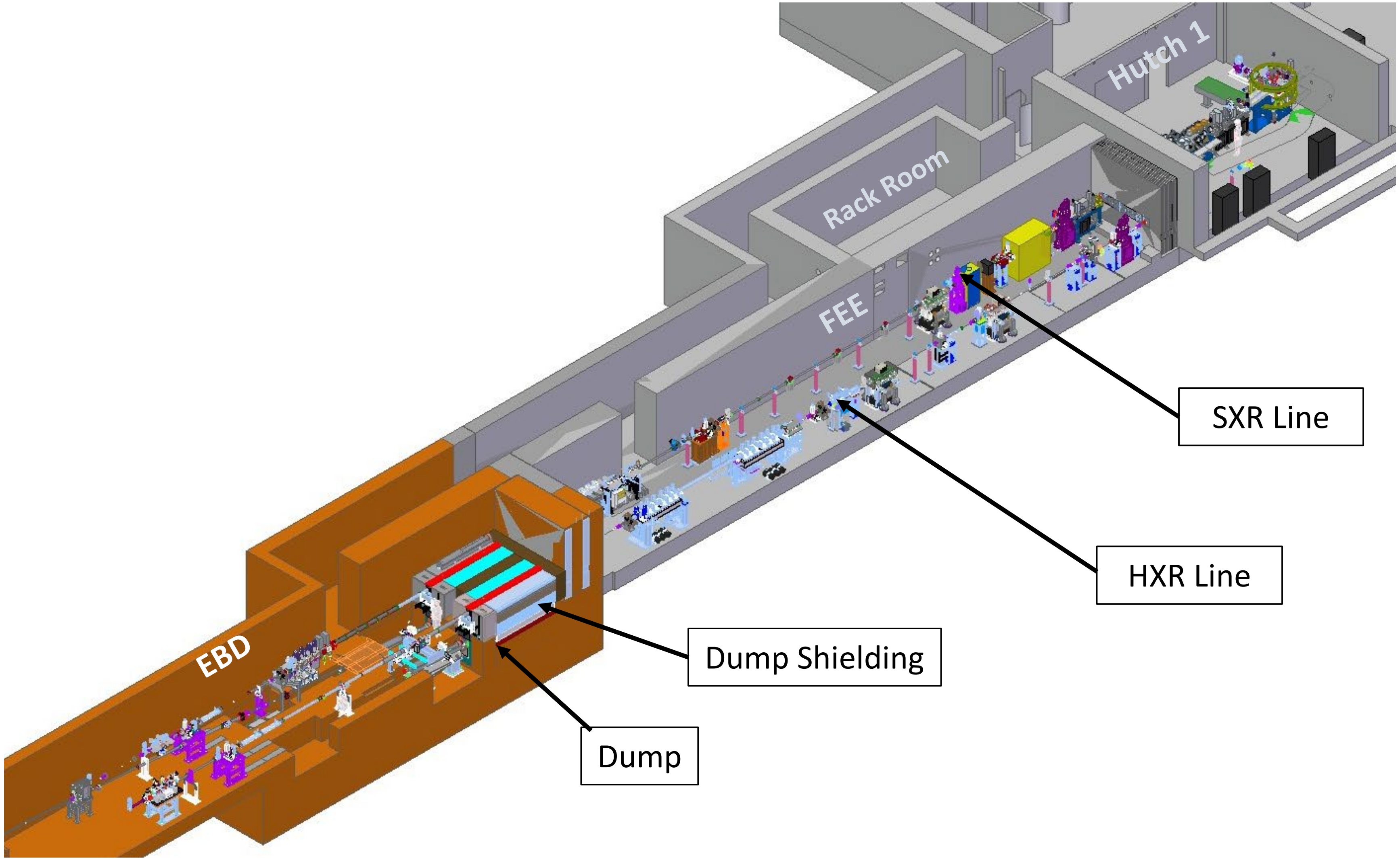
Penetration Shielding Cap

Solid State Amplifiers

Soft and Hard X-Ray Undulators

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	

Beam Dump Hall and Front End Enclosure



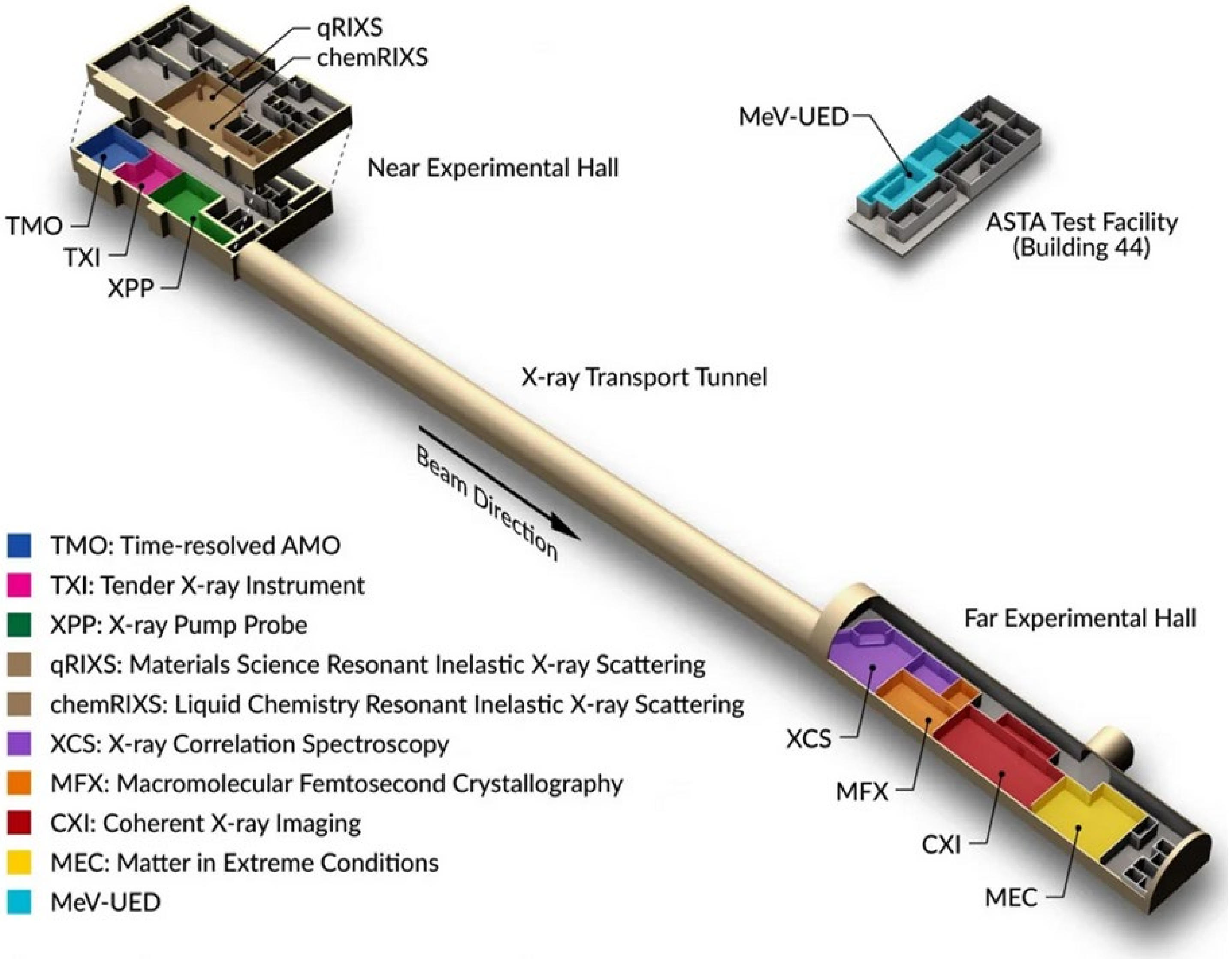
Electron Beam Dump Hall

LCLS Instruments

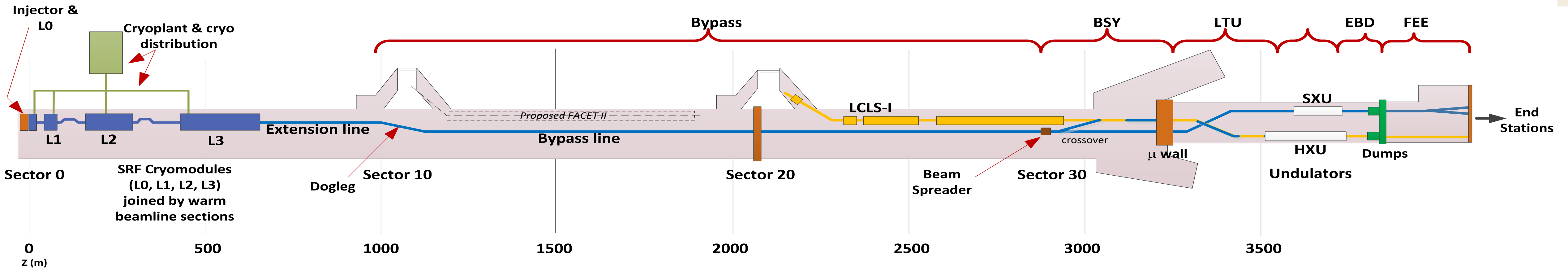
SC FEL to TMO and RIXS in July 2023

SC FEL to TXI in 2024

Hard X-Ray instruments will be upgraded to take SC FEL beams by the LCLS-II HE project, targeting 2027

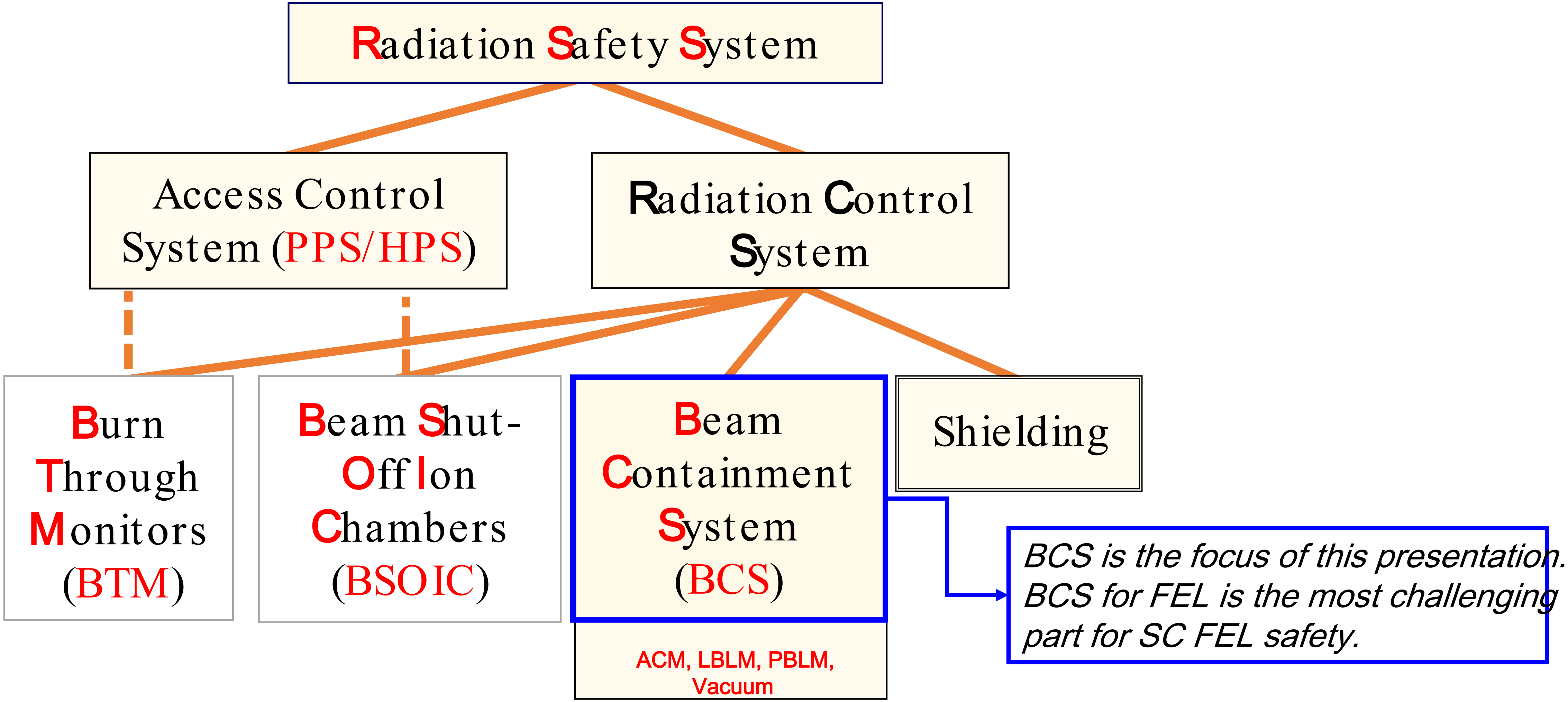


LCLS-II Radiation Safety Challenges

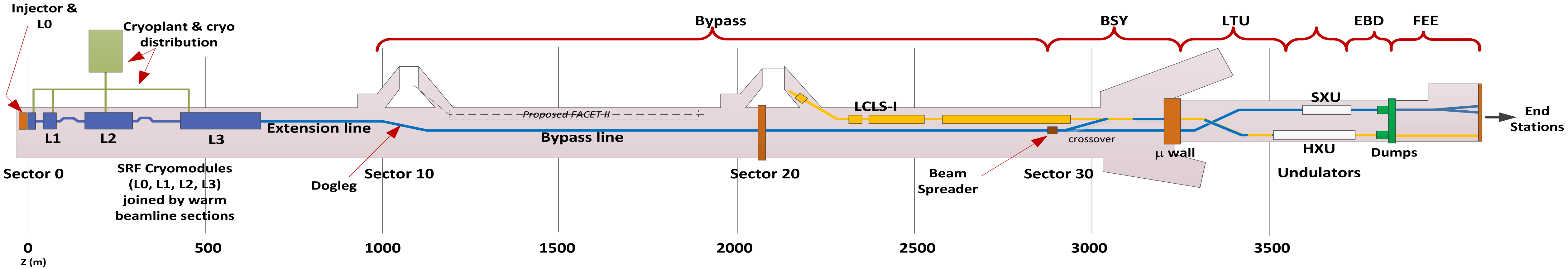


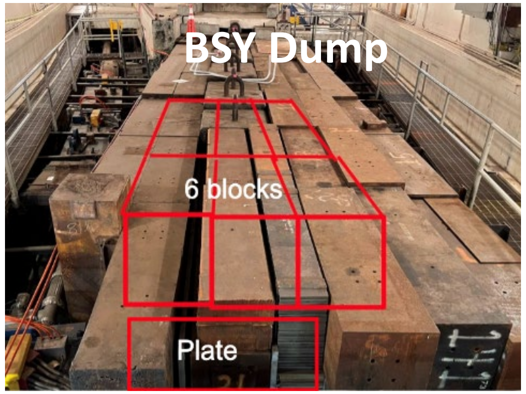
- High average electron beam power, MHz rep. rate machine
  - Must rely on safety interlocks to limit beam power
  - Fast shut-off time required to terminate errant beam conditions
- Pre-existing low-power facility
  - Over 450 penetrations from the Linac to the Klystron Gallery
  - Beam Transport Hall, Dump Hall, FEE designed for LCLS-I
- Containment of FEL

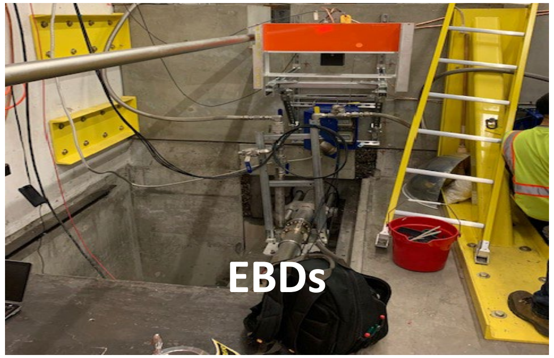
SLAC Radiation Safety System (RSS)



Shielding installation completed







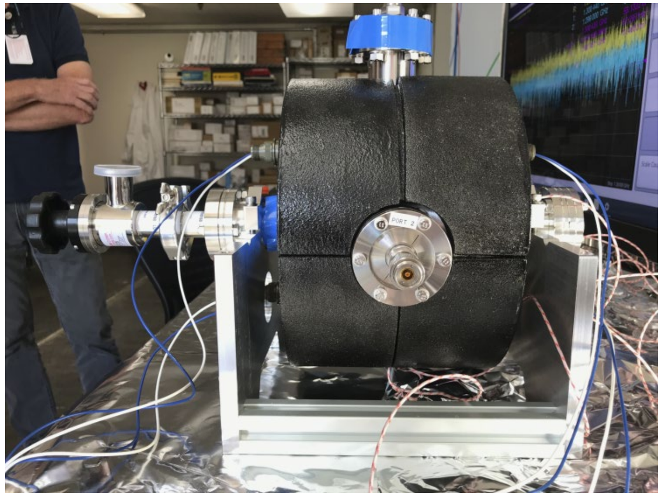
Beam Containment System (BCS)

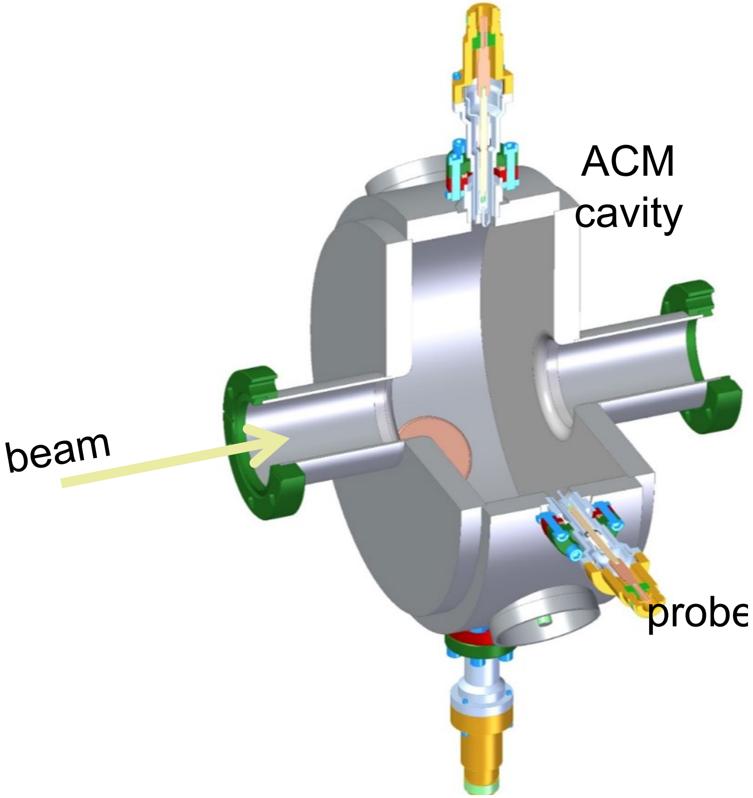
1) Limits beam power and keeps it within designated safe channels
   - Average Current Monitors, Protection Collimators with Burn Through Monitors
2) Limits beam losses in case of mis-steered beams, (limiting personnel dose outside of housing)
   - Long Beam Loss Monitors
3) Protects the integrity of devices that have a safety function , e. g. stoppers for Personnel Protection System, beam dumps, collimators
   - Point Beam Loss Monitors
4) Acts to turn the electron beam off if an unsafe condition arises
   - Fast shut off: Shutoff in max 120 μsec
   - Slow shut off: 1 s from receiving trip signal to shutoff

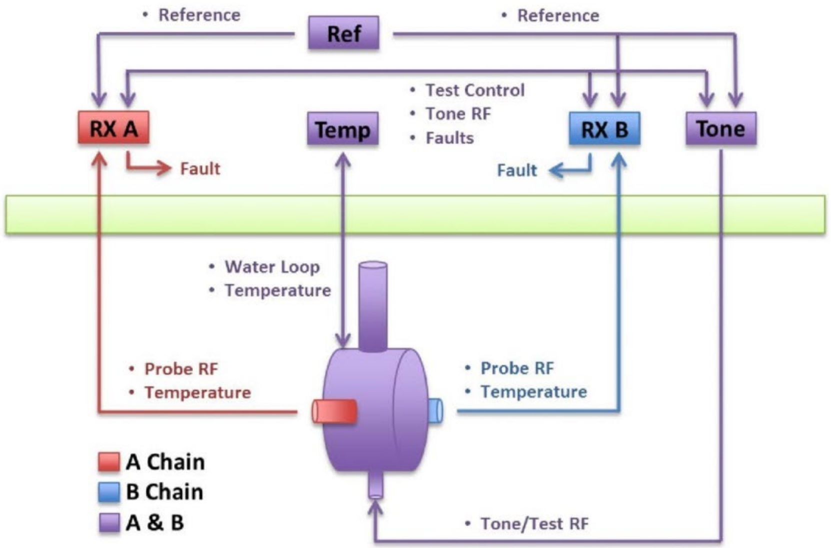
LCLS-II Electron Beam Containment System: ACMs

Average Current Monitors

- Two RF cavities, each read out in two chains
- Pilot tone for self-check
- FPGA for 1 ms moving integration window
- PLC for pilot tone faults, faster trips through DSC







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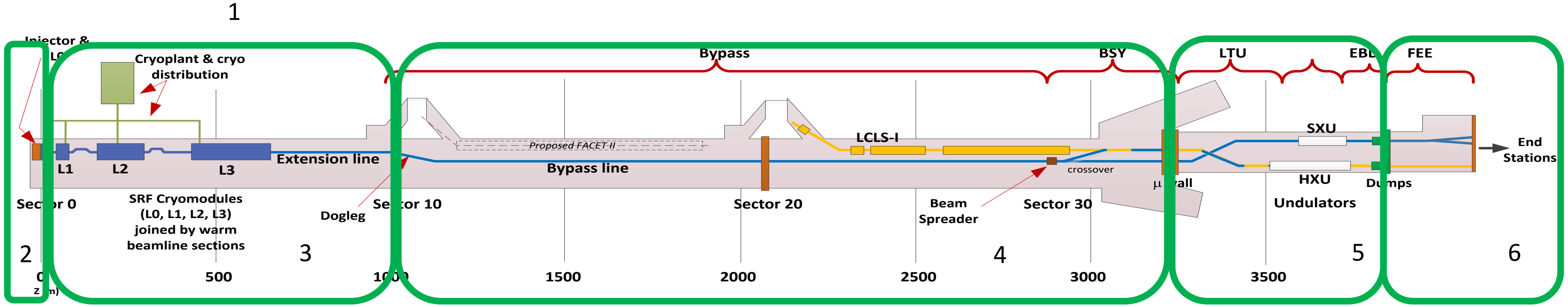
LCLS-II BCS: LBLM, PBLM

- Quartz fibers (radiation hard) , up to 200 m long.
- Cherenkov light read with PMT.
  (frequency range to limit effect from radiation damage)
- LED for keep-alive check.
- Electronics outside accelerator housing.
- Trip from beam losses 5 W to 1 kW.

- PBLMs are diamond detectors with a voltage applied across them
- Nanosecond time resolution.
- Single-crystal diamond,
- 10^6 dynamic range,
- Self-checking,
- Radiation hardned,
- Simple deployment (no gas or cooling)

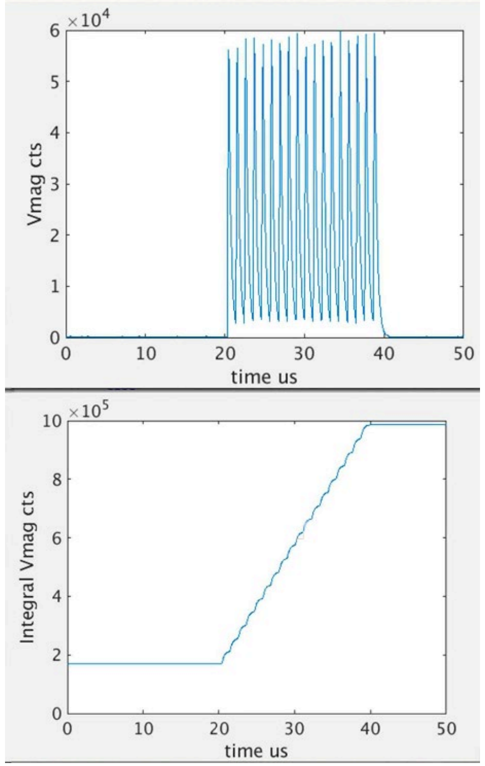
Commissioning Stages



1. Warm CM RF Processing
2. Injector commissioning
3. Cold CM RF processing
4. Electrons to BSY
5. Electrons to EBD
6. FEL SXR and HXR to FEE and SXR to H1.1, H1.2 and H2.2

- Authorization
- Hazard Mitigation through Commissioning Plan Document
- Establishing controls, performing radiation surveys while BCS Commissioning taking place
  (same structure as for LCLS-1 Commissioning)
  - All shielding of the relevant area must be verified to be in place and PPS certified
  - All BCS in the area must be tested/certified pre-beam

LCLS-II Electron BCS: ACM Commissioning



Integration:
pulses summed into signal

Linearity:
Small offset from pilot tone

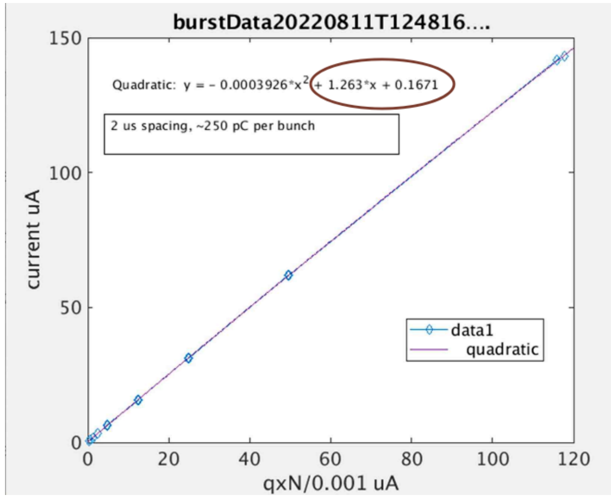
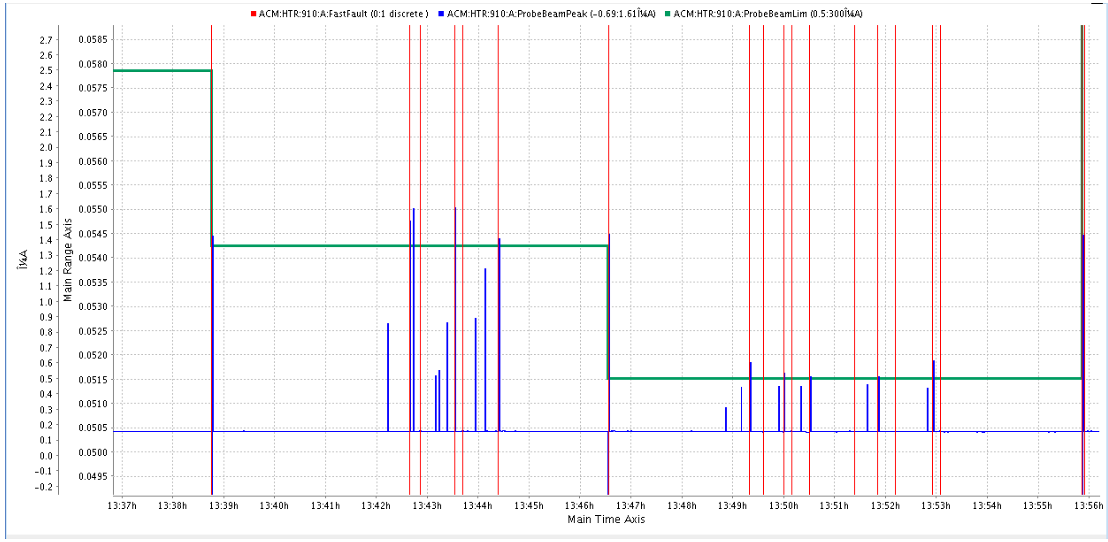


Table 2: Required parameters

	Parameter	Units	Value	IAT Results
✓	Integration time	μs	$\geq 1000, \ < 4000$	1000
✓	Accuracy	μA	$\leq 0.5 + 10\%$ of current	0.2 + 4%
✓	Precision	μA	≤ 0.1	~0.01
✓	Operational current range	μA	0.5 – 300	0.5 – 145 ← 250 uA
✓	Range of trip settings	μA	0.5 – 300	0.5 – 120
✓	Maximum burst current	μA	1000	1000
✓	Beam position tolerance	mm	±2	+/-2

Not affected by
beam position,
beam losses
upstream



Trip Tests

SLAC

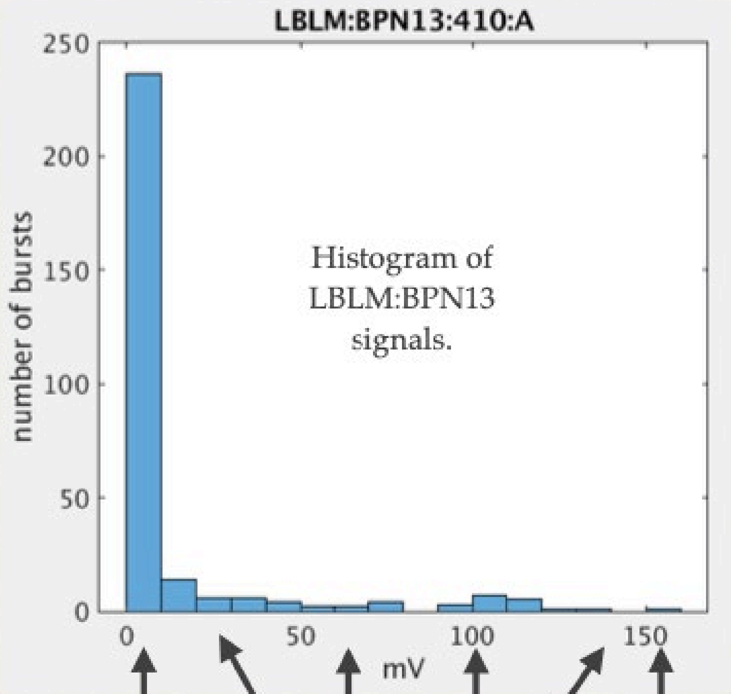
LCLS-II Electron BCS: LBLM Commissioning

Example for one LBLM

- ~300 bursts lost along whole accelerator
- Losses from intentional mis-steering at various locations and in various directions

most losses far from LBLM
→ recording noise

Number of bursts detected in each mV bin



Background: (noise and shots that landed elsewhere)

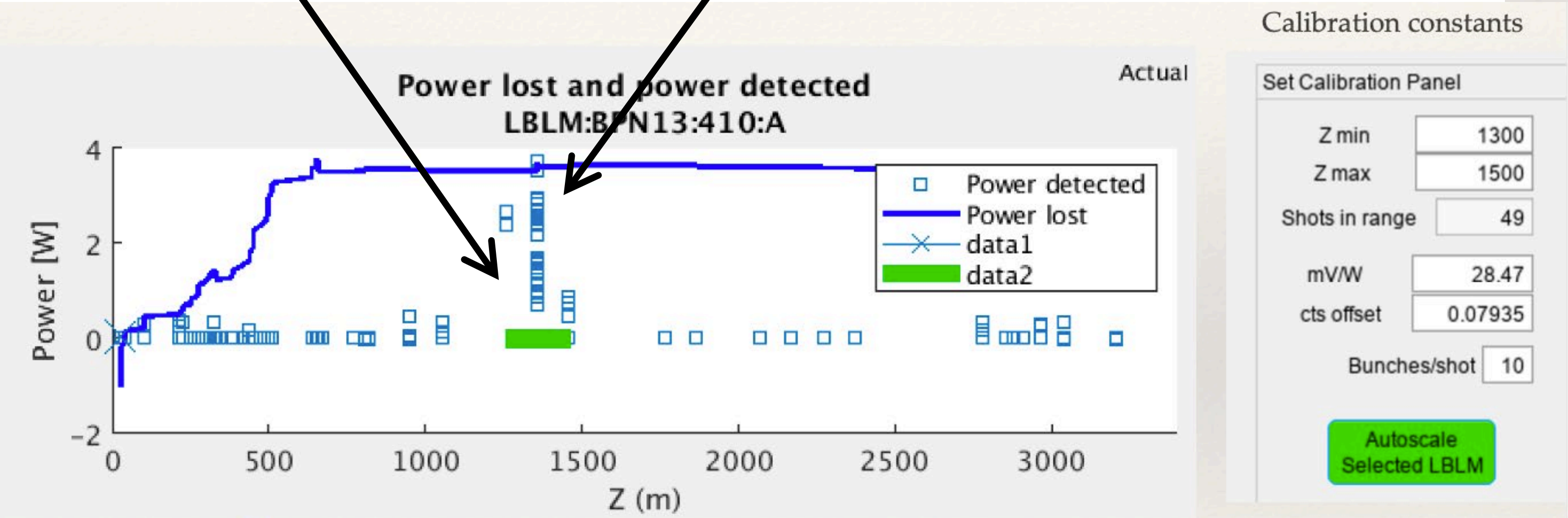
Shots lost near lblm

Strongest signal

higher signal when lost near LBLM

Z location of fiber

range of measurements at same location

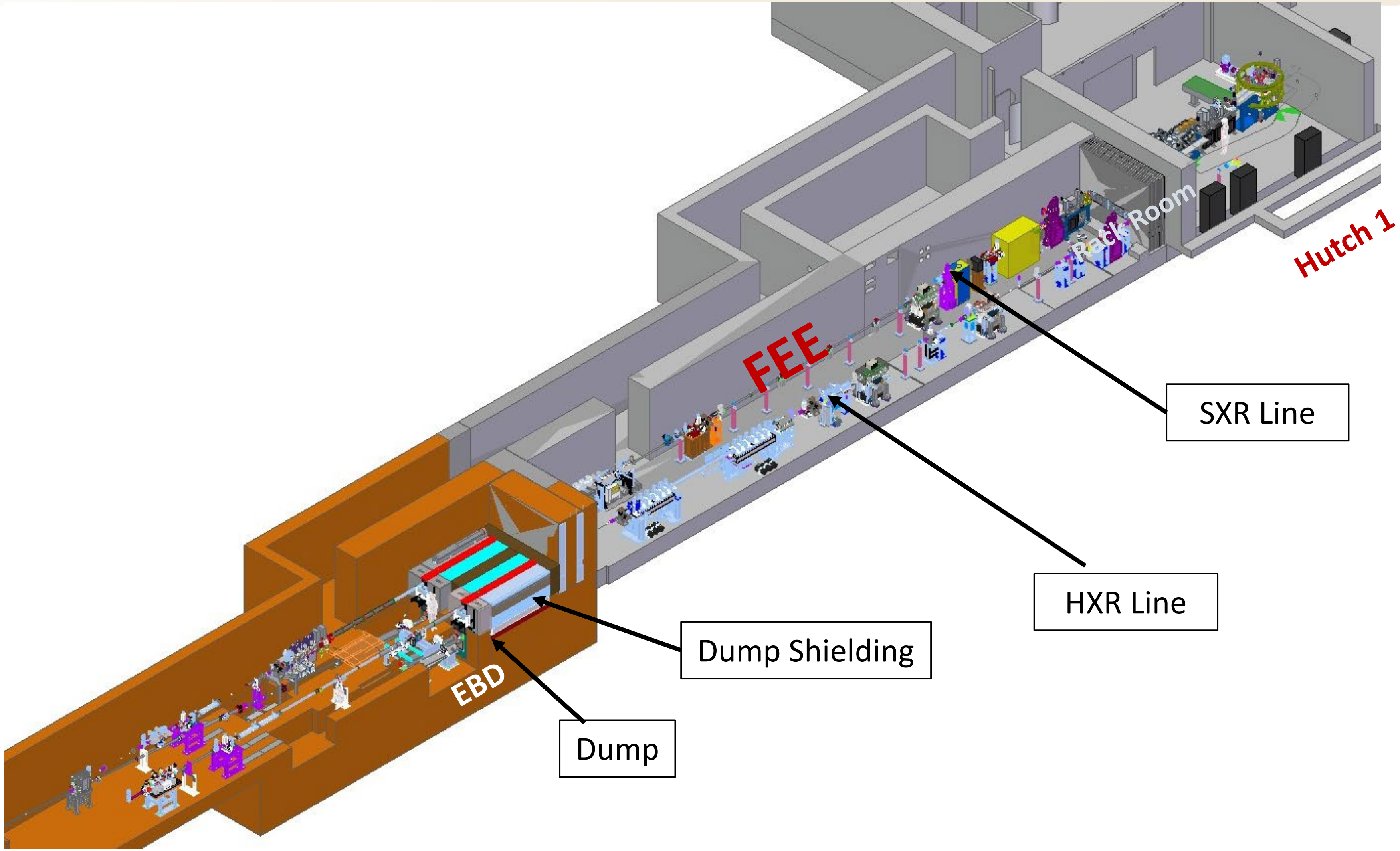


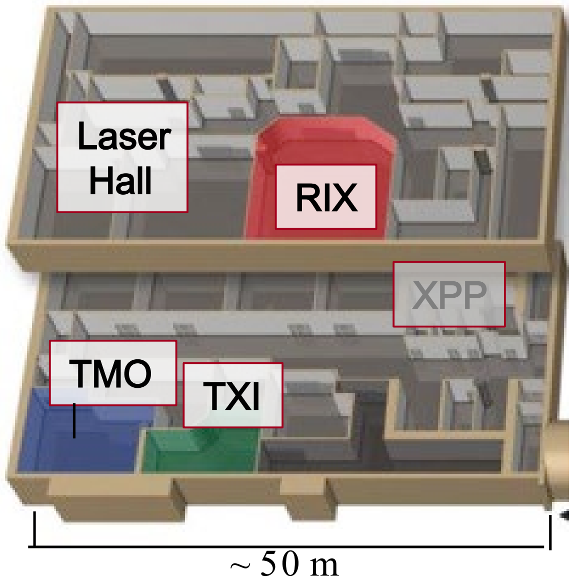
Envelope of lost power as determined by bpms

Power reported by LBLM for each burst assuming a given calibration

Courtesy of Alan Fischer-SLAC

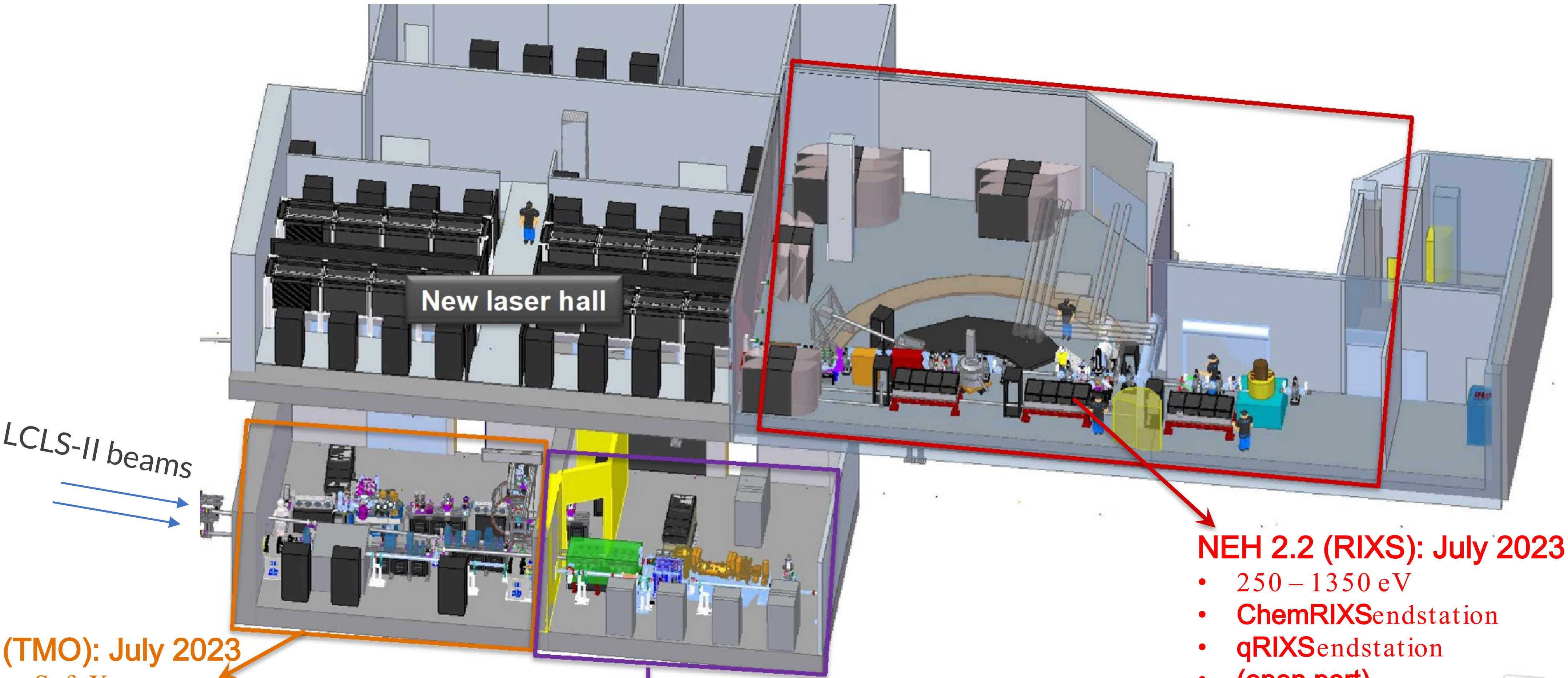
Beam Dump Hall, Front End Enclosure, Near Exp Hall





Near Experiment Hall (NEH)

Instruments for SC FEL

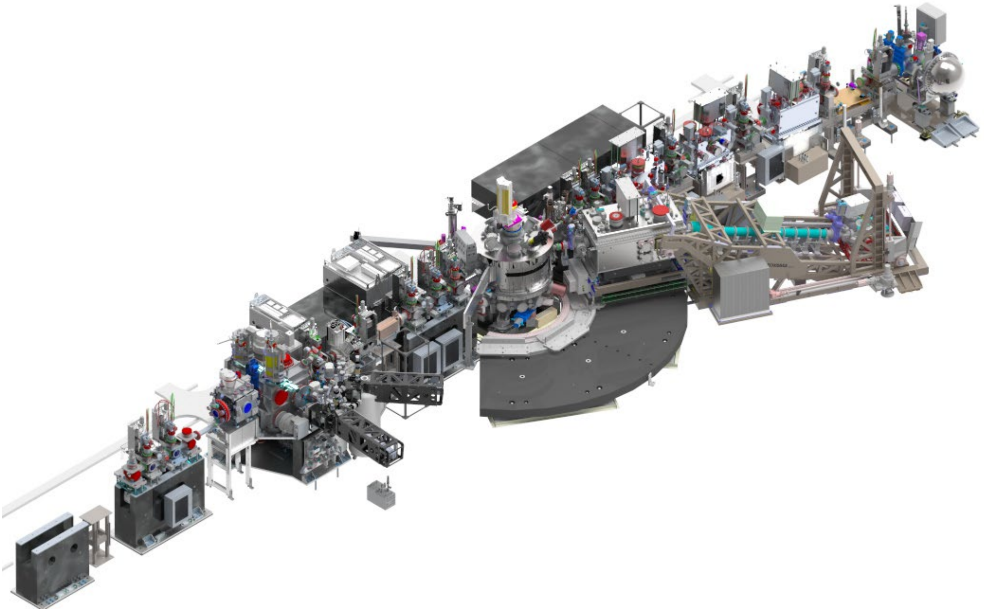


NEH 1.1 (TMO): July 2023
- High Flux Soft X-ray
- 250 – 2000 eV
- LAMP / IP1 endstations
- DREAM endstation

NEH 1.2 (TXI): 2024
- Tender X-ray Instrument
- 2 XFEL beams
- TXI endstation

NEH 2.2 (RIXS): July 2023
- 250 – 1350 eV
- ChemRIXS endstation
- qRIXS endstation
- (open port)

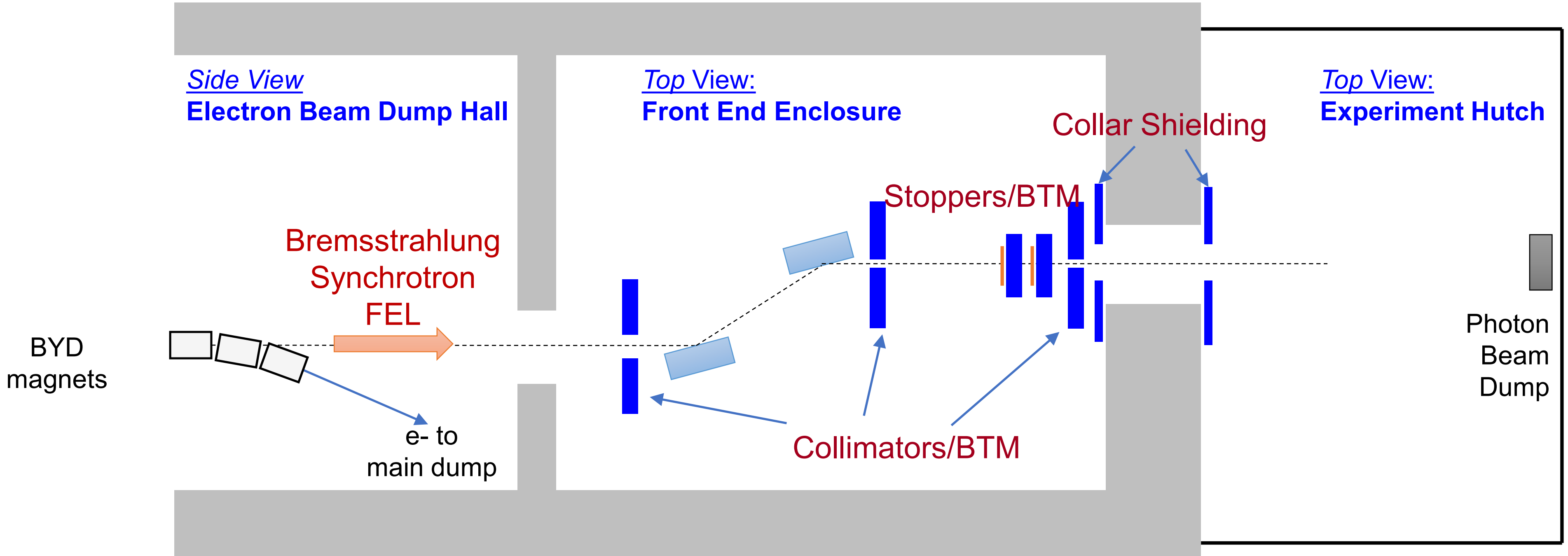
Hutch 2.2: RIX Instrument



Radiation Sources For Experimental Hutches

- Bremsstrahlung: high energy, low power (100s MeV, mW)
  - → dominant source for <u>FEE</u> shielding
- Synchrotron radiation: low energy, high power (<MeV, W)
  - → dominant source for <u>hutch</u> shielding
- FEL: desired for experiment (100s ev-10's keV, few-10's mJ, 100's W)
  - → dominant source to damage safety devices

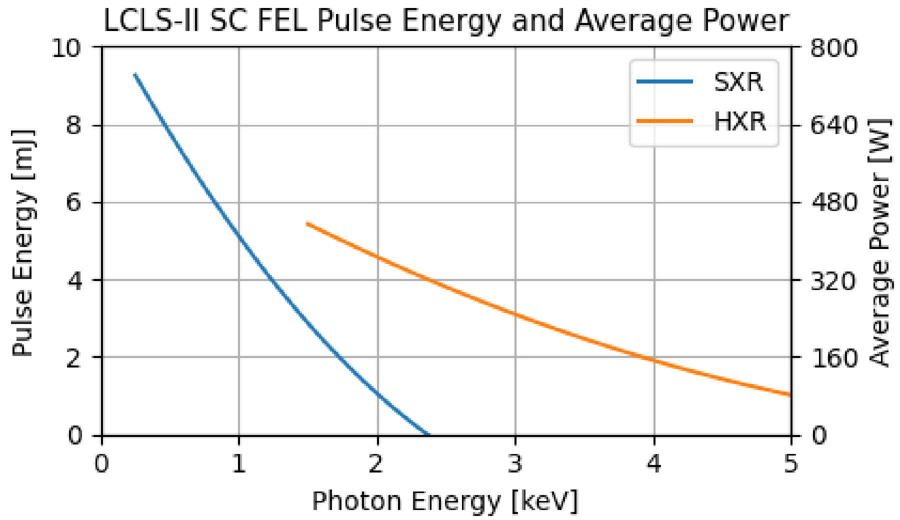
LCLS-II reuses the existing FEE and hutches



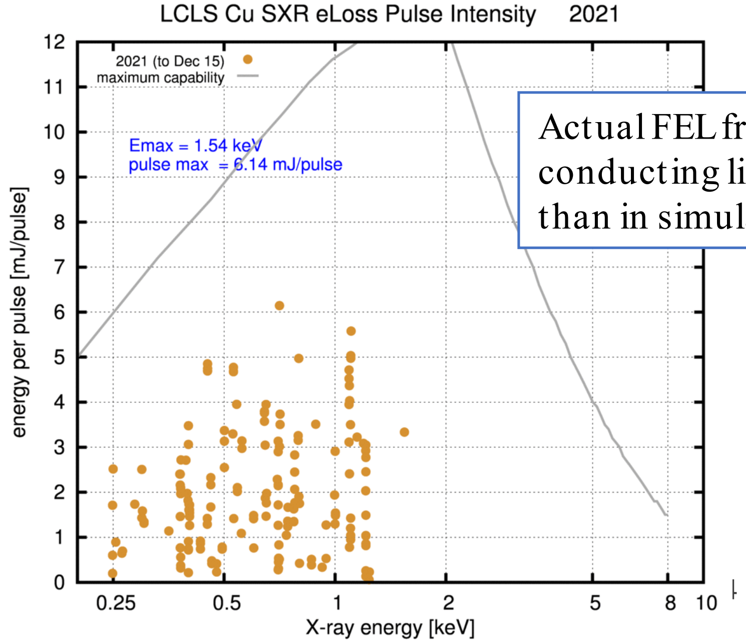
FEL Parameters

Estimate FEL parameters from Start-to-End (S2E) simulations

	Superconducting	Normal Conducting
Electron Beam	2-5 GeV, up to MHz	2-20 GeV, 120 Hz
SXR FEL Beam	0.2-2 keV Up to 9.2 mJ 740 W	0.2-10 keV Up to 13 mJ
HXR FEL Beam	1-5 keV Up to 5.4 mJ 430 W	1-25 keV Up to 10 mJ



- High pulse energy and high average power of FEL can damage nearly all materials.
- Main radiation safety challenge for FEL instrument is how to contain FEL beams.
  - LCLS-II uses CVD diamond on stoppers for SC beams
  - CVD diamond has excellent thermal conductivity (up to ~300 W)
  - Slow damage process due to slow graphite sublimation (~40 days of beam at carbon k-edge, 285 eV)

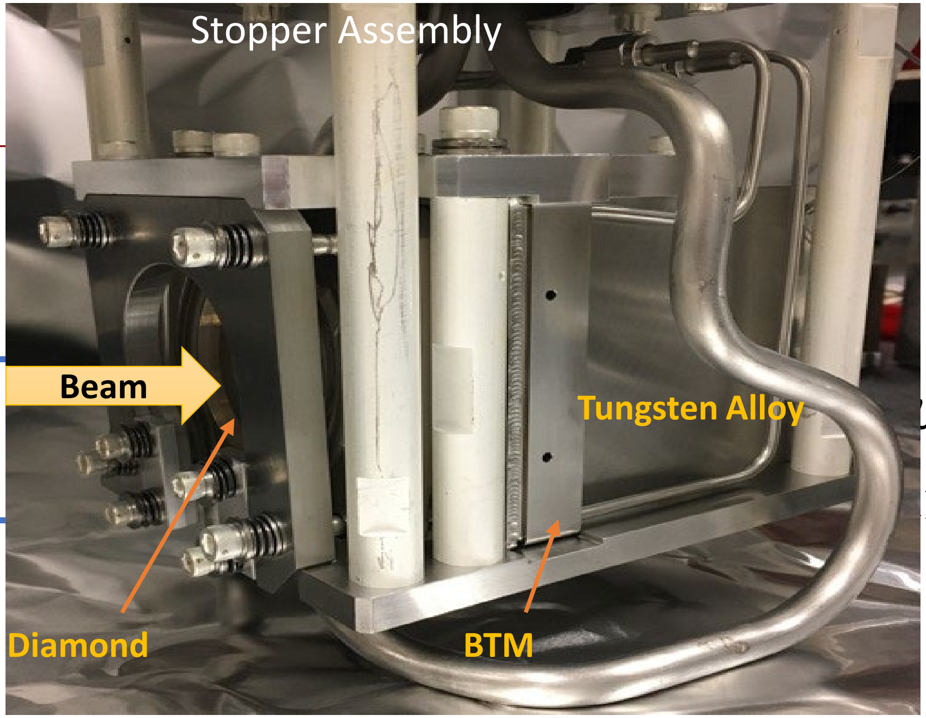


Actual FEL from normal conducting linac is less than in simulations.

Strategy for FEL Beam Containment

General principles of FEL beam containment

- Use CVD diamond on stoppers for SC beams
- Limit FEL beams in designed channels
- Fast Shut-off in abnormal conditions
- Bootstrap approach to power ramp up
  - Use ACM to limit electron beam current



ys)

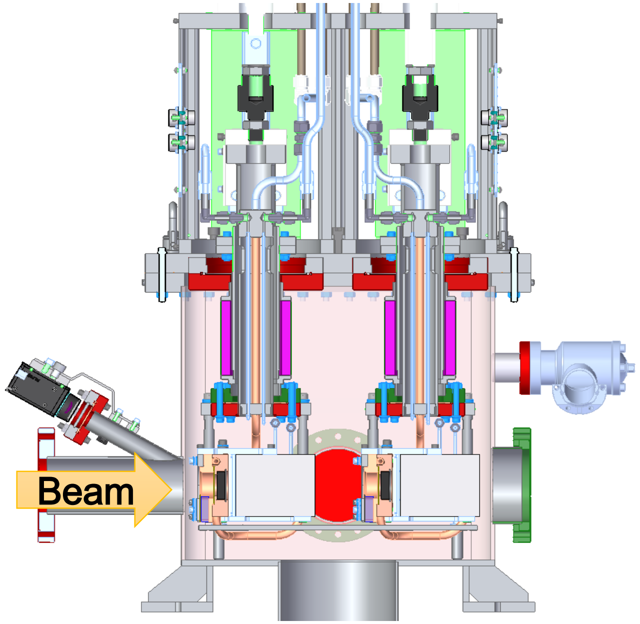
l beam

If FEL beams damage a safety device or drill through any vacuum boundary

- Burn Through Monitors
- Vacuum Interlock

Safety Interlocks

- Air Attenuation



Engineering drawing of FEL stoppers

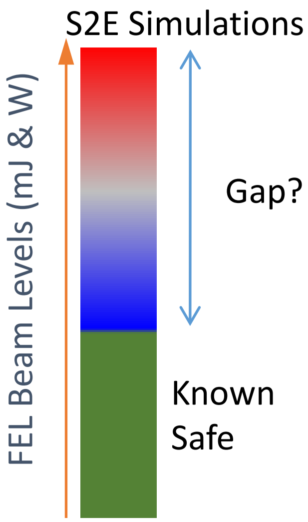
Bootstrap Process for SC Beams

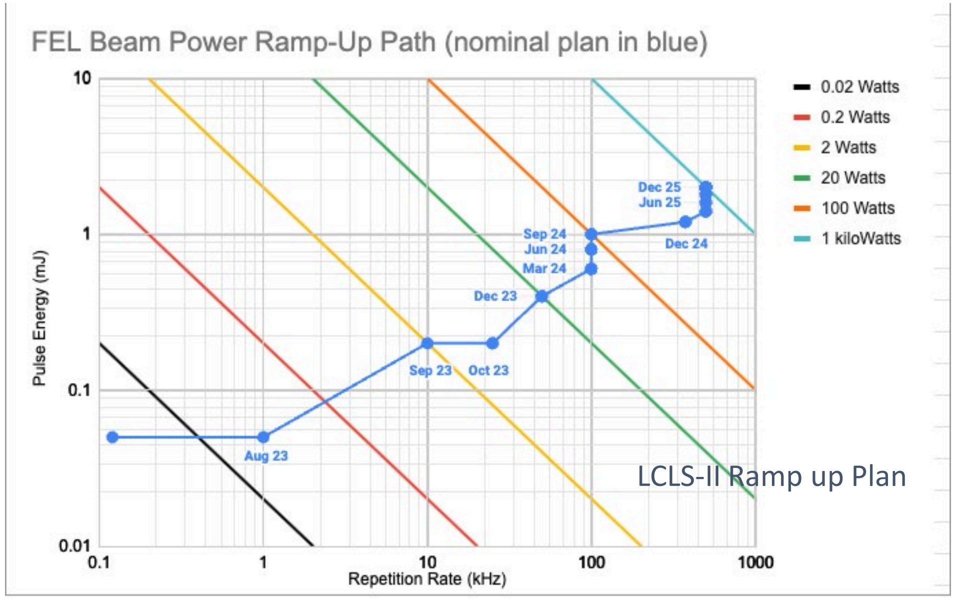
Purposes→ Allow for safe increase of FEL beam parameters

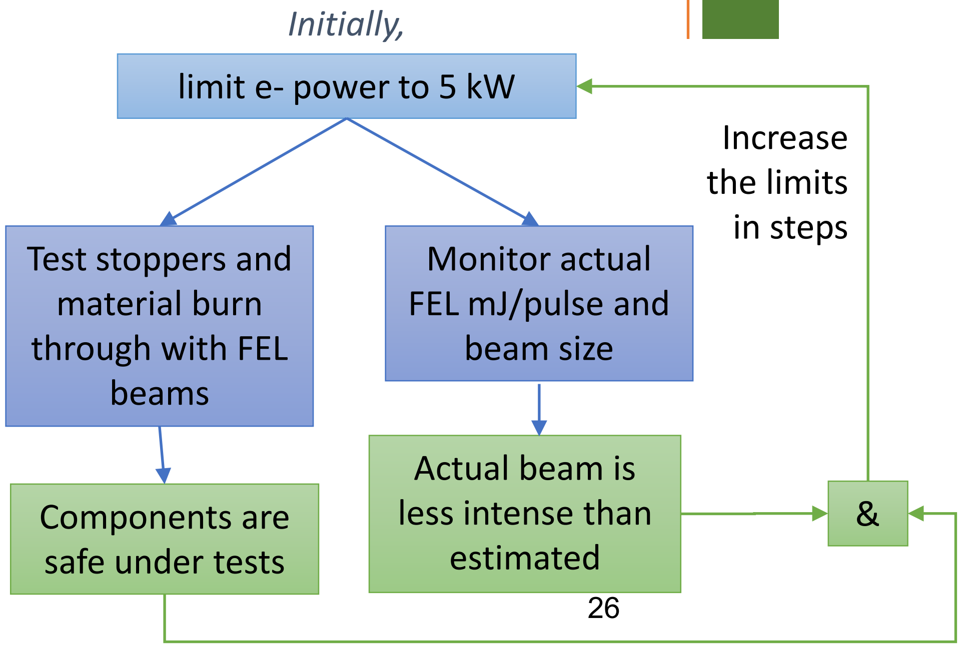
- Verify the beam rating of stoppers / collimators / dumps
- Verify there are no other damage mechanisms
- Monitor actual FEL beam parameters: e.g. mJ with gas attenuator

Controls for bootstrap

- Electron beam power to limit FEL beam power (W)
  - Interlocked by ACMs (BCS)







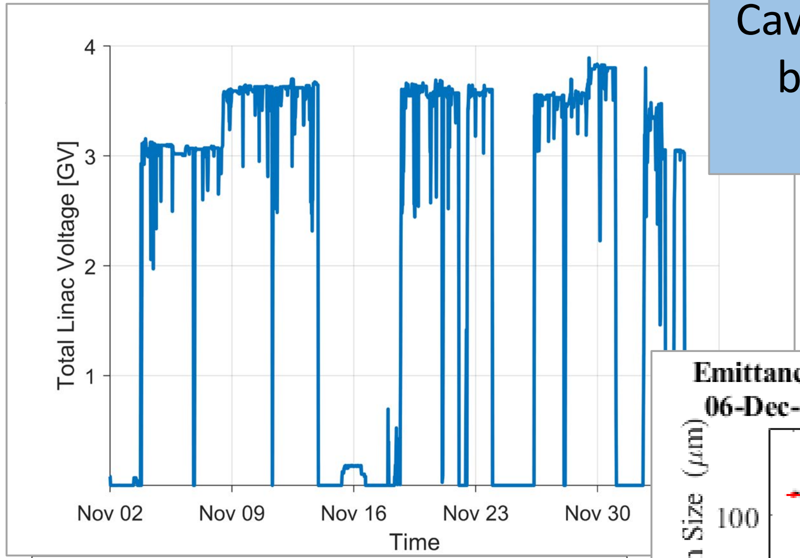
Summary

- Installation for LCLS-II project at SLAC has been completed successfully.
- The commissioning program is well underway, and the SC Linac has achieved many of its key project objectives.
- Excellent results were achieved for commissioning of Cryoplant, SCRF and Cryomodule systems and Injector performance.
  - Beam energy at 3.5 GeV has been demonstrated, 1 kHz cw Repetition Rate achieved, Beam emittance at 0.5 um.
- Radiation safety systems for the LCLS-II accelerator are being commissioned through a detailed and careful plan that allows for gradual increase of average electron beam power.
  - ACM already commissioned.
- FEL commissioning and power ramp up is planned through the Bootstrap plan
  - FEL beam energy and power are indirectly by monitoring and limiting the electron beam power
  - Monitoring of FEL beam spot size and energy
  - Monitoring of BCS absorber
  - Dedicated tests of stopper absorbers, material drilling and air attenuation

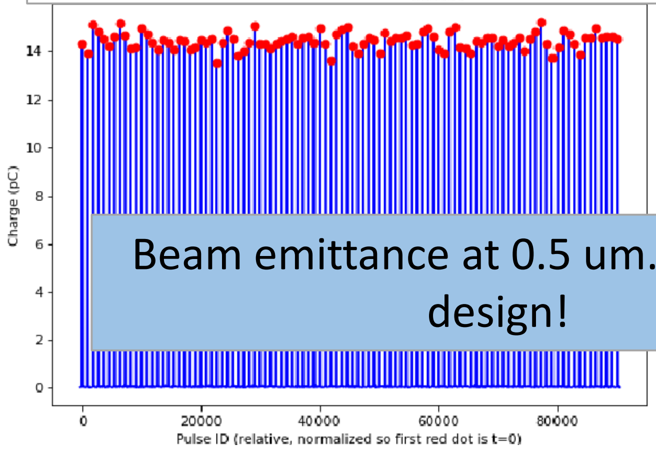
Recent Accomplishments

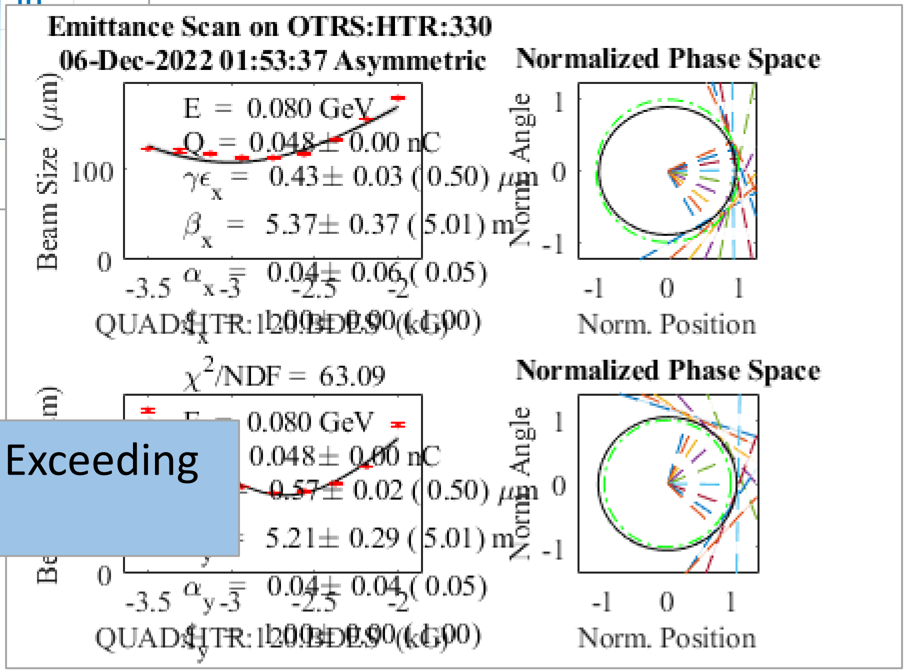
1 kHz cw Repetition Rate achieved on 12/06/22

On track to achieve 93 kHz



Cavities performance supports 3.5 GeV beam energy, beam at 3.5 GeV has been demonstrated





Beam emittance at 0.5 um. Exceeding design!

First high rep rate cw beam at SLAC and LCLS

SLAC

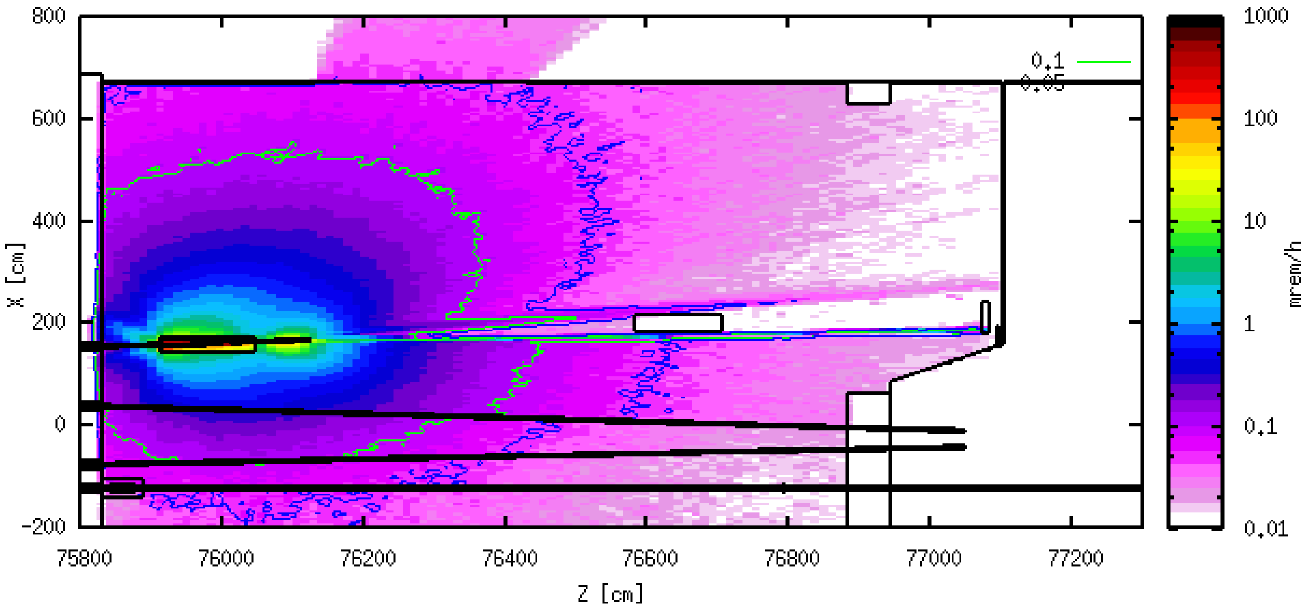
Thank You

Hutch Shielding for Superconducting Linac Beams

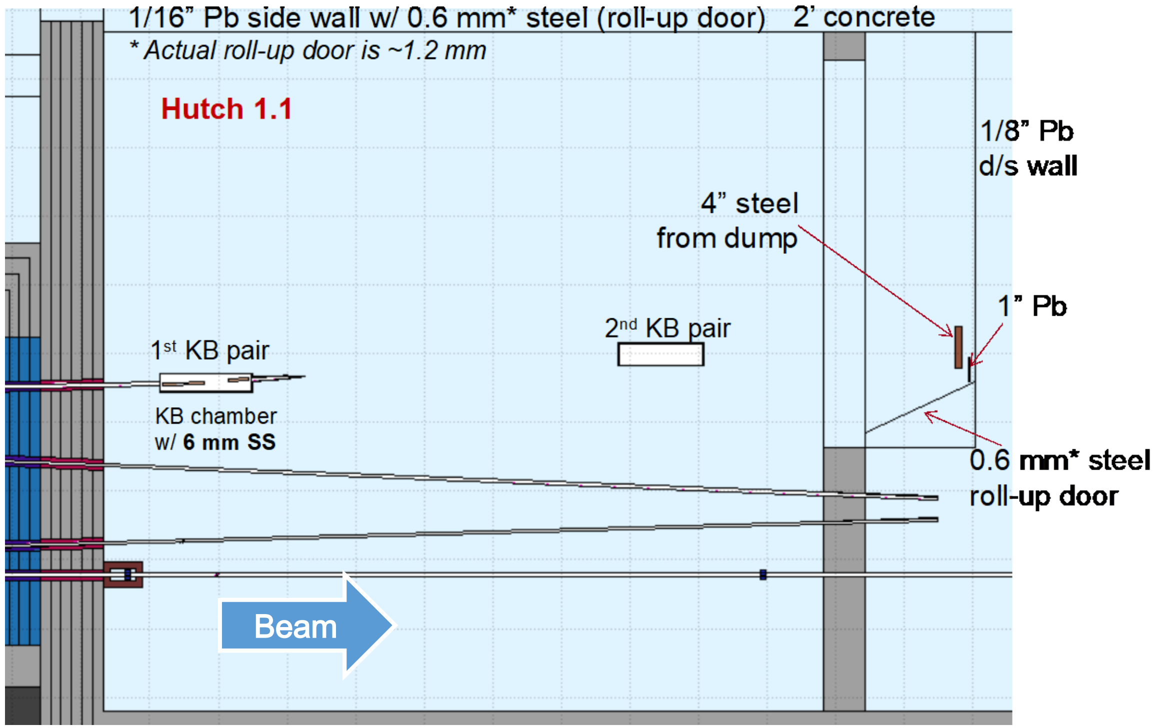
Monte Carlo (FLUKA) simulation for hutch shielding

Hutch shielding is dominated by synchrotron radiation (SR)

Dose for SR from 8 GeV 240 kW e- beam

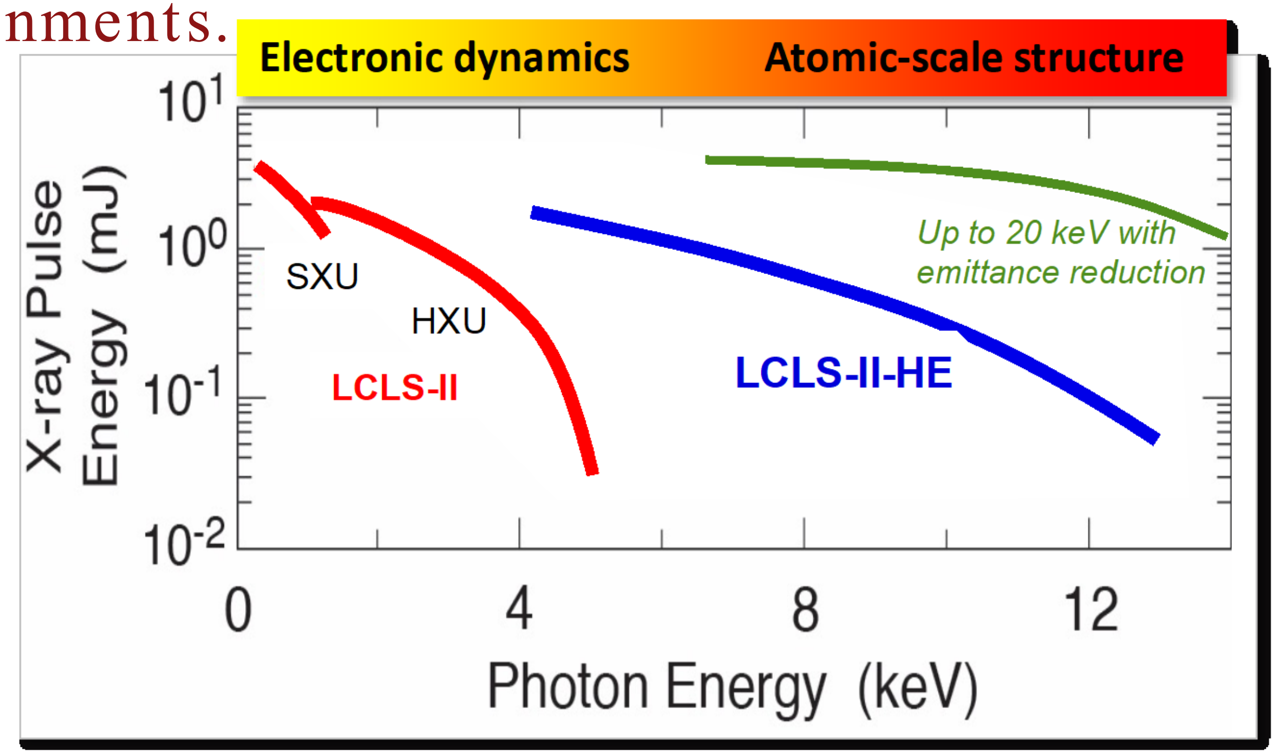


FLUKA Model of Hutch 1.1



LCLS-II-HE Mission

Deliver the ability to observe and understand the structural dynamics of complex matter at the atomic scale with hard x-rays, at ultrafast timescales, and in operational environments.



LCLS-II-HE provides high-rate, FEL radiation at Ångstrom wavelengths

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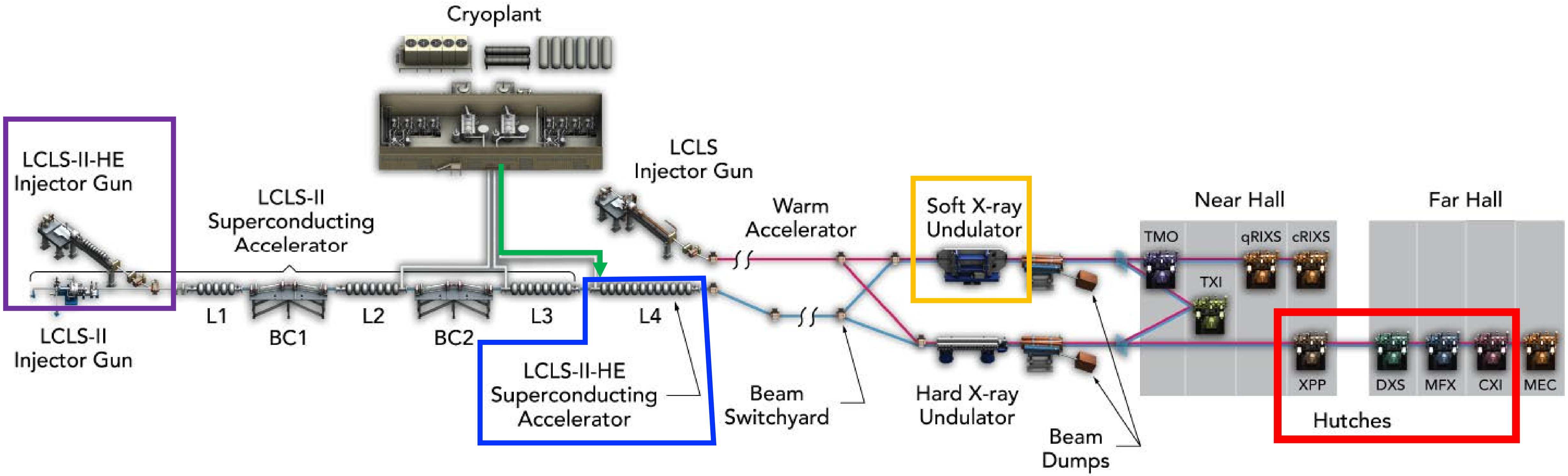
LCLS-II-HE Overview



1. Add 23 additional cryomodules (L4 linac) to double the LCLS-II accelerator energy: 4 GeV to 8 GeV
2. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac
3. New long period soft X-ray undulator
4. Upgrade the LCLS hard X-ray instruments for MHz beam and data rates
5. Design low-emittance injector and SRF gun for extended hard X-ray performance

MEC-U: Matters in Extreme Conditions - Upgrade

New Laser Facility at end of LCLS

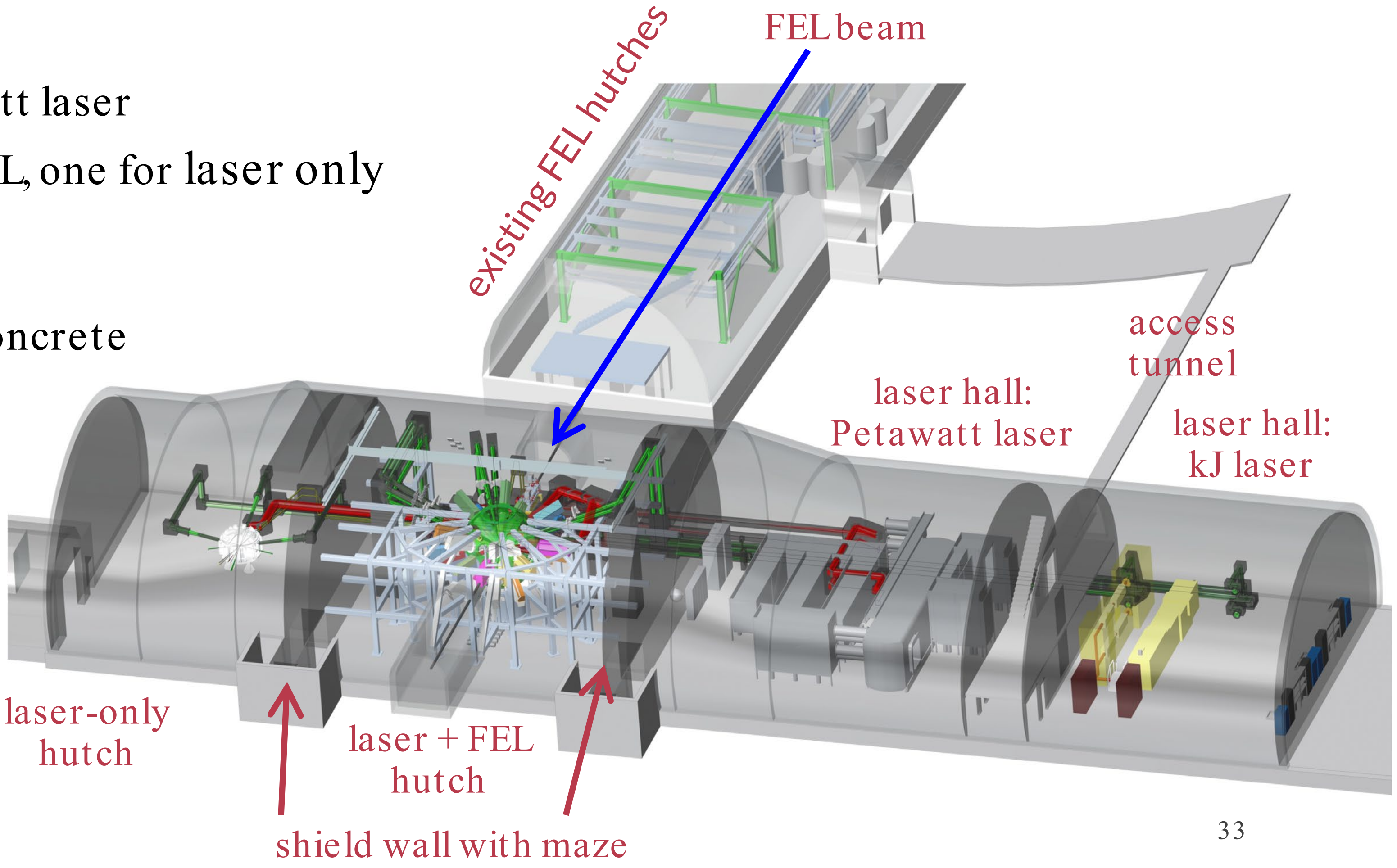
- Under design, construction from 2025, first light end of 2027
- 80 m long underground cavern
- 4 m diameter target chamber
- 1-kJ laser + 10 Hz 150 J petawatt laser
- Two hutches: one with X-ray FEL, one for laser only

Prompt radiation

- Two shield walls, 1.6 m heavy concrete
- with mazes, penetrations for laser, HVAC, cables …
- Distance at curved access tunnel

Residual radiation

- Choice of material
- expect administrative controls



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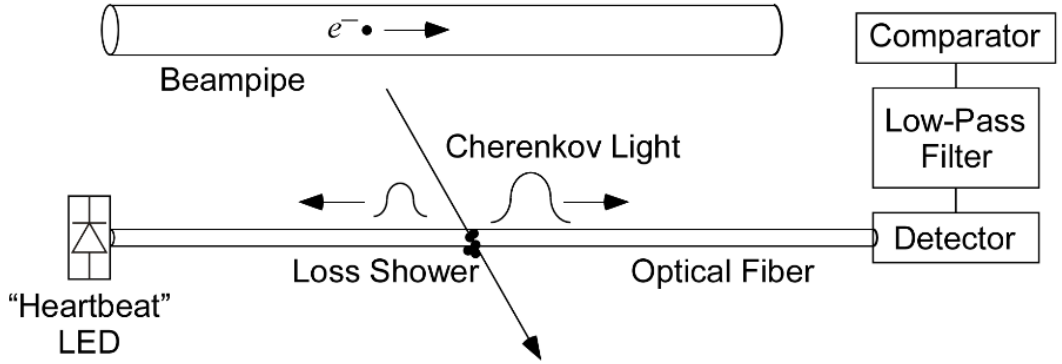
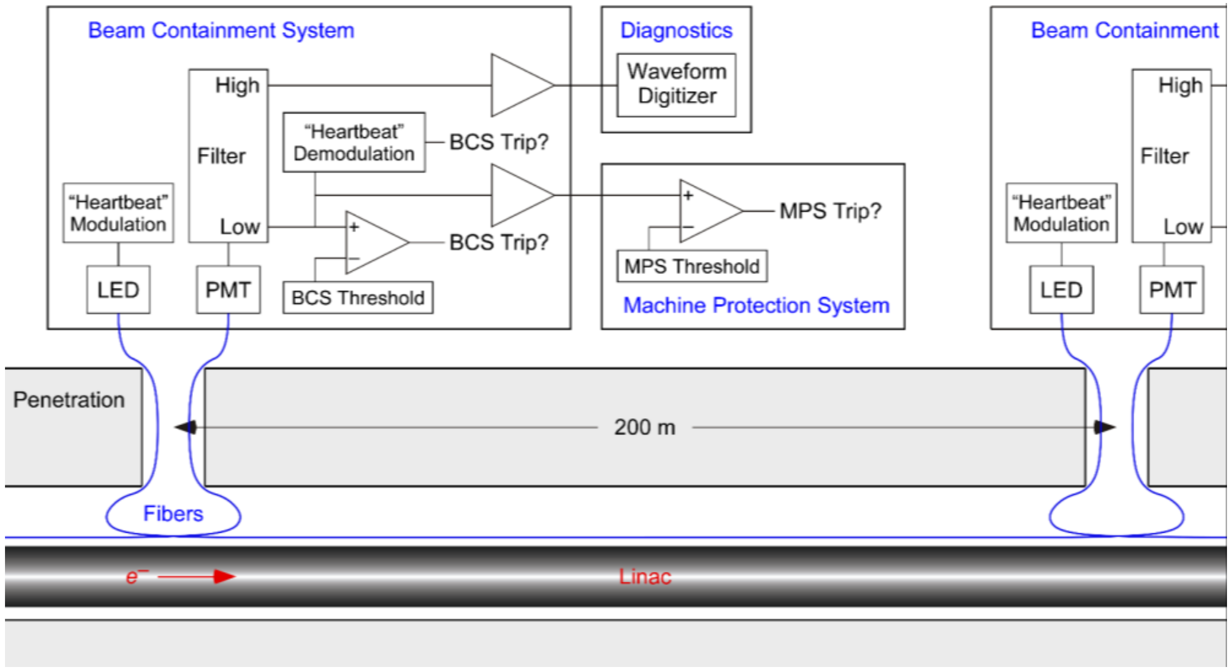
LCLS-II Electron BCS: LBLMs

Long Beam Loss Monitors new technology for SLAC

- Quartz fibers (radiation hard)
- Cherenkov light read with PMT
  (frequency range to limit effect from radiation damage)
- LED for keep-alive check
- Trip from beam losses 5 W to 1 kW





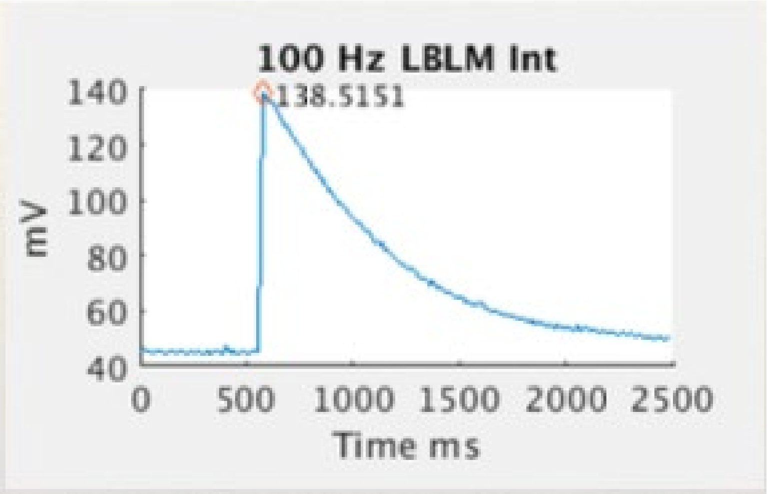
Installation

- Fibers blown through into plastic tube
- Up to 200 m long fibers
- Electronics outside accelerator housing

LCLS-II Electron BCS: LBLM Commissioning

Commissioning for LBLM on-going

- Four fibers commissioned Summer 2022
- Start for remaining fibers to BSY DUMP November 2022
- Finish them this week
- Beam current strongly limited by ACM → less reliance on correct LBLM trip settings
- After commissioning, set final trip limits, then raise beam current



response to single pulse: electronics with 0.5 s time constant

Performance

- Good performance, low noise, sensitive
- LBLMs at gun see dark current: Lower with collimators closed, right focusing solenoid
- As expected, variations from loss direction
  - distance of fiber
  - thin / thick target (local shielding)
    - some response counterintuitive (ceiling LBLM has higher response when shooting down than shooting up)

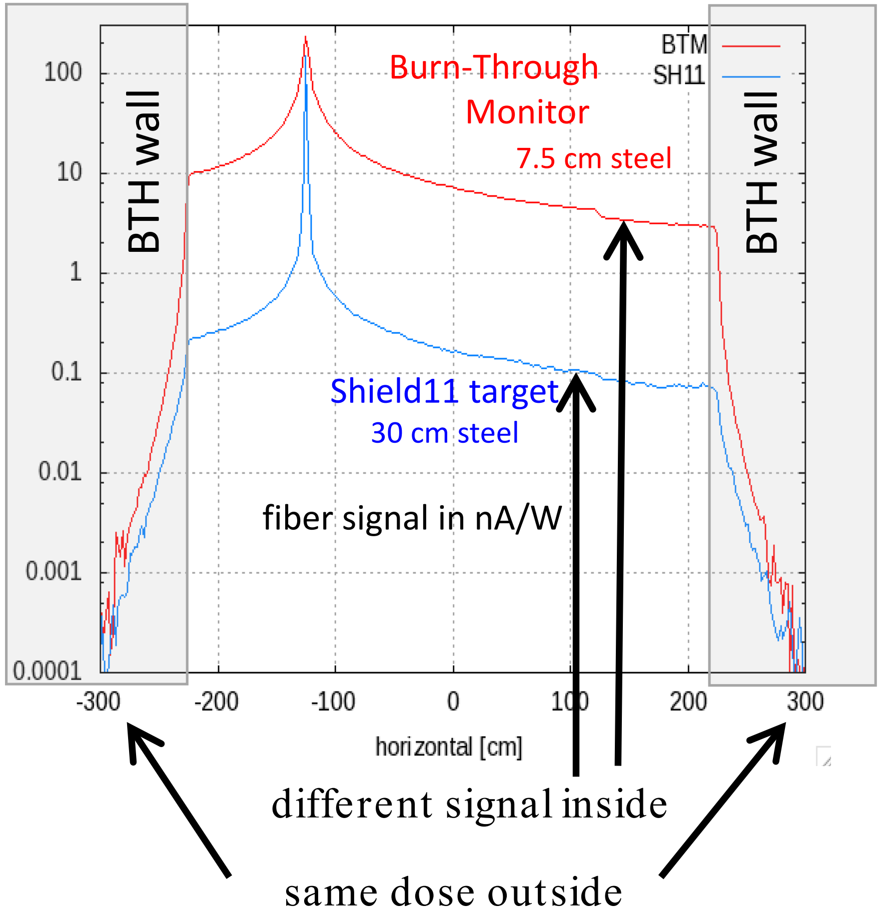
LCLS-II Electron BCS: LBLM Calibration Challenge

Difficult Calibration

- Cherenkov light created by charge particles but radiation outside mainly neutrons
- Uncertainly factor 20 to 50
  - Thin target (e.g., beam pipe) allows charged particles to reach fiber
  - Thick target (e.g., magnet, stopper) absorbs charged particles

Calibration Path

- Simulate response as possible
- Measure beam losses at many locations
  (script to mis-steer small bursts of beam along accelerator)
- Where steady losses possible (collimators):
  Compare radiation on fibers with radiation survey outside
- Decide on conservative trip limits based on type of targets in the area and where thick targets are w.r.t. penetrations



Bootstrap

Why Bootstrap is Needed

1. All safety analyses are based on simulated FEL parameters
2. SXR stoppers may suffer slow sublimation
3. Response time of BTMs and vacuum interlocks relies on the size of holes drilled by FEL beams
4. Material drill through time is estimated based on theoretic equations only
5. Calculation of air attenuation need to be validated by experiments

Bootstrap Plan Requirements

Set ACM limit to 1 μA before commissioning

- There are enough safety margins

Monitor from first light

- Photon stopper surfaces
- FEL parameters

Test before ramp up

- Photon stoppers
- Response time of safety interlocks and material drilling time
- Air attenuation

Before ramp up, evaluate whether there are safety margins based on the monitoring and test results

Threshold and Objective KPPs

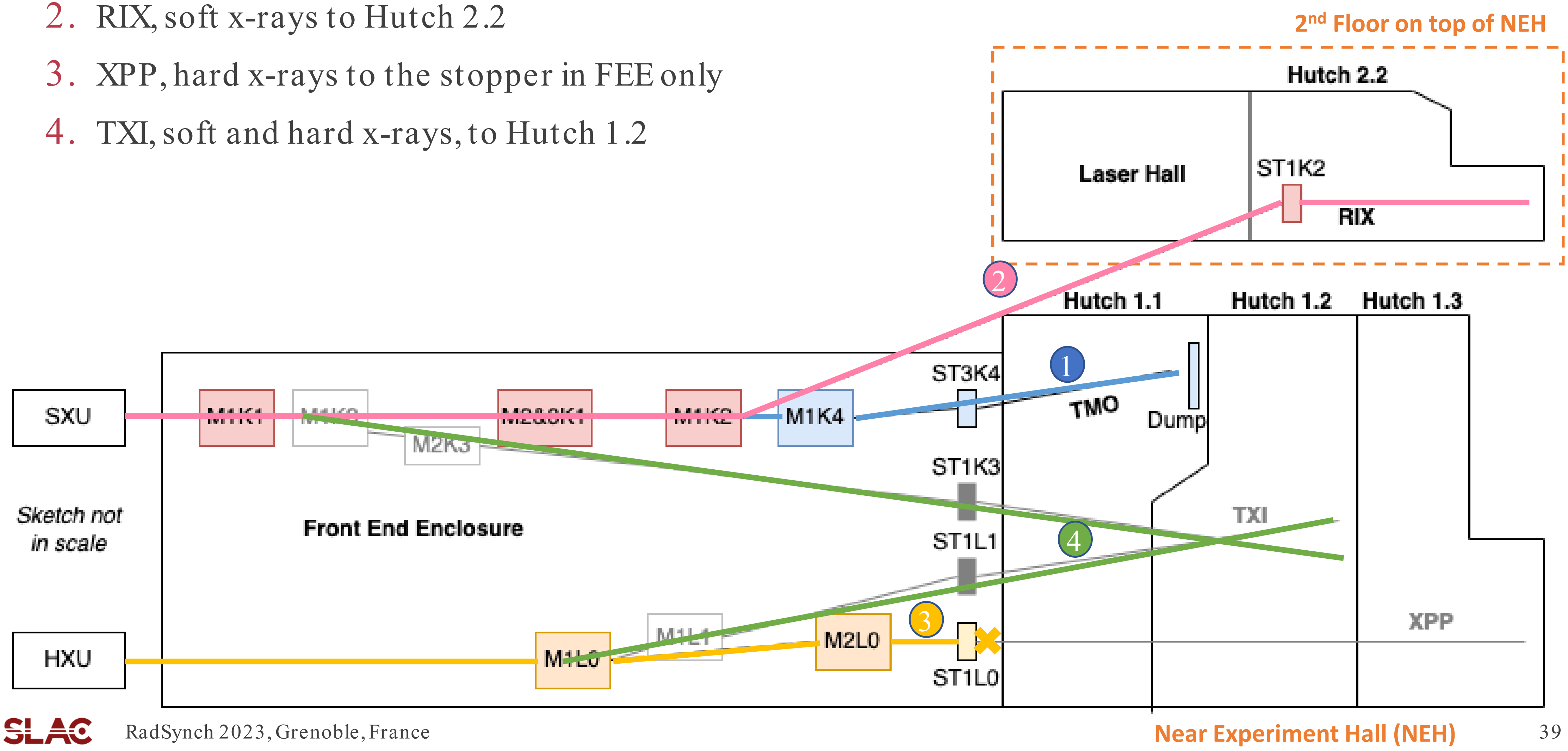
Performance Measure	Threshold (5 kW beam)	Objective (120 kW beam)	Measurements
Variable gap undulators	2 (soft and hard x-ray)	2 (soft and hard x-ray)	
Superconducting linac-based FEL system			
Superconducting linac electron beam energy	3.5 GeV	≥ 4 GeV	Spectrometer bend (magnet strength, screen)
Electron bunch repetition rate	93 kHz	929 kHz	BPM's, laser rate
Superconducting linac charge per bunch	0.02 nC	0.1 nC	Toroid, Faraday cup
Photon beam energy range	250–3,800 eV	200–5,000 eV	Absorption edges, spectrometer
High repetition rate capable end stations	≥ 1	≥ 2	N/A
FEL photon quantity (10^{-3} BW) per bunch	5×10^8 (10x spontaneous) @2,500 eV	> 10^{11} @3,800 eV	Gas energy monitor, GMD, Spectrometer
Normal conducting linac -based system			
Normal conducting linac electron beam energy	13.6 GeV	15 GeV	Spectrometer bend (magnet strength, screen)
Electron bunch repetition rate	120 Hz	120 Hz	BPM's, laser rate
Normal conducting linac charge per bunch	0.1 nC	[illegible] nC	Toroid, Faraday cup
Photon beam energy range	1–15 keV	1–25 keV	Absorption edges, spectrometer
Low repetition rate capable end stations	≥ 2	≥ 3	N/A
FEL photon quantity (10^{-3} BW[a]) per bunch	10^{10} (lasing @15 keV)	> 10^{12} @15 keV	Gas energy monitor, GMD, Spectrometer

Achieved

NC based scope for threshold KPP is complete, SC rate and x-ray KPPs are remaining.

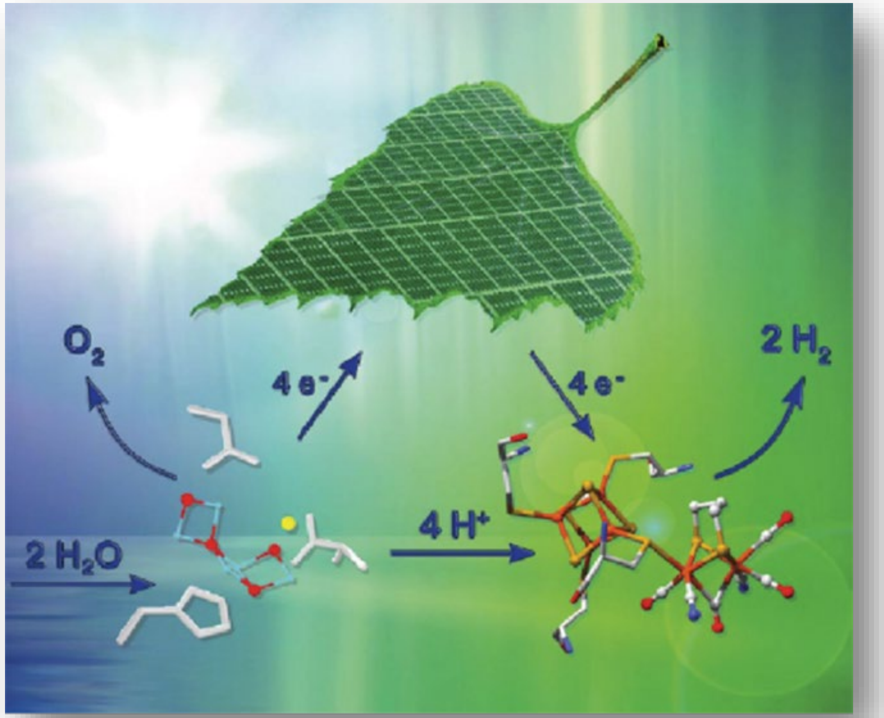
LCLS-II FEL Beam Lines

1. TMO, soft x-rays to Hutch 1.1
2. RIX, soft x-rays to Hutch 2.2
3. XPP, hard x-rays to the stopper in FEE only
4. TXI, soft and hard x-rays, to Hutch 1.2



Atomic resolution in space and time

- X-ray laser with strobe speed of 10fs (10fs×c = 3 μm)
- Allows:
  - Stop action on atomic and molecular timescales
  - Image atoms in molecules (X-ray wavelength = ~1Å)



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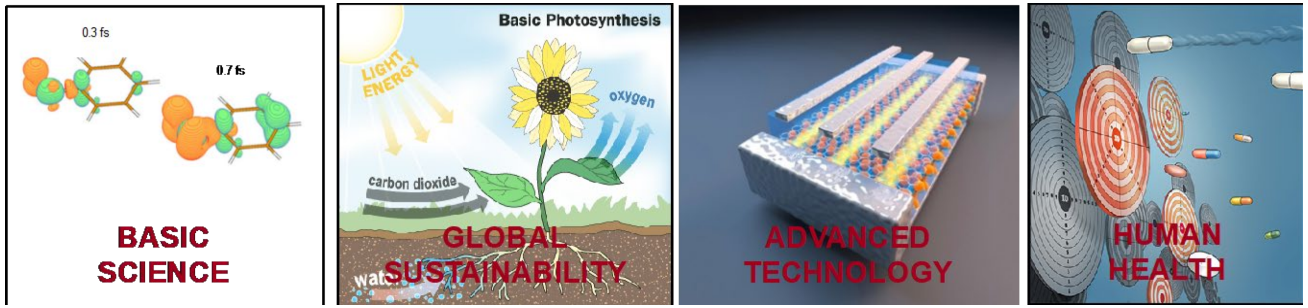
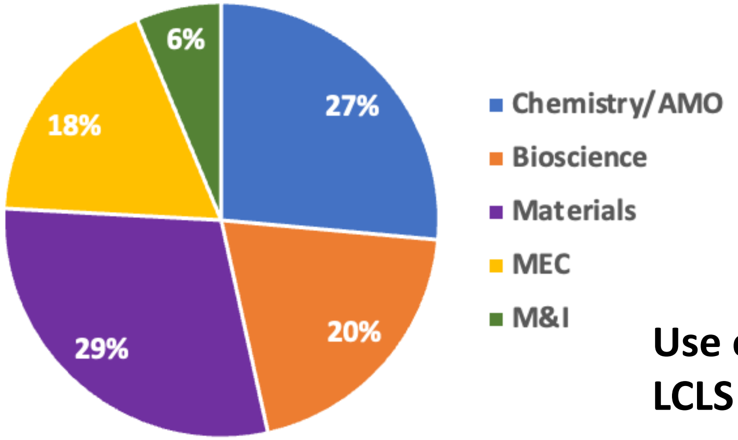
- Frontier opened in 2009 with ‘ultra-bright’, ‘ultra- fast’ x-ray pulses from Linac Coherent Light Source at SLAC

SLAC

X-ray FELsprovide game-changing scientific opportunities





Use of LCLS

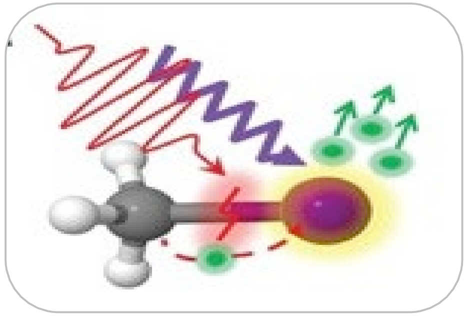
- **Drivers of chemical bond formation**
- **Design principles for new catalysts**
- **Understand and control emergent phenomena in quantum materials**
- **Reveal biological function at the molecular scale in real time**

The leap from 120 Hz to 1 MHz will be transformative

LCLS-II and HE will transform our understanding of dynamics in real-world material, chemical and biological systems

Seeing how physics drives chemistry

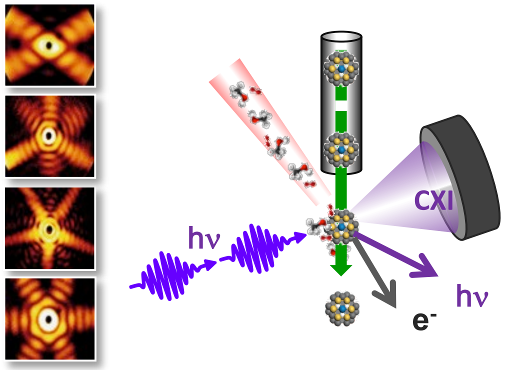
- Reveal coupled electronic and nuclear motion in molecules
- Capture the initiating events of charge transfer chemistry with sub-fs resolution



Ultrafast

How to accelerate chemical reactions

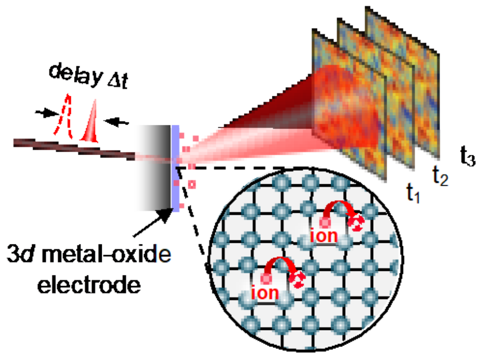
- Correlate catalytic reactivity and structure
- Real-time evolution with chemical specificity and atomic resolution



High repetition rate

Understanding material function and failure

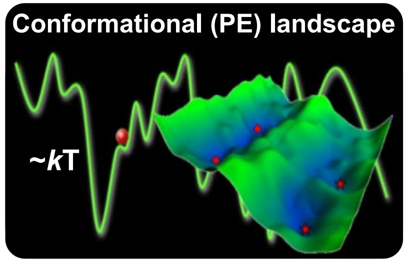
- Characterize dynamic systems without long-range order
- Directed design of energy conversion and storage materials



Coherence

Watching biology in action

- Study large scale conformational changes via solution scattering
- Physiological conditions
- Dynamics ties structure to function



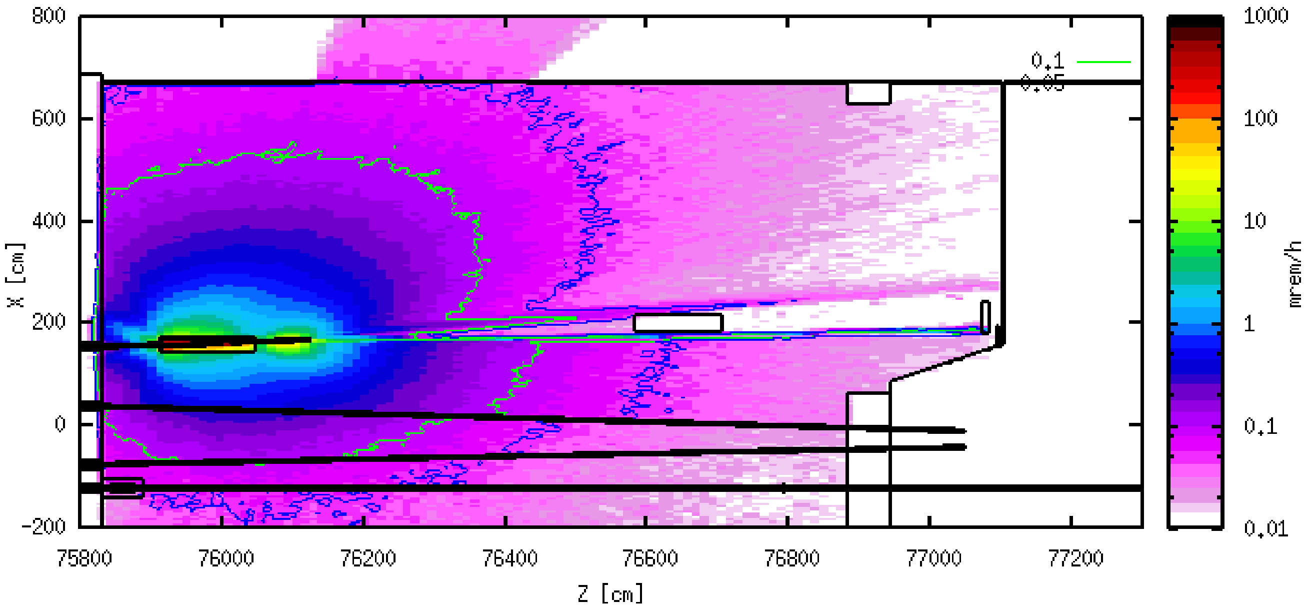
Extreme brightness

Hutch Shielding for Superconducting Linac Beams

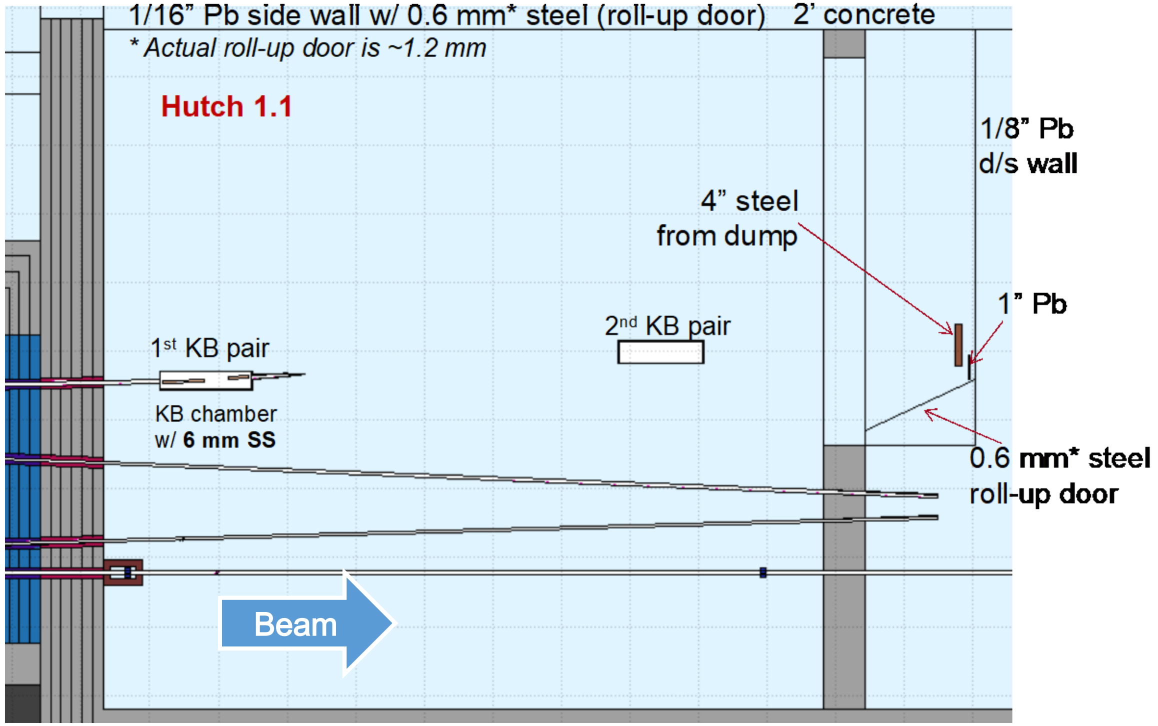
Monte Carlo (FLUKA) simulation for hutch shielding

Hutch shielding is dominated by synchrotron radiation (SR)

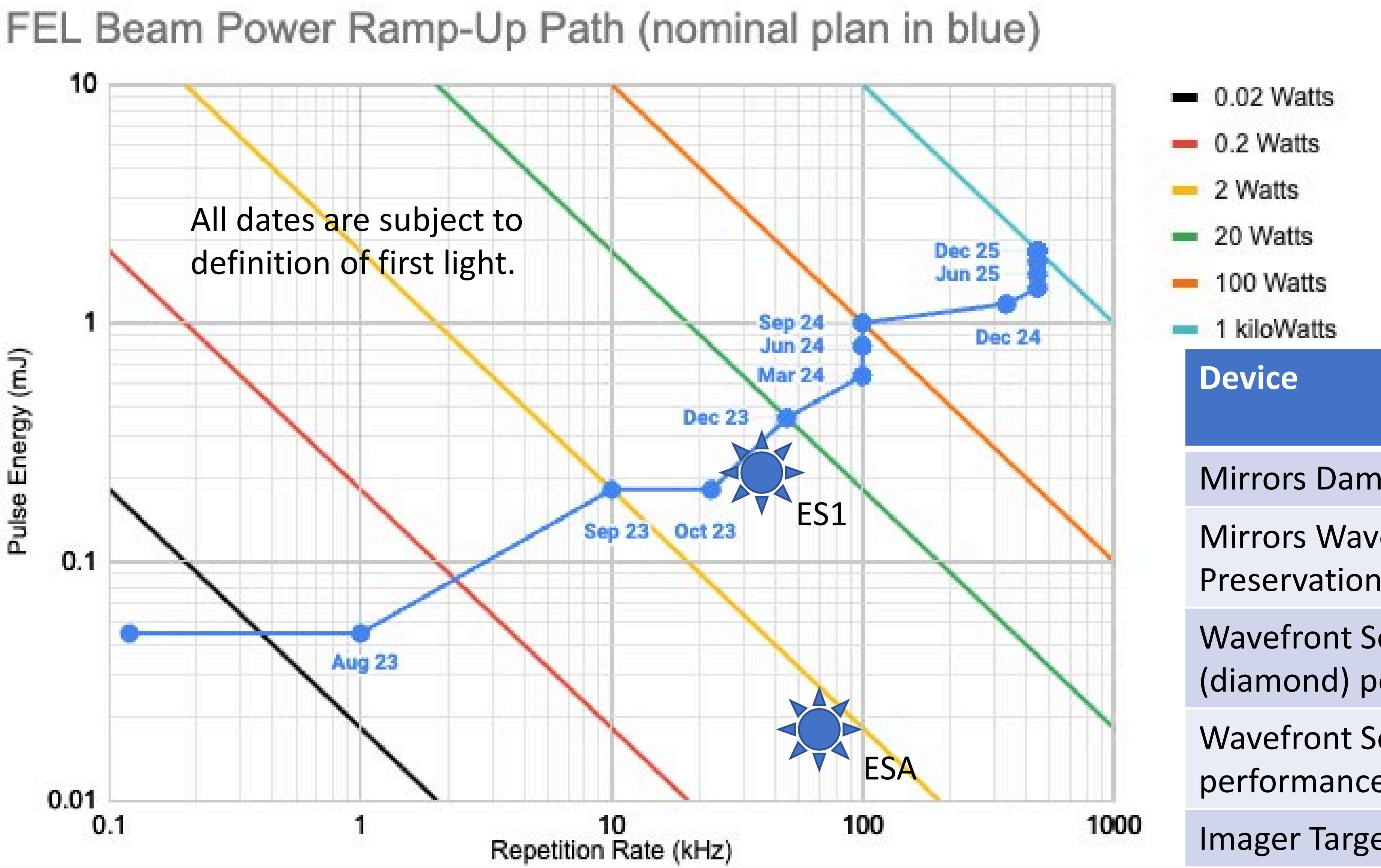
Dose for SR from 8 GeV 240 kW e- beam



FLUKA Model of Hutch 1.1



Average Power Ramp Up Plan

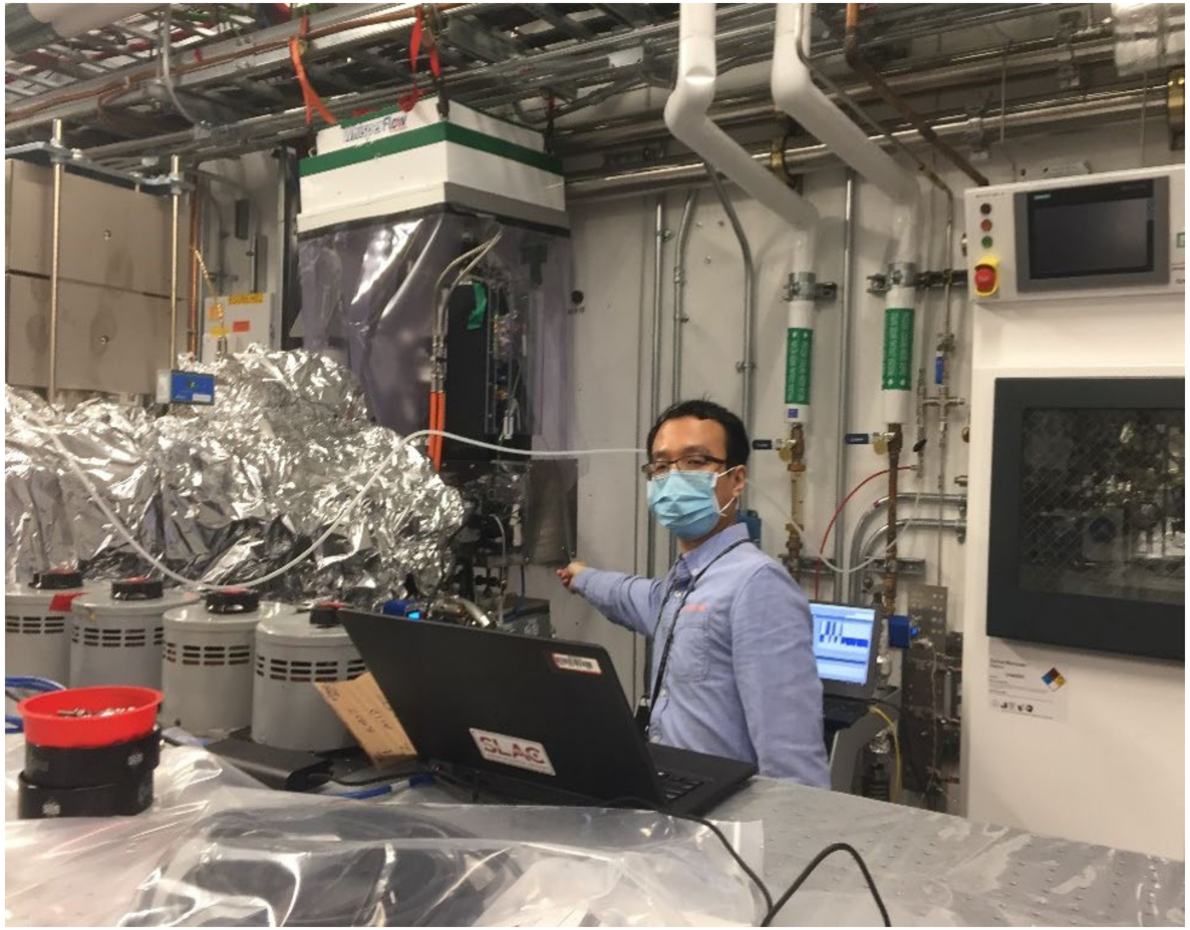


1uA -> 50 W (MAP)
[LCLS-II-TN-17-04]

Power levels will be regulated by the PMPS system

Device	Maximum Power
Mirrors Damage	200 W
Mirrors Wavefront Preservation	20 W
Wavefront Sensor Target (diamond) performance	20 W
Wavefront Sensor Target (Si) performance	1 W
Imager Target (damage)	1 W

LCLS- Commissioning of FEL beam to NEH H2.2 Stoppers



Description of LCLS-Science

Image single molecules

- Study structure of complex organic molecules without the need for a crystal

Observe chemical reactions in "real time"

- Stroboscopic picture of reaction progress

Observe novel states of matter

- Multi-photon effects
- Collective effects in materials
- Plasma behavior

Matter in Extreme Conditions

- High-intensity short pulse pump laser
  - High Energy Density
  - Ionizing radiation (electron, X-ray, hadrons) due to interaction of short-pulse high intensity laser with materials

Bootstrap Plan for FEL Beams

Bootstrap process is needed to accommodate uncertainties in radiation safety design.

- Uncertainties come from FEL beam parameters and assumptions/models used in radiation safety analyses

Bootstrap Process:

1. Start operation with small beams
2. Perform monitoring and experiments
3. Evaluate results to decide the next limit level