Design of the LCLS-II-HE Photon Burn-Through Monitor Electronics

IBIC 2026 Contributed Talk

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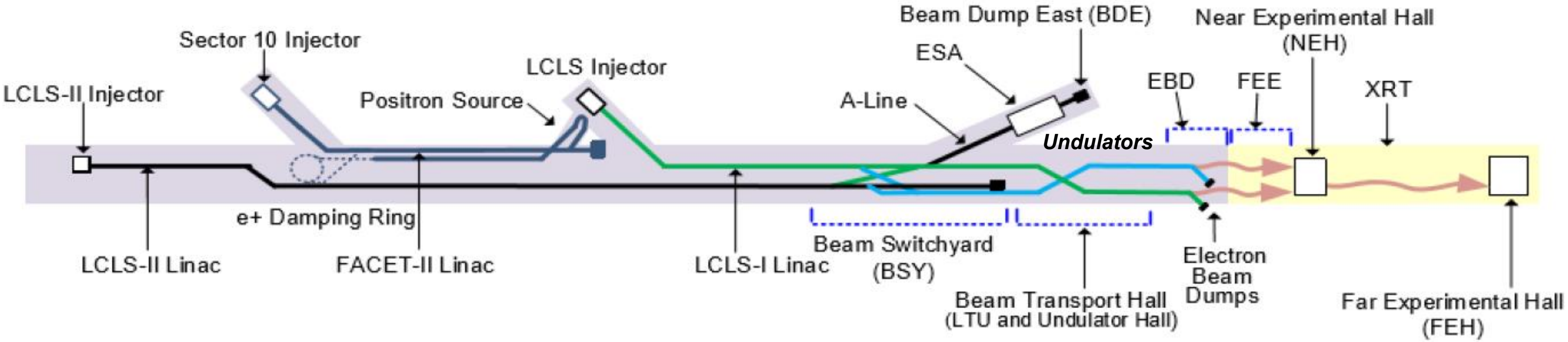
Outline

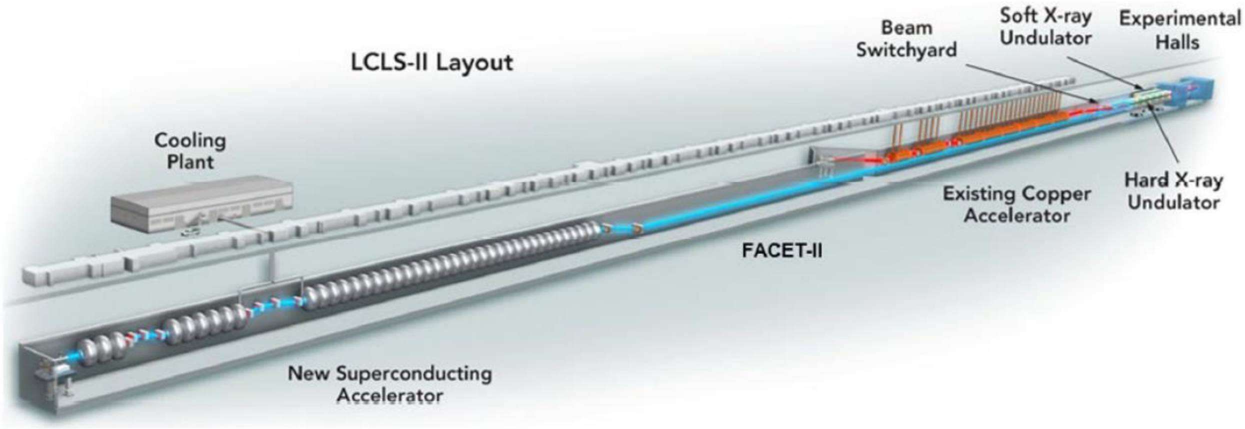
- Introduction to LCLS / LCLS-II / LCLS-II-HE
- SLAC Beam Containment System
- Burn-Through Monitors
- Our New BTM Detectors
- BTM Electronics Design
- Test Results
- Summary/Status

Introduction – LCLS / LCLS-II / LCLS-II-HE

- **LCLS**: SLAC's first X-ray free electron laser -- commissioned 2009: uses final 1/3rd of original SLAC 2.856GHz normal-conducting LINAC: Pulsed up to 120Hz (max), 14GeV e- beam fed Fixed-gap hard X-ray undulator
- **LCLS-II**: Commissioned 2023: Superconducting, replaced original first 1/3rd of NC Linac with 35 cryomodules, operating at 1.3GHz CW, 4GeV beam, up to 1MHz beam rate. New variable-gap soft X-ray, hard X-ray undulator upgraded to variable gap.
- **LCLS-II-HE**: Upgrade is *underway:* Adds an additional 23 cryomodules to LCLS-II, increasing the beam energy to 8GeV, soft X-ray undulator upgrades, X-ray transport & XPP instrument upgrades

Introduction – LCLS / LCLS-II / LCLS-II-HE





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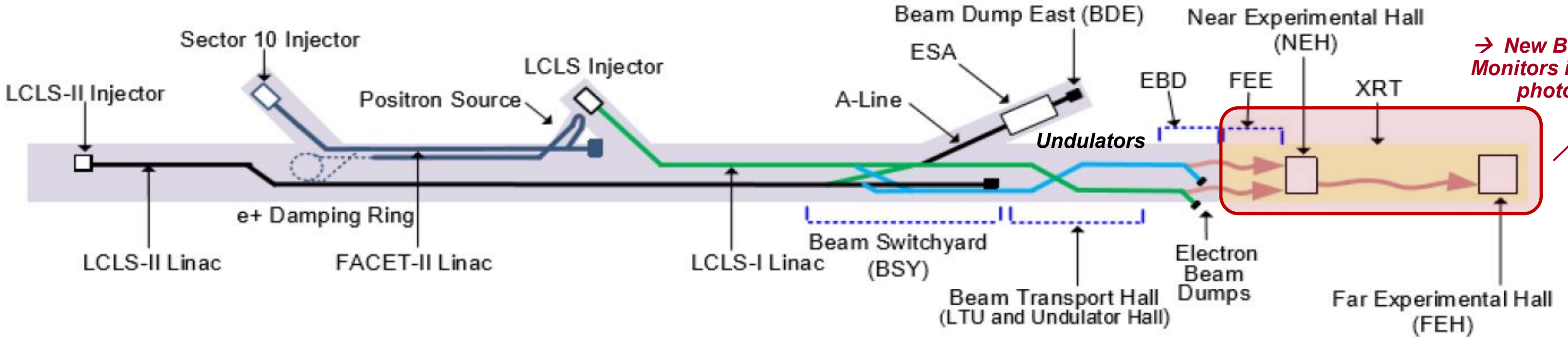
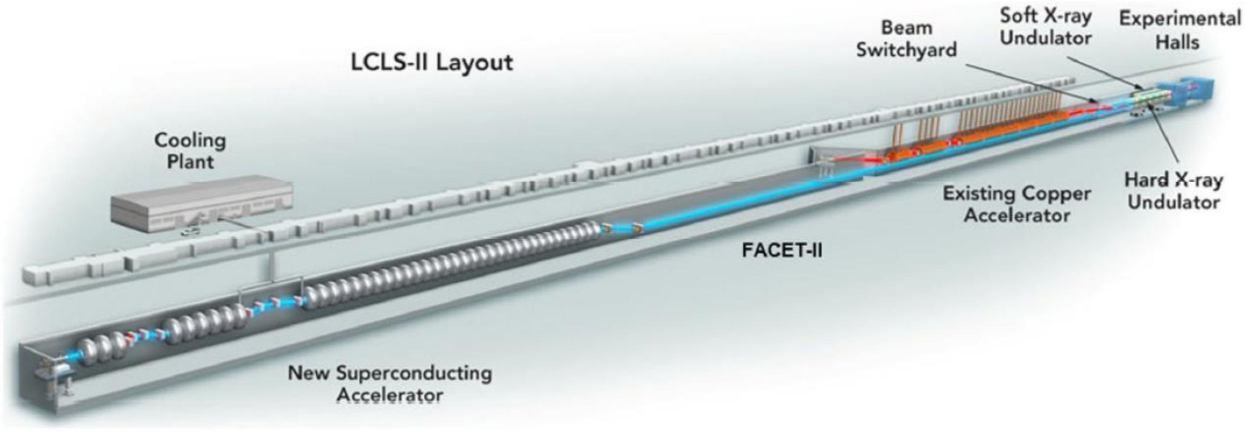




The SLAC LCLS-II Beam Containment System (BCS)

What is the Beam Containment System?

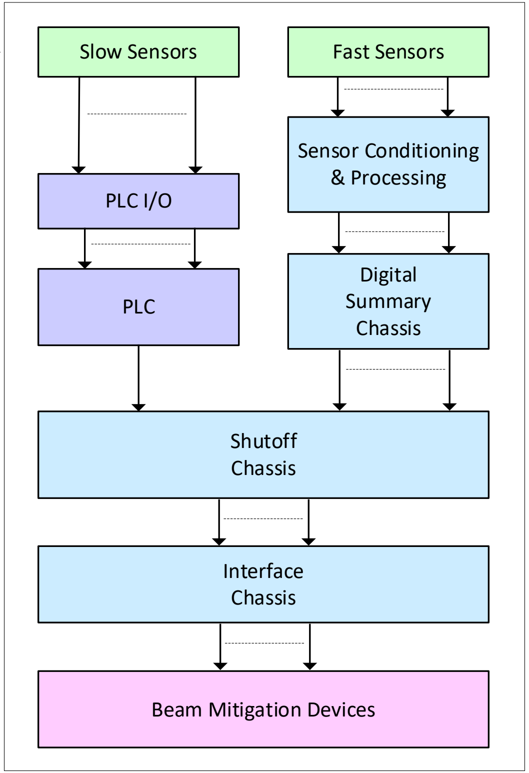
- It is a radiation safety system consisting of a set of mechanical and electronic restraints
- Designed to protect people outside of shielded areas (keeps the beam away from the people)
- A distributed system spanning the full 4km of the accelerator/XFEL facility (from the gun to the photon beam dumps)

→ The BCS Serves four main functions:

1) Limits personnel radiation dose outside of accelerator/XFEL housing from mis-steered beams (limits beam loss and stray beams)
2) *Protects the integrity of safety devices which contain the beam (stoppers, collimators, dumps)*
3) Limits the beam power and keeps it within designated safe channels
4) Acts to turn the electron beam off (and hence, X-ray beam) should an unsafe condition arise

The SLAC LCLS-II Beam Containment System (BCS)

BCS General System Diagram



Vacuum interlock, water flow, temperature, device position indicators, magnet current monitor

Beam loss monitors, average beam current monitor, **burn-through monitors**

Summary nodes: aggregates sensor status signals (logical AND)

Collects & Processes the all of the digital status signals and forms the beam permits

Devices: Gun RF Interrupt, gun photoinjector AOM, gun laser shutter, HXR kicker magnet interrupt

The BCS is a layered system:
Sensors → Processing → Mitigation Device

There are two main paths:
- Slow (> 500ms)
- Fast (< 200us)
(determined by system requirements)

Wherever possible, every layer has redundancy (including sensors): A & B chains

BCS Burn-Thru Monitors (BTM)

- Traditionally, burn-through monitors at SLAC have consisted of a gas-filled chamber or bladder placed in the back of, or adjacent to (in path of possible beam mis-steer) a safety system component (Stopper/Collimator/ Dump)
  - When the beam breaches the chamber's pressure boundary, a sensor would detect the pressure change and initiate a BCS fault
- These devices worked suitably well for electron beam containment at lower rates (120Hz max)

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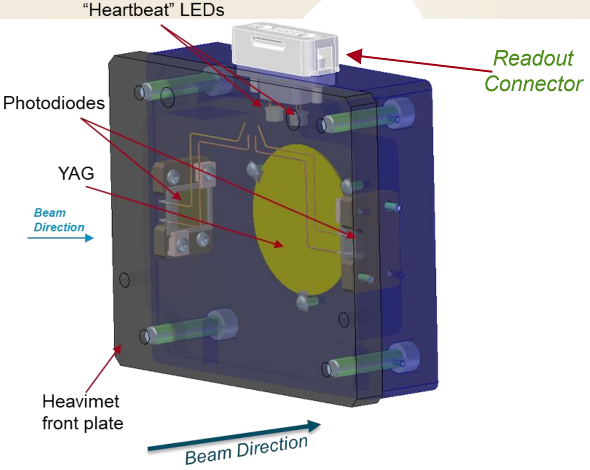
Motivation:

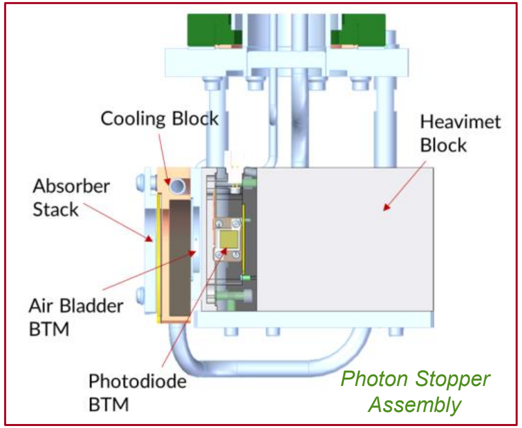
→ For LCLS-II and HE, the XFEL produces powerful X-ray beams at high rate (up to 1MHz), this type of BTM *will not respond fast enough* to detect and prevent a harmful beam condition

- The solution is to use an electronic BTM detector: the X-ray beam will interact with a material to generate a flash of visible light, which can be detected by a photodiode (concept borrowed from Eu-XFEL)
- We have developed three new BTMs:
  - Stopper
  - Collimator
  - Dump

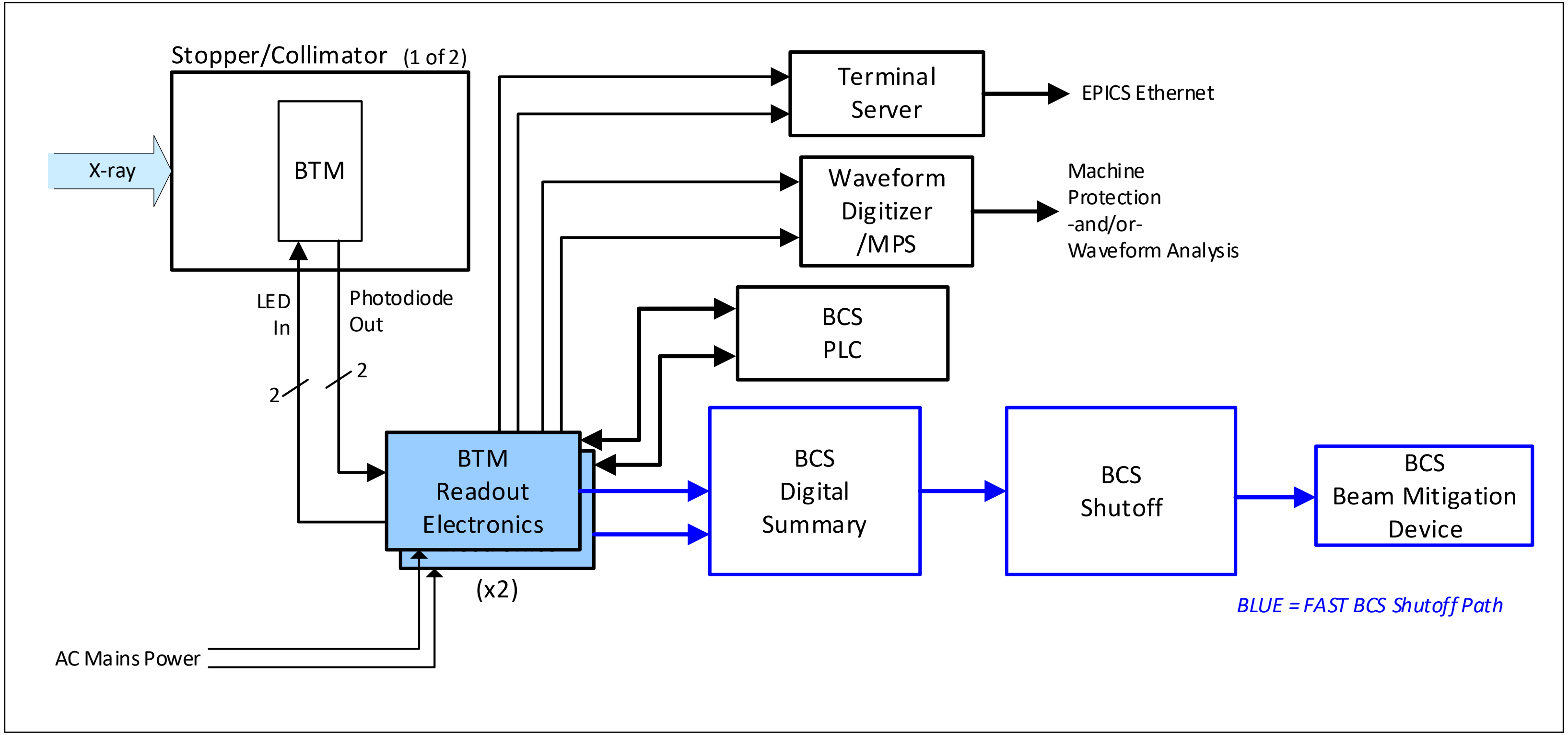
Photon Stopper BTM

- BTM Detector (part of the stopper) (115x130 cm) / Collimator is similar
- Stopper designed to handle 100W photon beam energy, indefinitely
  - Absorber stack: CVD Diamond (low energy beam) / SiC (high energy)
  - Water Cooled
  - Two Stoppers in series are inserted
- X-ray strikes the scintillator crystal, producing a flash of visible light detected by the photodiode
- The LED is part of the self-check mechanism: drives a low-level CW signal picked up by the PD, close to the noise floor
- Air-bladder BTM sits in front of it to provide secondary confirmation of a true burn-through event
- There are two Photodiode/LED pairs which are connected to (2) separate sets of readout electronics for redundancy
- PD = Hamamatsu S3590-08: 10x10 mm silicon photodiode: Response range = 340…1100 nm / LED = Marktech MTE5066WS-UR 660nm / YAG:Ce scintillator, peak emission: λ = 550nm; decay time ~100ns
- **Photon dump** is physically larger (0.6 x 0.6 m), uses gadolinium oxysulfide (GOS) scintillator & larger area photodiode (for lower expected signal levels)





Readout Electronics System Architecture



One Stopper Instance Shown

Electronics System Design

- Design uses core circuit elements from LCLS-II Beam Loss Monitor Systems
- Readout module is self-contained, packaged in SIM (Small Instrumentation Module) format / Dump version adds a preamp between detector and SIM
- Interfaces directly to the BCS system fast path: 24VDC fast opto-coupler (< 200usec)
- BCS PLC Interface:
  - Status: Digital Fault (raw & latched), Analog BCS Comparator Threshold Level (monitored and fault on anomaly)
  - Control: Fault Reset, Test Fault Generation
- Processed Photodiode Signal: Available to MPS and/or digitized for recording of events
- Serial Data Stream: Diagnostics, Fault status, settings, self-check status send to EPICS over RS-232 link; 1Hz update date (send only)
  - Specific EPICS PVs are alarmed and archived
- System follows strict BCS operational rules:
  - Configuration controlled -- Certain controls are designed to only be accessible via front panel: Comparator threshold setting, self-check drive and window compare thresholds / Access controls - Installed into a locked rack
  - Regular checks and system certifications

PD-BTM Electronics Packaging

Expert Console Interface
(USB to Laptop)

Processed PD analog out for diagnostics

BCS Comparator threshold level manual setting

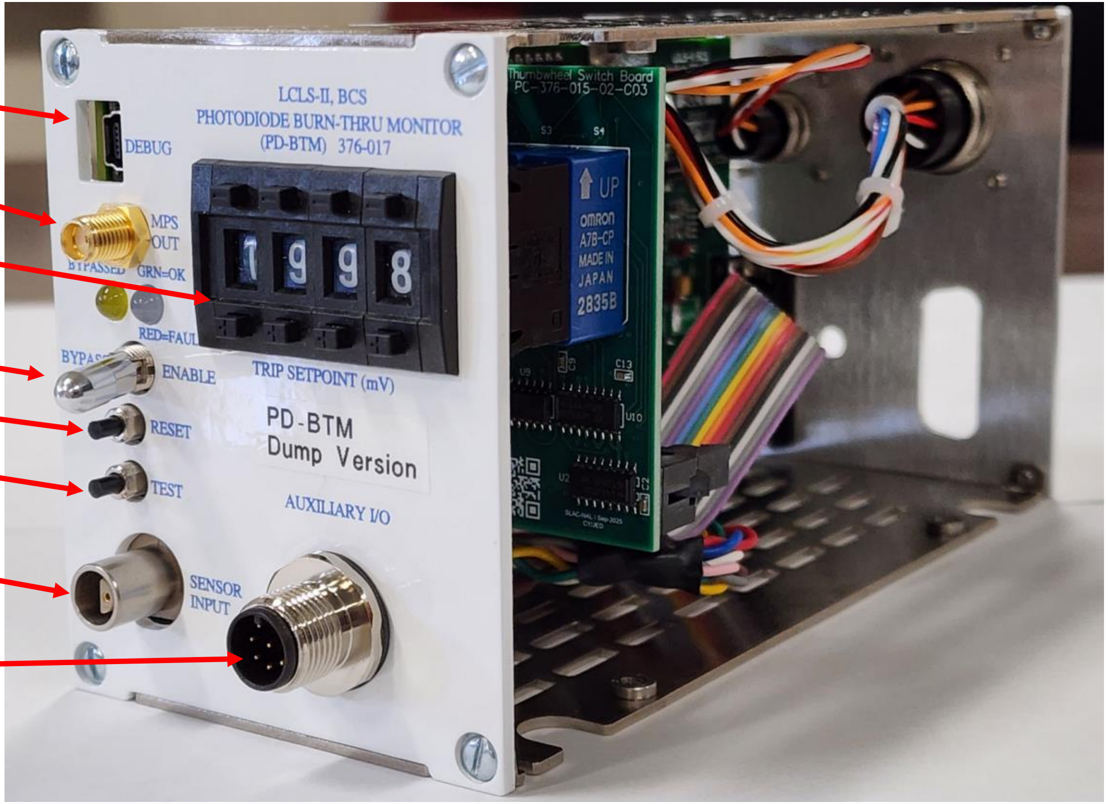
BCS Chain Bypass Switch

Fault Reset

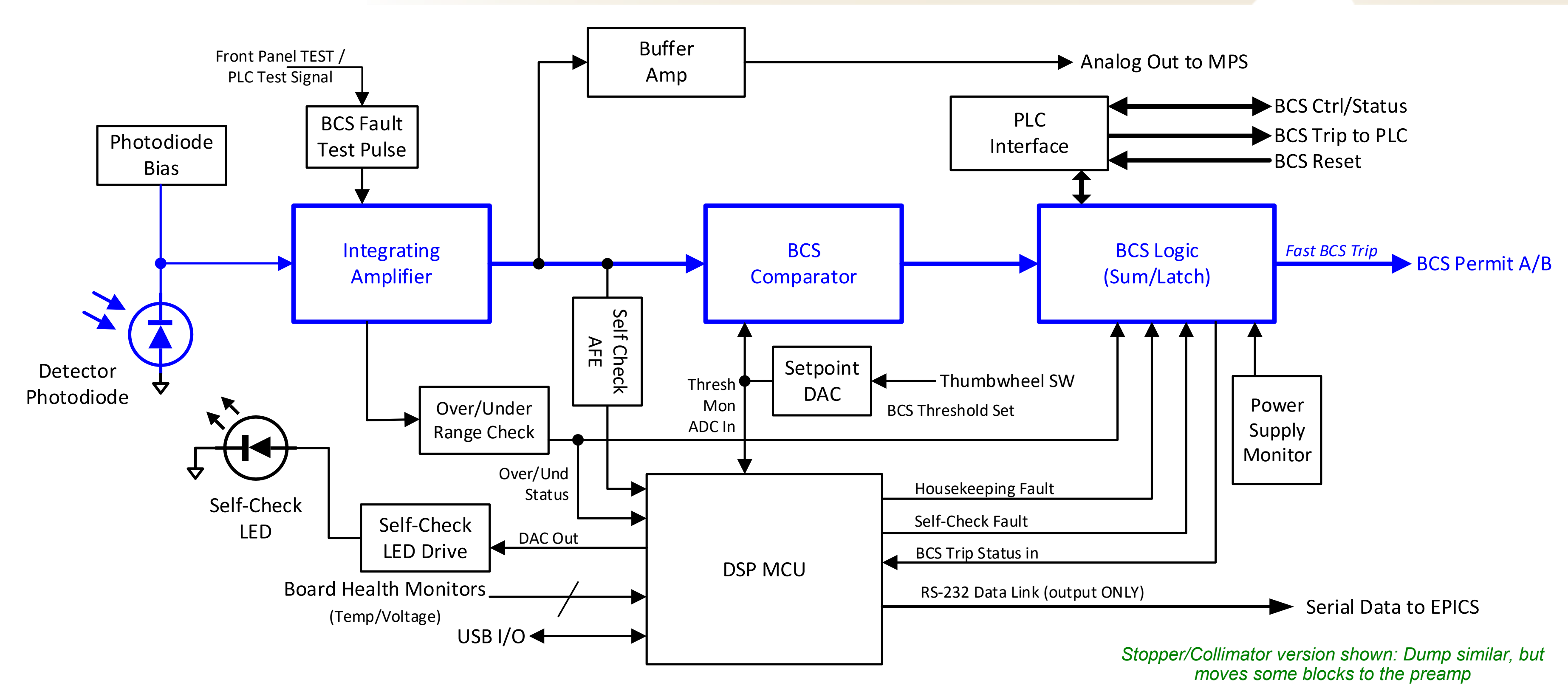
Test Fault Generate

<u>Sensor In</u>:
Stop/Coll: Photodiode I/O
Dump: Diff signal In

<u>Aux I/O</u>:
Stop/Coll: Self-Check LED
Dump: Self-Check LED + PD Bias readback, +24VDC preamp power



PD-BTM Electronics Design – Block Diagram



PD-BTM Electronics Key Features

Electronics Features & Functions:

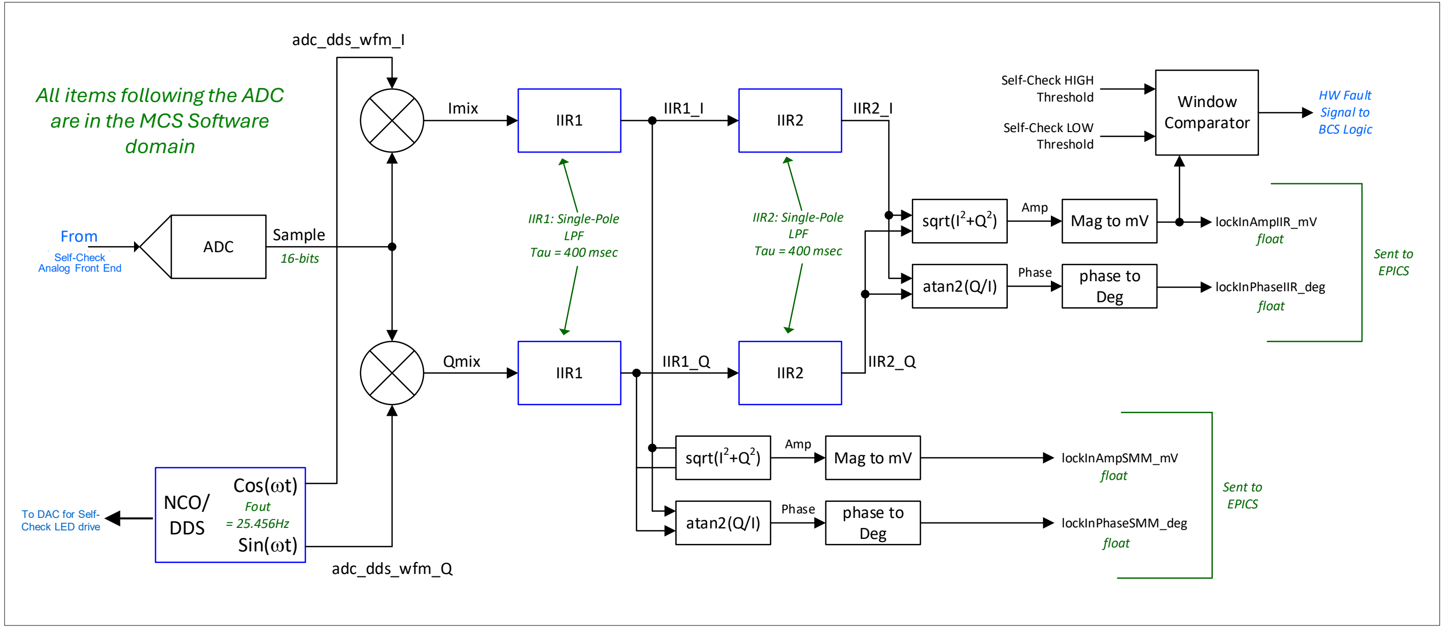
1) Generates DC Bias for the Photodiode
2) Photodiode charge signal is collected by fast analog integrator
3) Comparison of integrated PD signal against settable threshold (via DAC) using fast analog comparator
4) Self-Check of Detector & Signal Processing Chain
5) Built-in Test Fault Generation
6) All fault signals connect directly to fault logic
7) MCU: Handles status monitoring / data streaming / self-check mechanism
8) Board Health Monitoring (voltage, temperature, input signal range check)
9) Local USB console ifc for diagnostics & operating parameter setup

Self-Checking Mechanism

System Self-Checking:

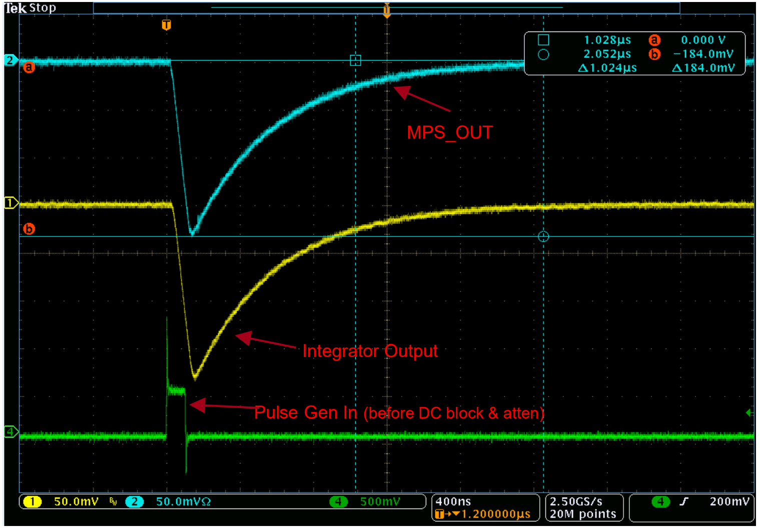
- Drives LED with low-level 25.456Hz sinewave using DSP MCU NCO, output on DAC
- Amplitude several orders of magnitude below lowest possible fault thresh / close to noise floor
- Using lock-in amplifier technique for signal recovery: allows for very low-level LED drive
- Signal picked off of integrator output, then analog bandpass filtered before MCU digitizes
- Can respond to self-check fault in < 2 sec

BTM Self-Check Lock-In Digital Signal Processing Chain



Test Results: Bench & X-ray Beam Tests

Stopper/Collimator Version Bench Test



Note: Pulse generator signal is fed into DC block + 20dB atten to give 50mV signal → expect -220mV peak integrated output pulse (with 470pF integ cap)

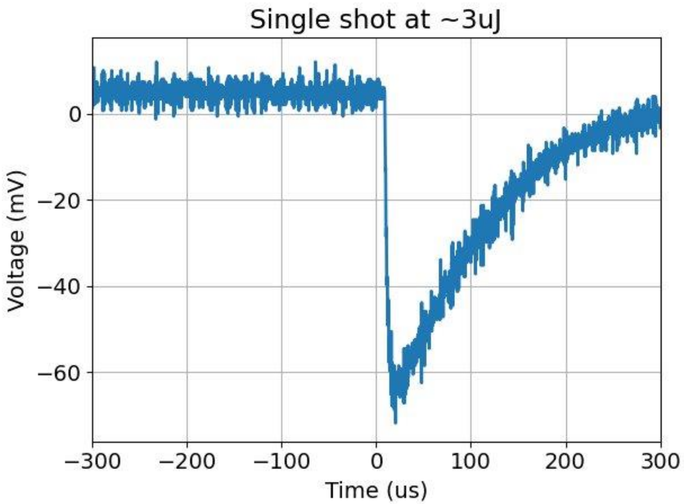
Setup: Pulse Generator →Stop/Coll SIM Module

Bench testing verified AFE, self-check mechanism, fault detection & processing. Agrees closely with SPICE sim

→ BTM Electronics Fault response measured </= 20µs

Integrated Dump System X-ray Beam Test (non-destructive) at XCS

Results from Digital Oscilloscope



Plot: M. Seaberg

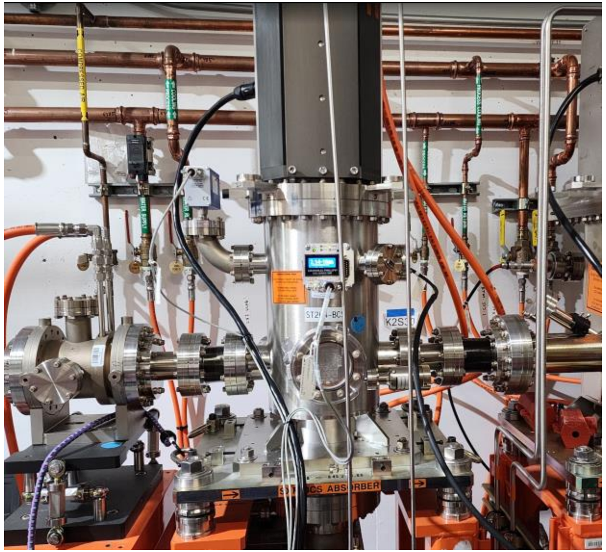
Signal is from X-ray → Scintillator → Photodiode → Electronics (Preamp + SIM) → LeCroy Digital Oscilloscope

This test was done to compare the calculated signal output vs measured: measured (14pC) results are 2x computed (7.5pC). Possibly due to additional signal from mirrored surface and potentially X-ray scattering/emission from hitting the diode

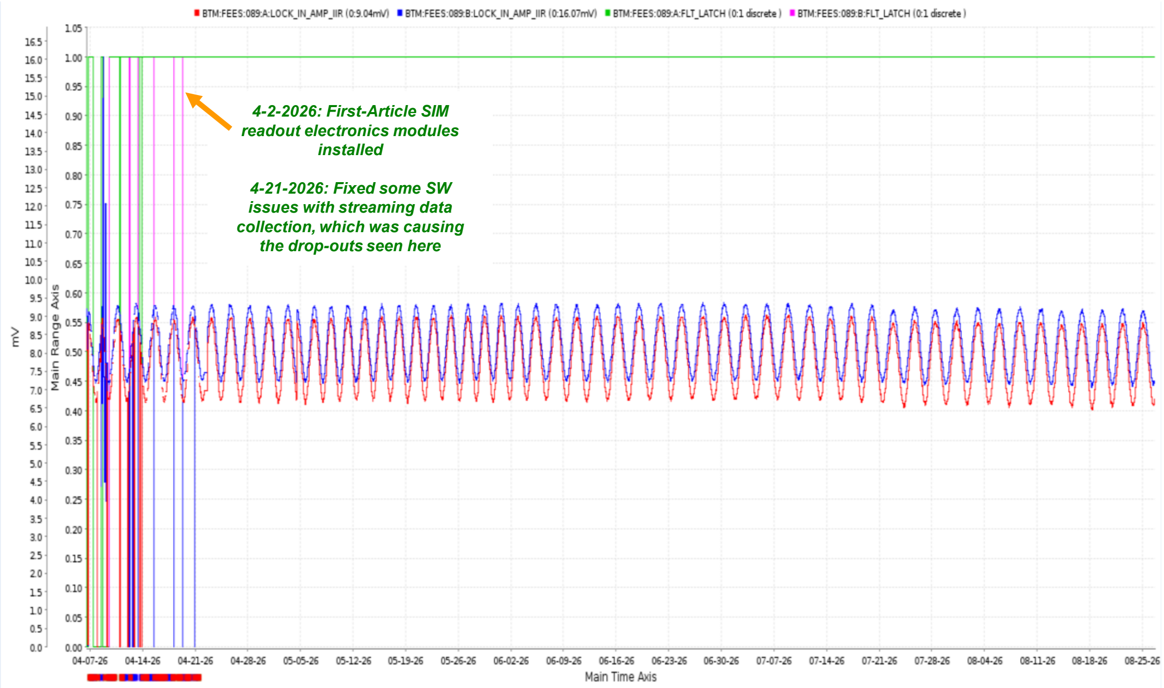
In-Situ System Tests at LCLS FEES Test Stopper

SLAC

First-Article Units installed at FEES test stopper, in April 2026 / EPICS Archiver plot shows history of fault signals and recovered self-check signal amplitudes



Soft X-ray beam test stopper in LCLS Front End Enclosure (FEE) / located just prior to the photon experimental hutches (near hall) / SIM electronics located ~150 feet away



EPICS Channel Archive of FEES PD-BTM units: Self-Check recovered signal & Fault Status (A=Red, B=Blue) & BCS Fault Status (A=Green, B=Cyan)

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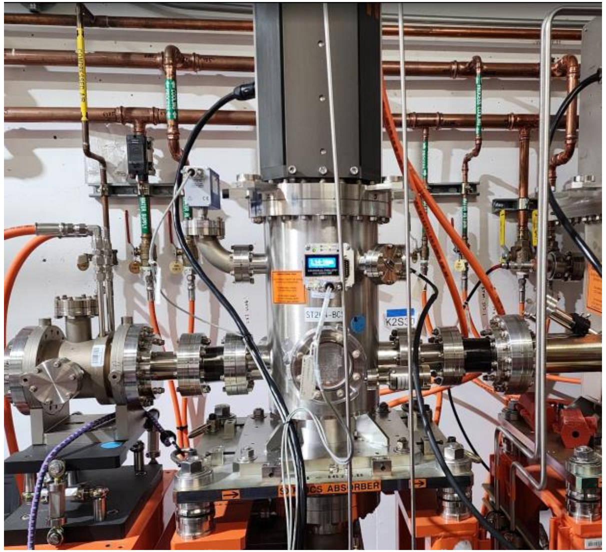

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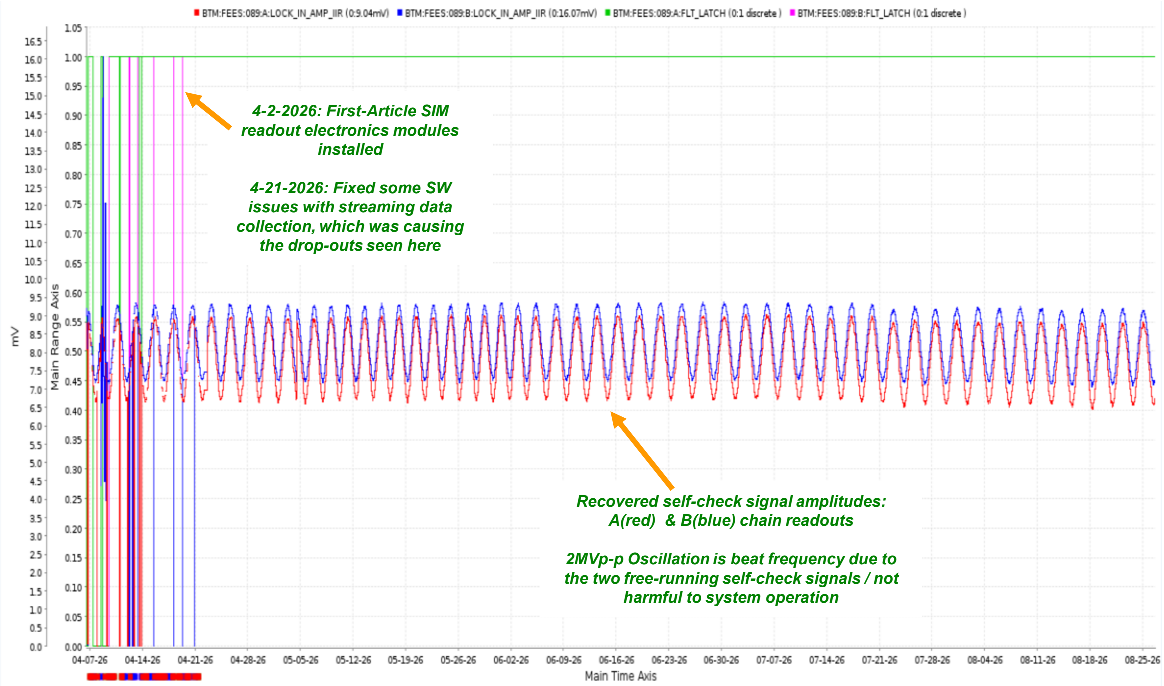

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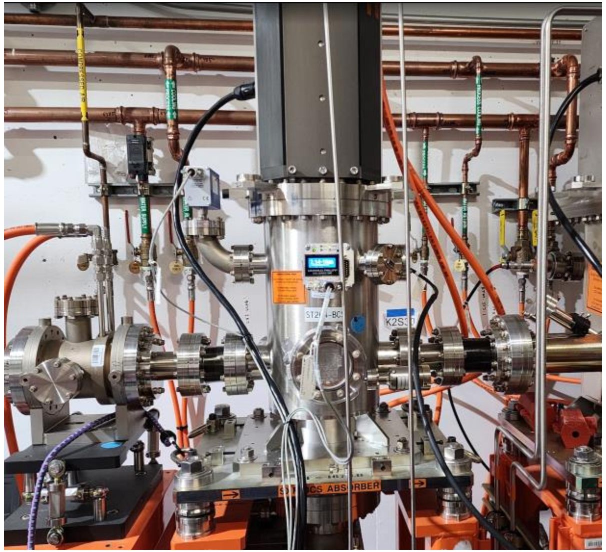

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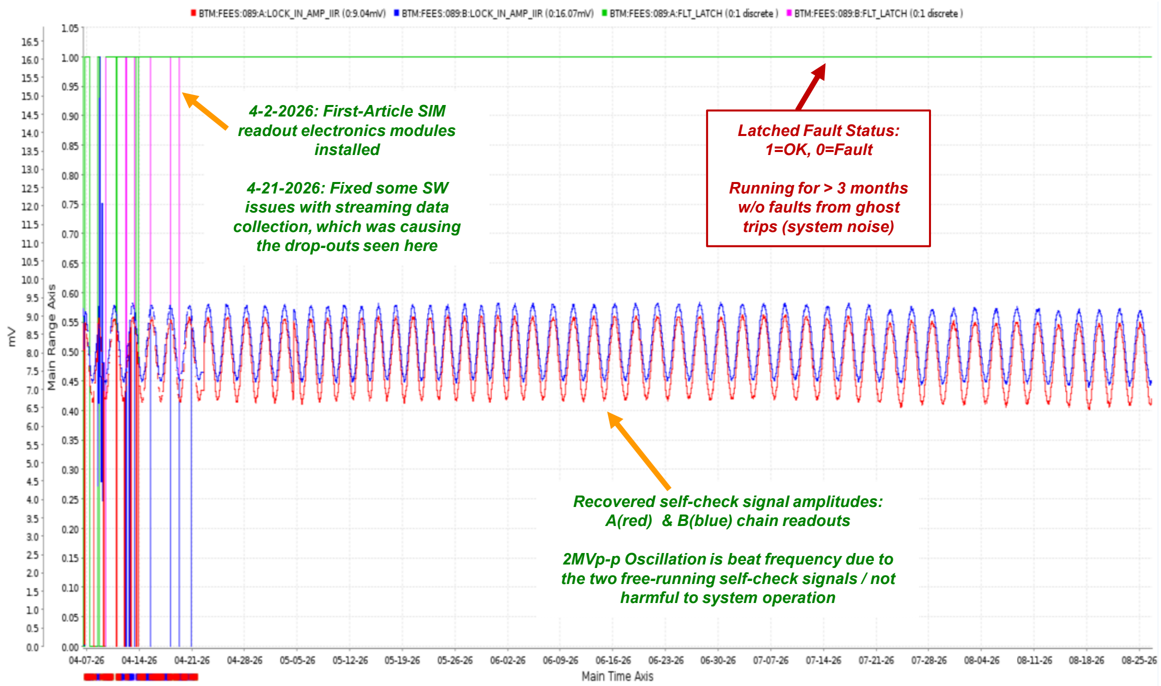

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Summary and Status to Date

SLAC

- We have developed a new type of BTM detector and its readout electronics
- Initial X-ray beam tests have demonstrated that it meets system requirements for performance and sensitivity
- Long-Term testing using FEES test stopper is underway
- Some noise issues were identified and fixed
- Prototype, First-Article & Pre-production electronics have been designed and tested
- Further beam tests scheduled for Stopper/Collimator/Dump to gather more data for threshold settings & verify prod HW this upcoming fall
- Preparing for production runs (60 units) → Installation begins May-2027

Acknowledgements – Photon BCS BTM Team

Diling Zhu	(Lead Photon BCS System Physicist)
Alyssa Prinz	(Rad Safety Physicist: initial BTM concept studies)
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Matt Seaberg	(Dump Physicist)
Yiping Feng	(Photon BCS Physicist)
Christine Clarke	(Original BCS Lead Physicist)
Ruslan Kadyrov	(Original BCS BLM/BTM Electronics Engineer)
William Langeveld	(Consulting Physicist - BTMs)

Thank you

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