SLAC's LCLS-II Superconducting Accelerator Facility: Ramp-up to Higher Power

Johannes Bauer, Jan Blaha, Thomas Frosio, James Liu, Mario Santana, Andrew Rosenstrom, Shanjie Xiao, Sayed Rokni

SLAC National Accelerator Laboratory, Menlo Park, California

June 27, 2025

RadSynch25, Campinas, Brazil

SLAC NATIONAL ACCELERATOR LABORATORY

Work supported by
Department of Energy contract DE-AC02-76SF00515

Stanford University | U.S. DEPARTMENT OF ENERGY

Outline

- Overview of LCLS and Beam Containment System
- Challenges with Long Beam Loss Monitors
  - Continuation of Operation and Ramp-up
  - Plan forward for Long Beam Loss Monitors
- Dark Current from accelerator modules
- Upgrade Plans: LCLS-HE

Linac Coherent Light Source at SLAC

Three types of LCLS

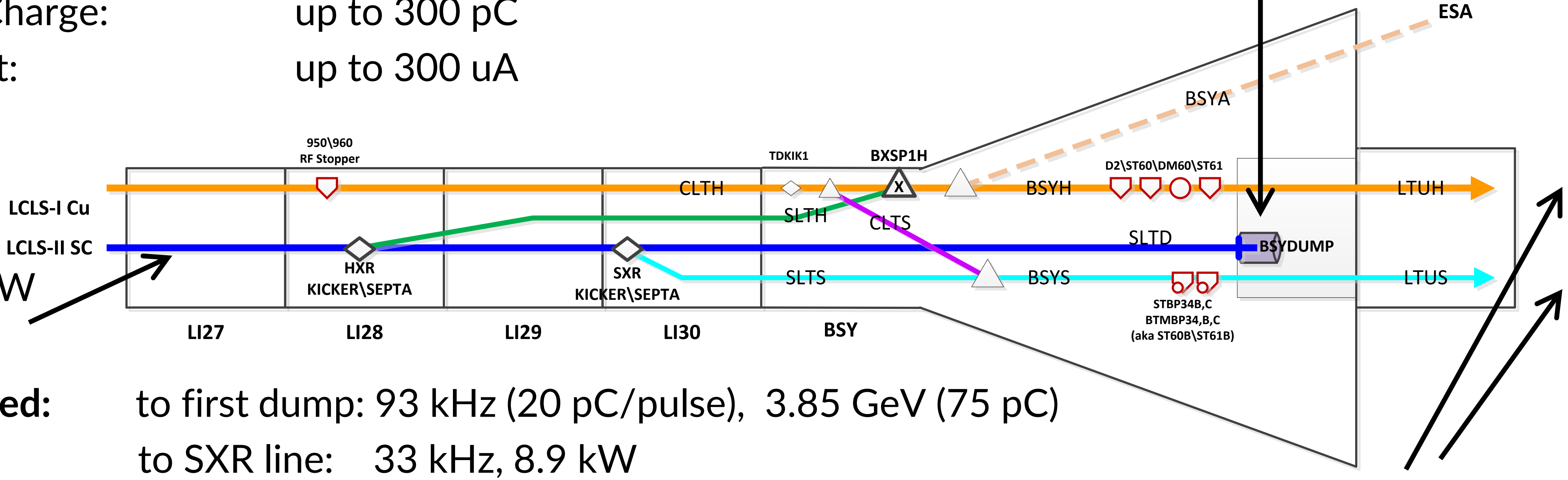
LCLS-HE	LCLS-II	LCLS
Super-Conducting	Super-Conducting	Normal Conducting
First Light 2027	First Light 2023	First Light 2009
up to 1 MHz	up to 1 MHz	120 Hz
2 to 8 GeV electrons	2 to 4 GeV electrons	2 to 16 GeV electrons
250 eV to 12.8 keV	250 eV to 5 keV	250 eV to 25 keV

LCLS-II Parameters

Maximum Operation Parameters

Electron Energy:	2 to 4 GeV
Repetition Rate:	up to 927 kHz (~1 MHz)
Pulse Charge:	up to 300 pC
Current:	up to 300 uA

Up to 120 kW to first dump



Up to 120 kW in Linac

Up to 120 kW to beamline dumps

Achieved: to first dump: 93 kHz (20 pC/pulse), 3.85 GeV (75 pC)

to SXR line: 33 kHz, 8.9 kW

in hutches: up to 0.8 mJ/pulse @ 400 eV

This talk about the **power ramp-up** of the **electron beam**

LCLS-II Beam Containment System

SLAC Linac has ~540 large **penetrations**, many **nearly above** beam pipe

Need system to keep beam away from people

→ **Beam Containment System**

limits beam power
reacts to high beam losses
ensures beam stays on path
protects safety systems

Dose Limits for Design:

- Normal Operation:
  - 1 mSv/h (100 mrem/h) at hutches/offices/public
  - 10 mSv/h (1000 mrem/h) elsewhere
- Mis-steering: 4 mSv/h (400 mrem/h)
- Failure of Safety System: 250 mSv/h (25 rem/h)

New **challenges** due to **high rep-rate,** *e.g.*, ion chambers may saturate at high power

→ new technologies in use at SLAC

LCLS-II Beam Containment System

BCS related to power ramp-up

- Limitation on energy

  Hardware Limit (option: limits on magnet strength in chicane)

- Limitation on current

  2 Average Current Monitors

  New RF-based system (pill-box), covers large operational range

- No limit on repetition rate

  no control we can take credit for

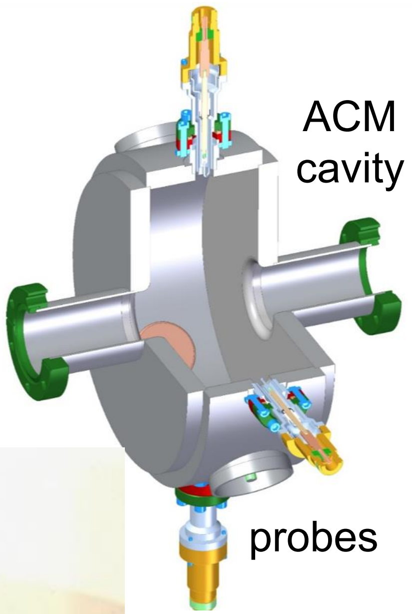
- Loss Monitors along whole accelerator to dumps

  Long Beam Loss Monitors = LBLM

  47 quartz fibers running along whole 4 km

  each 30 to 200 m long

  first use of fibers at accelerators as safety system to protect people



LCLS-II Beam Containment System

Loss Monitors at dumps, collimators

Point Beam Loss Monitors = PBLM

29 diamond-based radiation detectors

Some other BCS not directly related to ramp-up

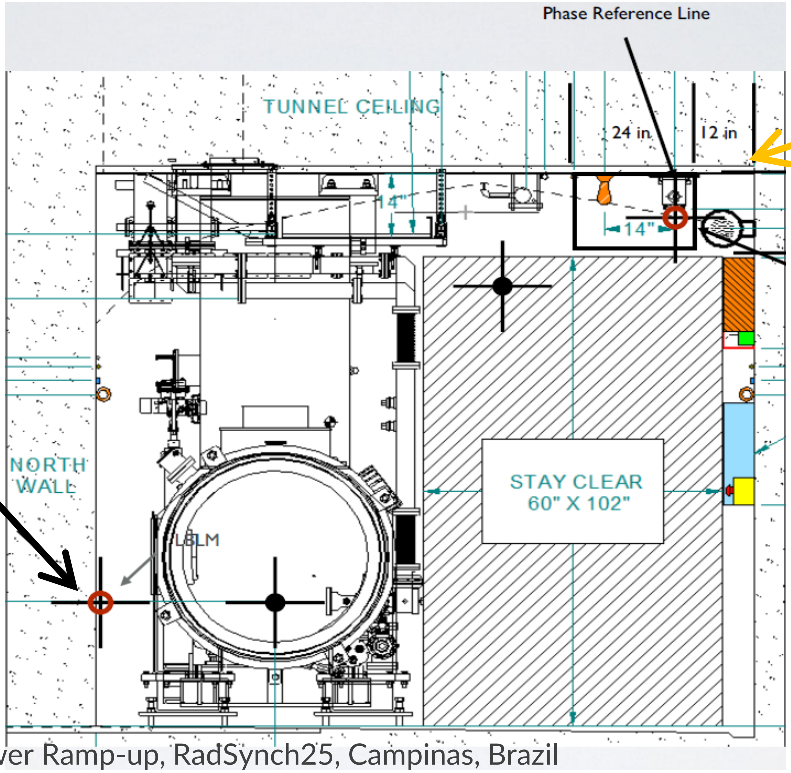
- Ensure dumps are cooled — 6 Water flow switches
- Detect beam drilling hole in vacuum pipe — Vacuum sensors
- Ensure magnets do not mis-steer beam that they miss protection collimators — 20 Magnet Current Monitors

LBLMs: Installation

At least one fiber along accelerator

- Along cryomodule, along bypass line, above magnets
- Depending on area, 1, 2 or 4 fibers in parallel
- Distance 30 cm to few meters (ceiling, wall, above beamline)
- Overlap between fibers to avoid coverage gaps

at ceiling



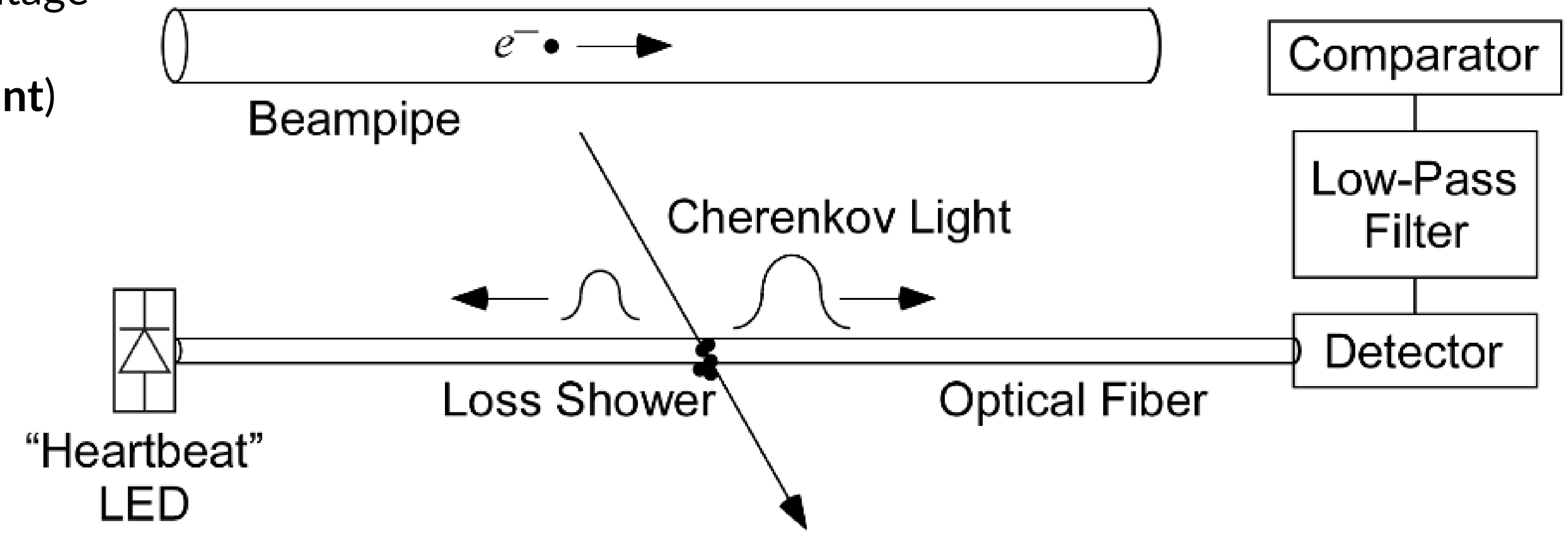
along cryomodule

along cryomodule / beamline

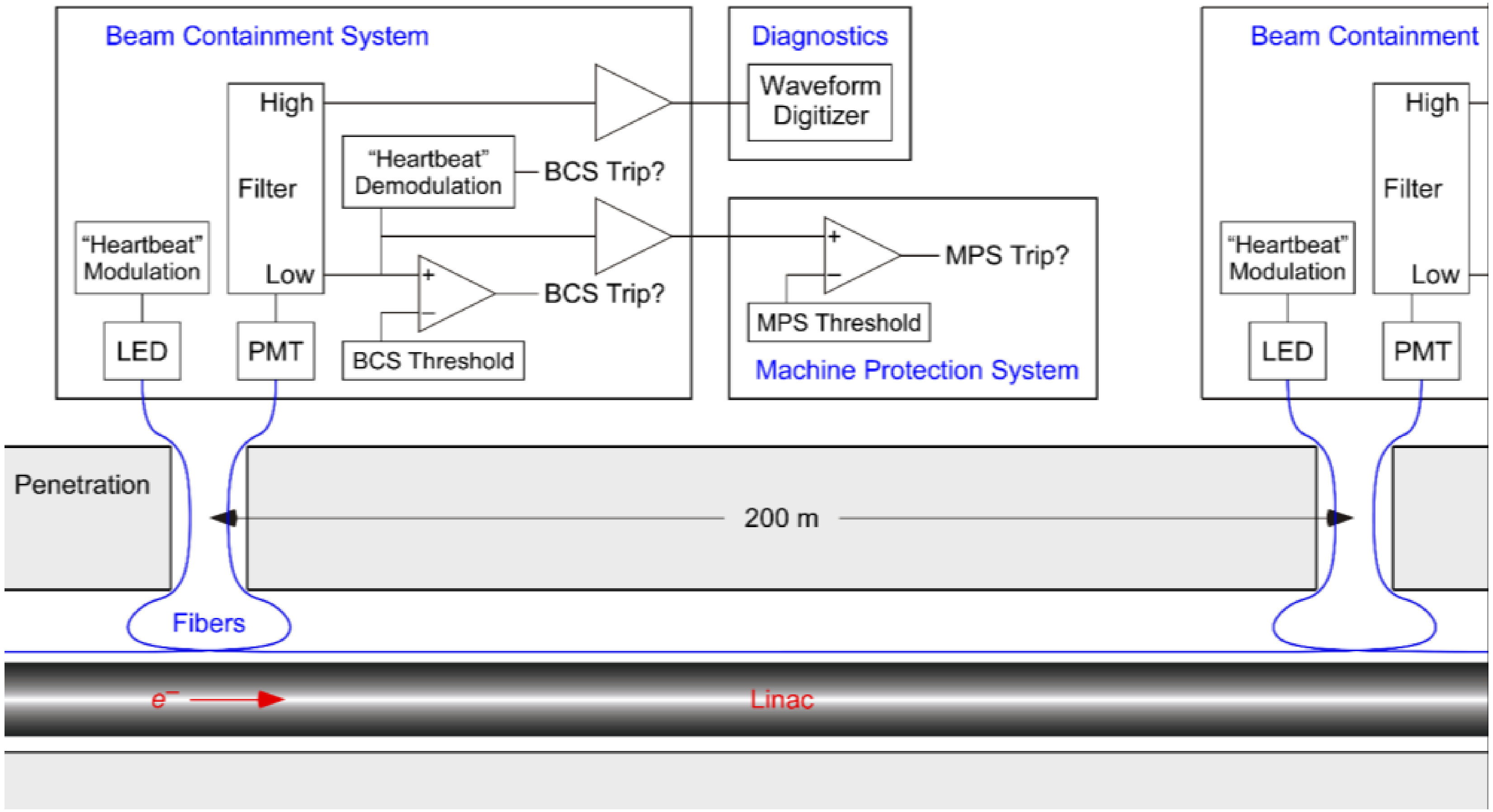
LBLMs: Principle

Detection of beam loss

- Charged particles create **Cherenkov light** inside quartz fiber (diameter 2 mm diameter total, 0.6 mm diameter core)
- Internal reflection brings light to **PMT at downstream end**
- Electronics with preamp gives voltage (mV)
- **Trip** of system when voltage above threshold (**500 ms RC time constant**)



LBLMs: Electronics



Self-check:

- LED at upstream end sends light through fiber; LED light modulated by low frequency (e.g., 0.8 Hz)
- Lock-in Amplifier detects frequency; trips if 0.8 Hz signal missing

NOTE: continuous self-check, not just checking from time to time!

Inherent Uncertainty in LBLM Measurement

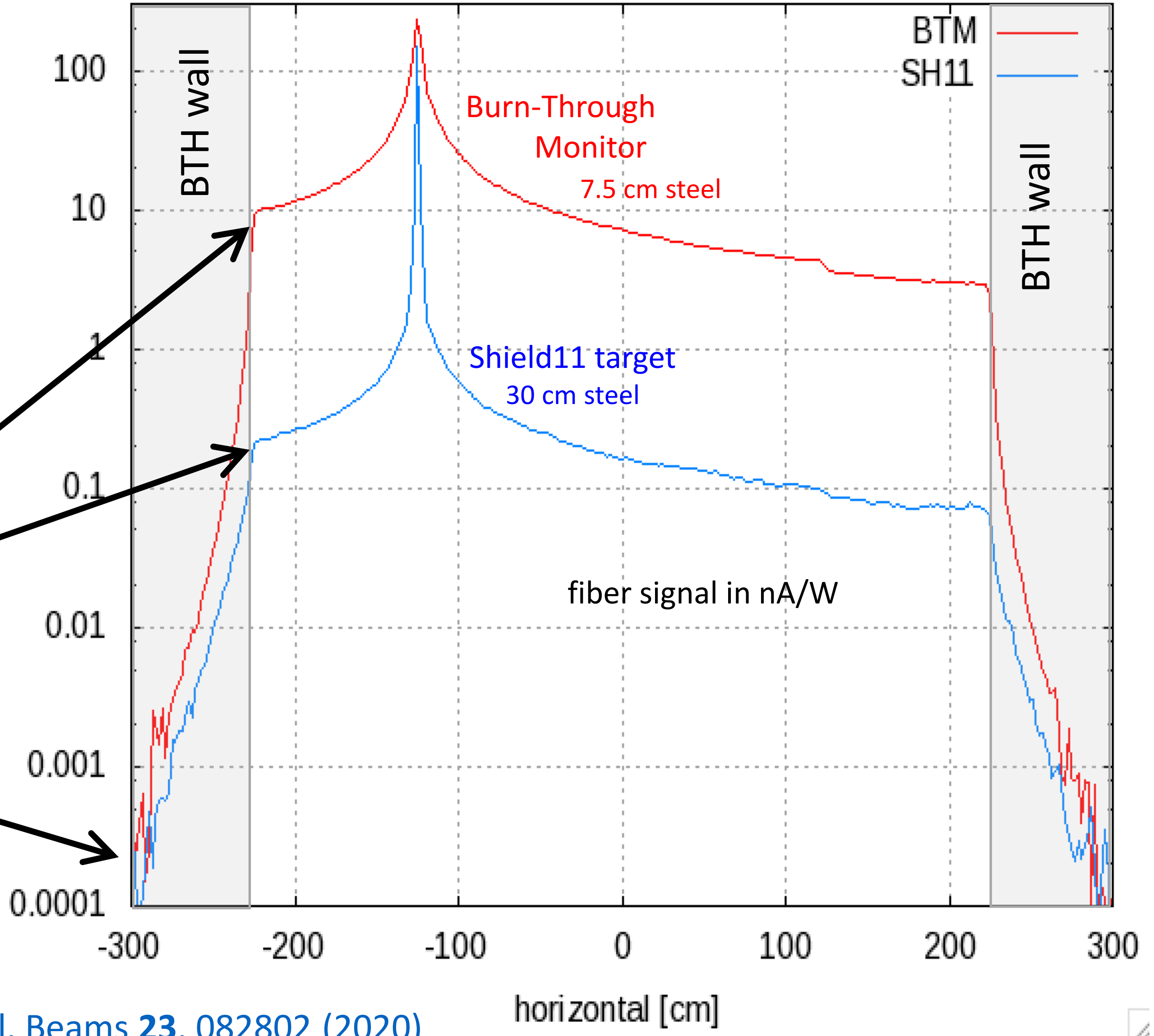
Dependence on where loss occurs

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

different signal inside

same dose outside

A good reason to set trip limit low



[Phys. Rev. Accel. Beams **23**, 082802 (2020)]

LBLM Calibration

- “Manually” mis-steer beam (10 Hz , few W)
- Create one good loss point for each fiber
  with highest LBLM reading recorded (mV)
- Determine power lost (W): look at Beam Loss Monitor
  before and after loss point
- Offline, calculate response rate mV/W
- Maximum trip limits
  - 1 kW electron loss at most places
  - 35 W electron loss where shielding is minimal
- Actual trip limit as low as possible without causing false trips due to noise

Start of Operation

All BCS was tested without beam

PBLM & LBLMs became part of official safety system

First light in 2023

PBLMs and LBLMs worked well, low noise, very sensitive to losses

- LBLMs close to injector detected losses due to RF Gun Dark Current
  → Proper adjustment of collimators stopped most dark current from propagating

Operation ramped up to 5 kW

Current Challenges with LBLMs

(1) Low signal from PMT
    Developed after ~1 year of operation on more and more units (late 2023, early 2024)

(2) False self-checking trips
    a) during beam operation
    b) dependence on ambient temperature

Two questions:

(1) How to continue power ramp-up until LBLMs modified and commissioned?

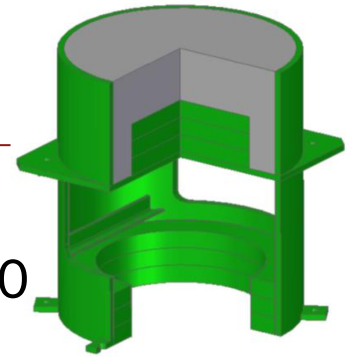
(2) How are LBLMs modified?

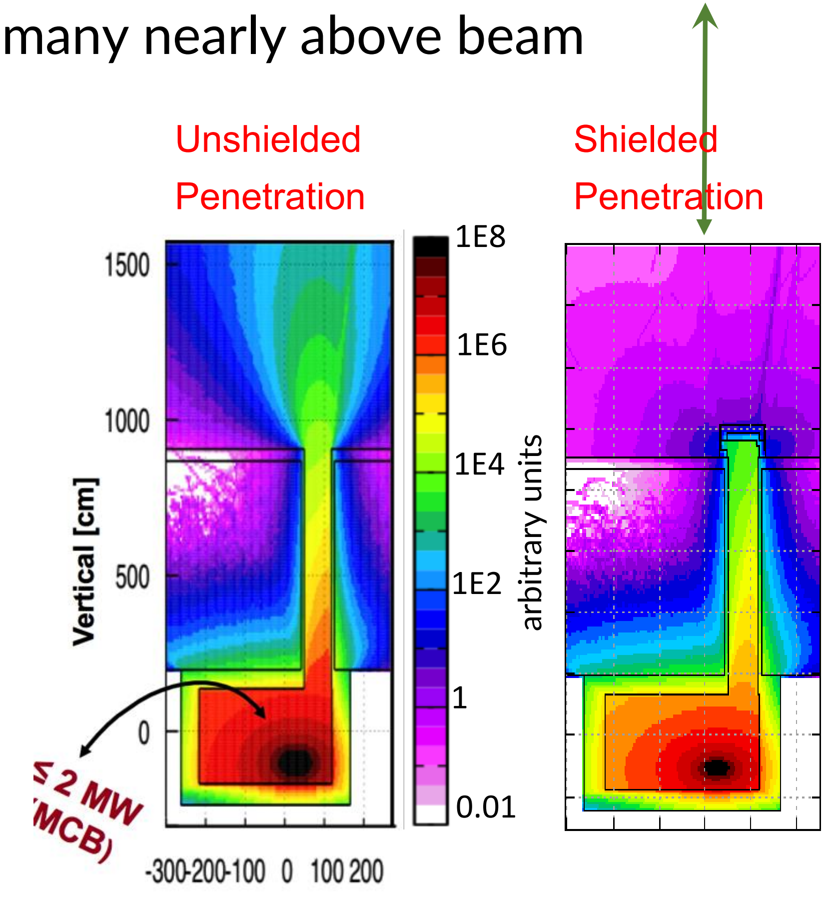
How to continue ramp-up without LBLMs? (1)

RP went back to drawing board:

- LBLMs were to trip at about 1 kW beam loss in most areas, 35 W in less-shielded BTH area
- Penetration shielding design: 1 kW beam loss → 125 µSv/h
  > 1 kW loss was to be stopped by LBLM trip

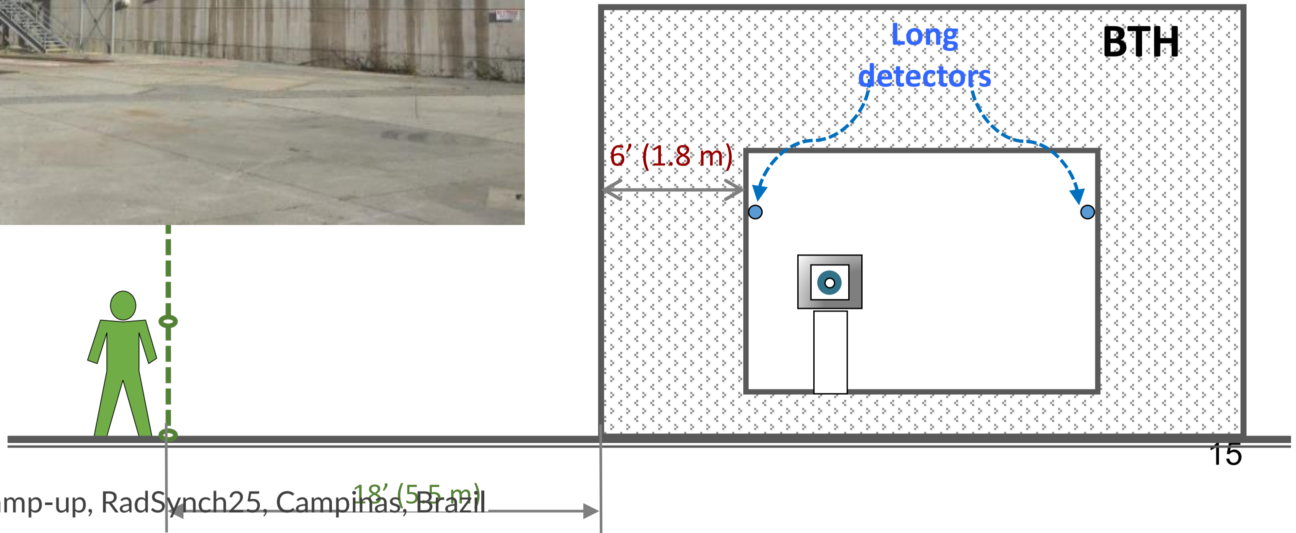
SLAC Linac has ~540 large penetrations, many nearly above beam





without LBLMs:

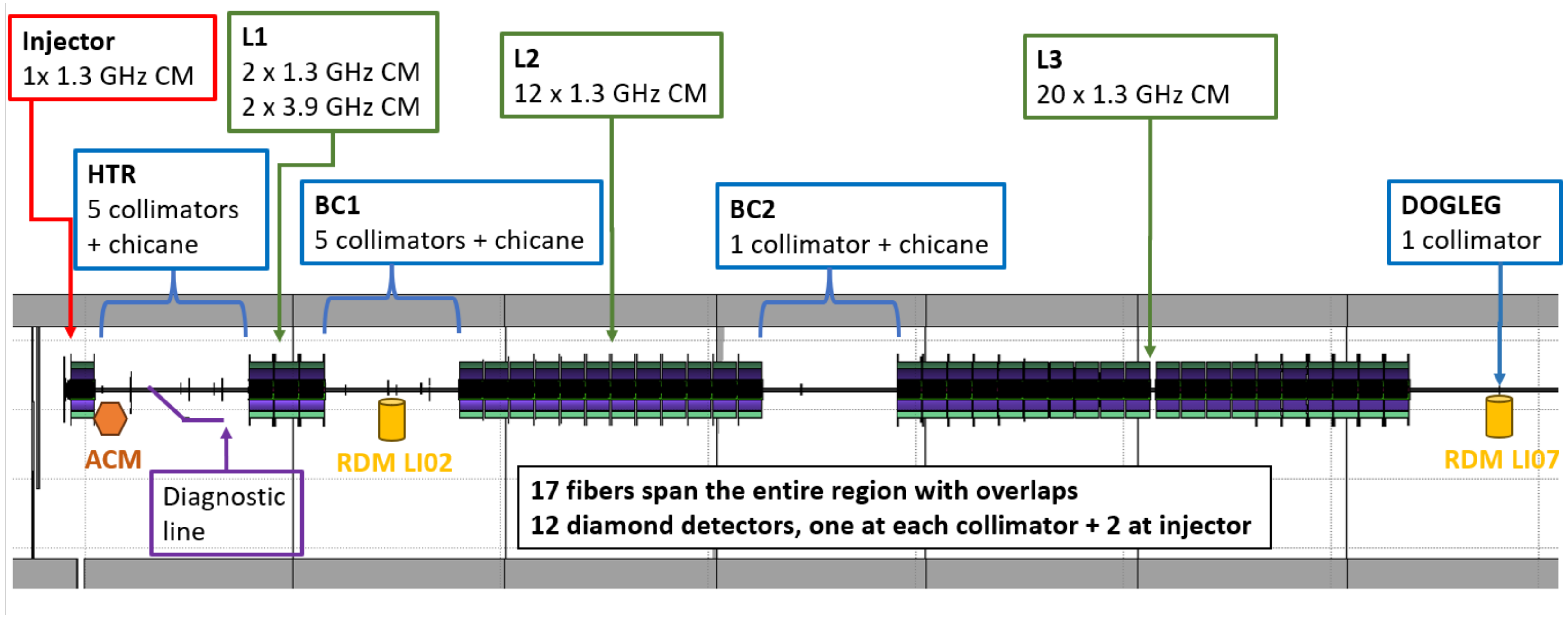
120 kW loss → 15 mSv/h



How to continue ramp-up without LBLMs? (2)

- Set Average Current Monitor to **low trip setting**, initially 0.5 µA
  - → power not exceeding 5 kW maximal at highest possible energy uncertainties restrict to ~2 kW operational at realistic 4 GeV
- Lock Bunch Compressor **magnets BC1 and BC2 in OUT position**
  - → dark current cannot pass from one accelerating section to another

  (with LBLMs working, persistent high radiation would shut off the cryomodules)



How to continue ramp-up without LBLMs? (3)

- Point Beam Loss Monitors (PBLMs)
  - set PBLMs to **lowest possible setting** (5 W loss)
  - put back PBLMs **into interlock** (were taken out of interlock since covering area, not device)
  - **move PBLM** underneath penetration in undulator area
- Require **more shielding** at some penetrations
- Increased radiation monitoring and radiation surveys

→ **increased ACM trip limit** for maximum allowed power of 16 kW (beam up to ~10 kW possible)

→ **LCLS-II experiments in hutches**

Plan forward for LBLM (1)

Lots of progress made!

Bench tests, some tests with beam took place,
not yet 100% certain all will work until full operation

- Low response from PMTs
  - Hamamatsu data shows expected **PMT lifetime** with given self-check LED signal consistent with consistent with timeframe of our PMT failures

    Since radiation damage to fibers is low in red/nearIR, a red-sensitive PMT was chosen,
    filter blocked shorter wavelengths → needed special photocathode

  - New Hamamatsu model has 20 x longer lifetime (= accepts 20 x more light before failure)
  - 60 PMTs ordered, all PMTs exchanged, spares will be kept
  - **LED intensity is being reduced**

Plan forward for LBLM (3)

- Self-check failures
  - First issue: self-check failures **during beam operation**
    - Beam operation makes extraction of 0.8 Hz self-check signal difficult: more noise, too large 0.8 Hz signal
    - First tried with frequency other than 0.8 Hz: should not be a multiple of beam rep-rate: 1 Hz, 10 Hz, …
    - **Algorithm** to extract frequency was improved, tested with archived data and real-time data: promising so far
  - Second issue: **Sudden jumps** in self-check signal
    - Cooling system started at high ambient temperature
    - Improvement made to **cooling system**
  - Also: **LED output depends on temperature**, but LED was not cooled
    Now cooling extended to LED

Plan forward for LBLM

- Chassis were revamped:
  - New PMT model
  - New firmware
  - New cooling system
- Currently being certified without beam (hopefully done early July)
- Lots of hardware changes → need for testing with beam
  - hopefully before 1-year long downtime starting Dec 2025

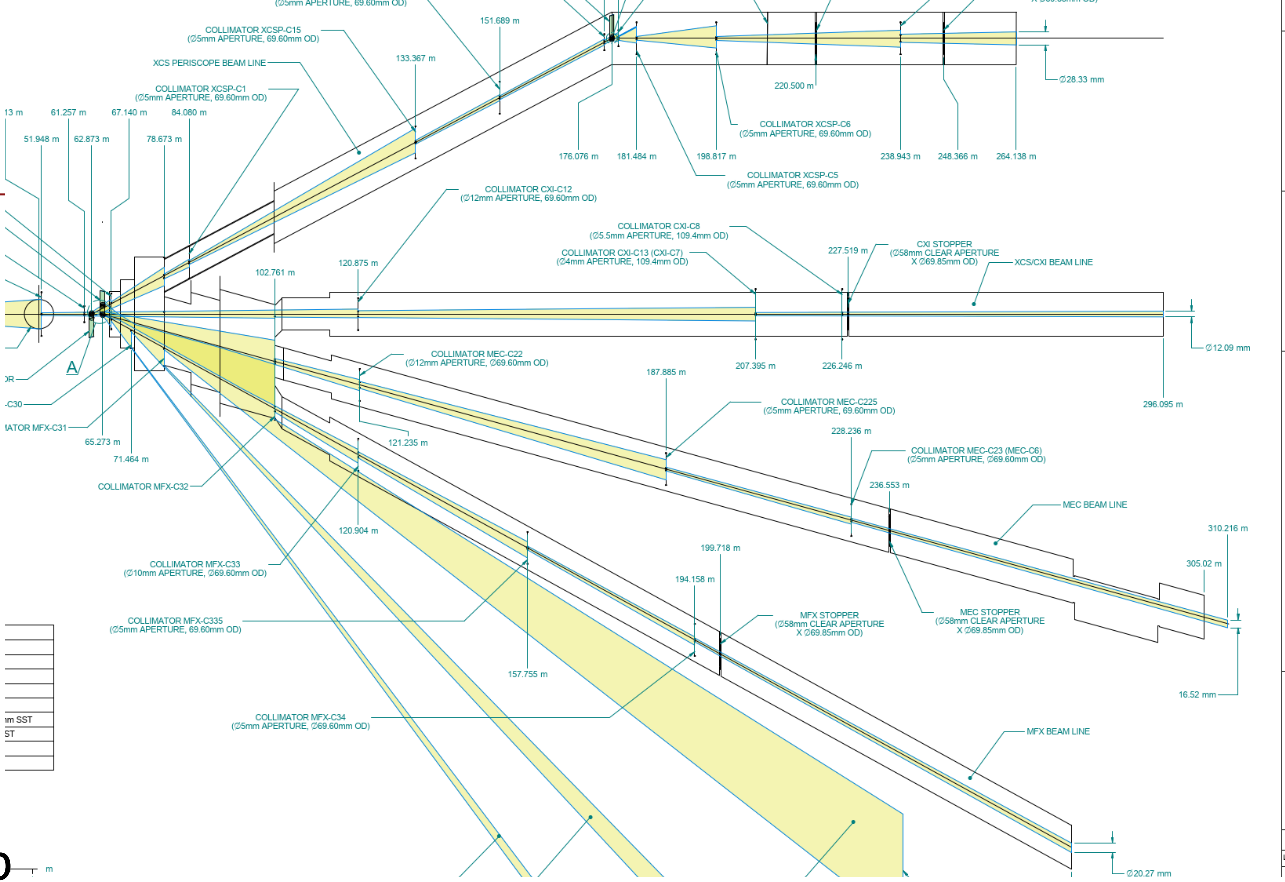
Further Ramp-up

- SLAC Linac has 540 penetrations at 0.7 m diameter
  → too expensive to add more shielding
- Linac is 3 km long, equipment right above that needs access during operation
  → not possible to keep people away, especially not for longer time
- **Need LBLMs to increase allowed power**

Ramp-up of FEL

- Power of FEL depends on electron power
  → increase in electron power allowed
  only if also **FEL power** increase is safe

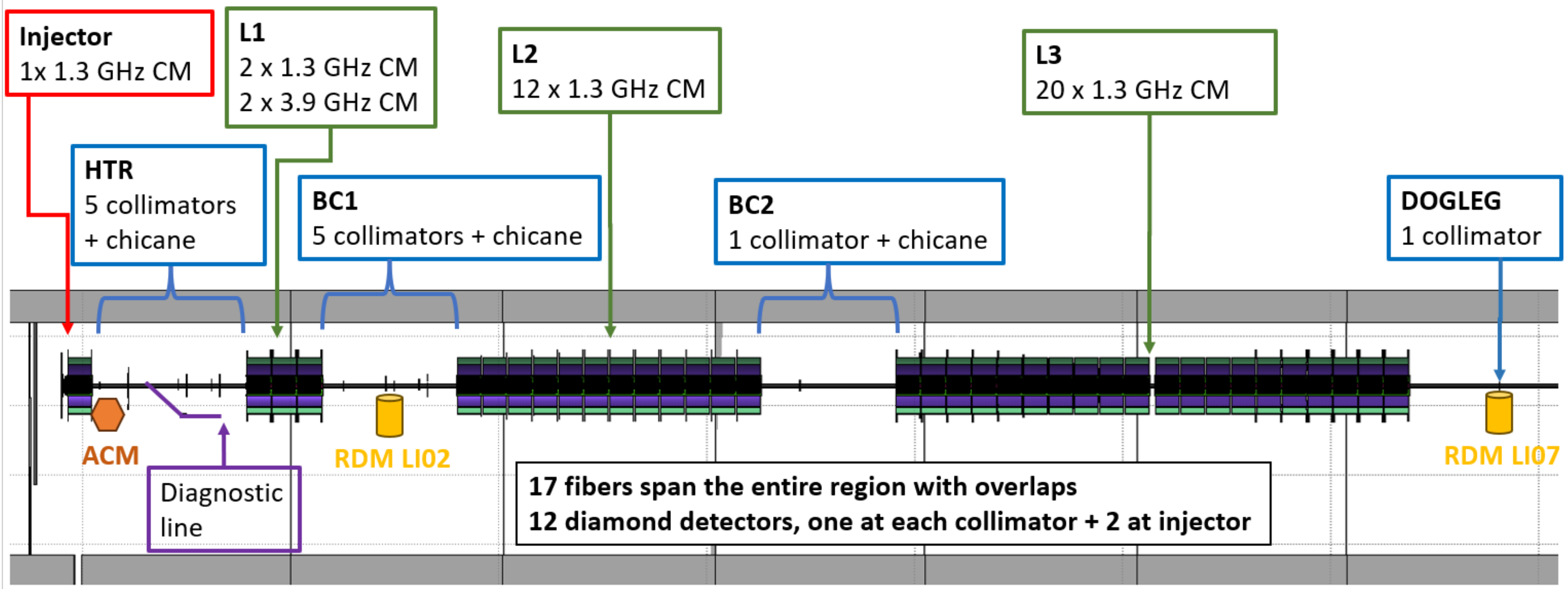
- **Shanjie Xiao** will talk about FEL Bootstrap
  - Special tests on how much material can withstand the FEL
  - Regular monitoring of integrity of in-beam devices as FEL power ramps up



- Additional observation
  - **Mechanical "hardstops"** should ensure mirrors cannot bend the FEL into unsafe directions → "hardstops" were not as hard as expected
  - Currently limit on FEL power by limiting electron power via ACM
  - Solution: add **limit switches**

Other Commissioning: Dark Current

- **Indication** from measured radiation that **Dark Current (DC)** between L1 and L2 **rose** by 5 to 10 since start
- **On-going studies** on DC in cryomodules (Mario Santana, Thomas Frosio)



- DC studies **important** for RP
  - DC source of beam loss:
    challenge to find physics arguments that limit dark current
  - With higher gradients of LCLS-HE cryomodules even more possibility for high DC
  - Knowledge of DC important for *Cryomodule Repair and Maintenance Facility* (CRMF) design

Upgrade to LCLS-HE

Still ramping up LCLS-II, already building on LCLS-HE

- Since cryomodule production was set up at Fermilab and TJNAL, easy to order more cryomodules for HE

- LCLS-HE is adding 23 cryomodules to existing 35 cryomodules from LCLS-II
- New cryomodules will run at higher gradient (from 16 MV/m to 20.8 MV/m)

  → top energy increases **from 4 GeV to 8 GeV**
- **Up to 240 kW in Linac**, up to 120 kW in each beamline and to first dump
- Cryomodules being delivered, installation in Long Downtime in 2026
  - NC LCLS will continue, LCLS-II will shut down December 2025
- **First light expected by October 2027 (electron beam)**

Upgrade to LCLS-HE: Radiation Protection

Shielding

- Some improvements to shielding needed
  LCLS-II was designed for up to the same 240 kW

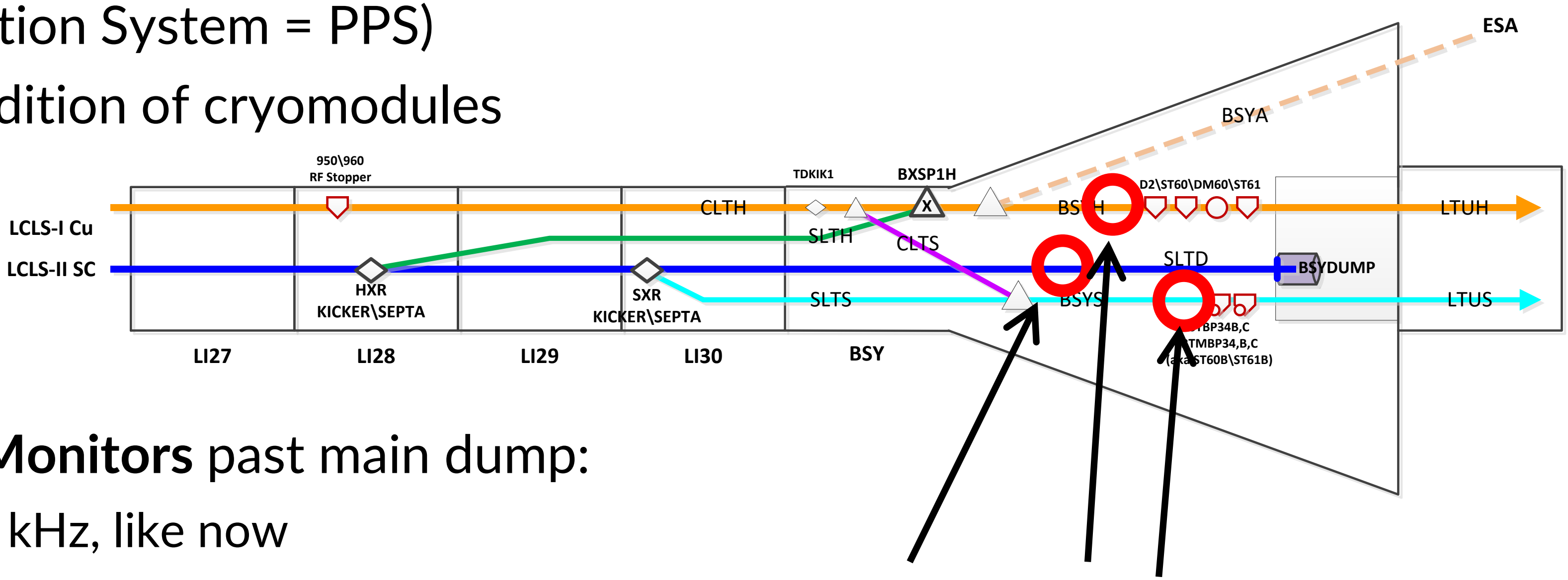
Dump Designs

- Were shown to be **safe for HE beam** (up to 120 kW)

Access Control (Personnel Protection System = PPS)

- **Minor adjustments** due to addition of cryomodules

Beam Containment System (BCS)



- Need **second LBLMs** next to new cryomodules
- **Additional Average Current Monitors** past main dump:
  - Each beamline limited to 120 kHz, like now
  - ACMs to be modified to trip not just on average current, but also on charge in pulse

Conclusion

- In process of ramping up LCLS-II electron beam
- New PBLM & LBLM radiation monitors are quite sensitive
- Challenges with LBLMs are being addressed
- Able to continue LCLS-II commissioning
  with additional PBLM radiation monitors, extra shielding, and limits on current
- Need commissioned LBLMs before further power ramp-up
- Electron beam power affects FEL beam power
- Separate program to ensure higher FEL beam power operates safely
- LCLS-HE: upgrade in energy and power requires relatively few upgrades to Radiation Safety Systems