Beam-Loss Detection for LCLS-II

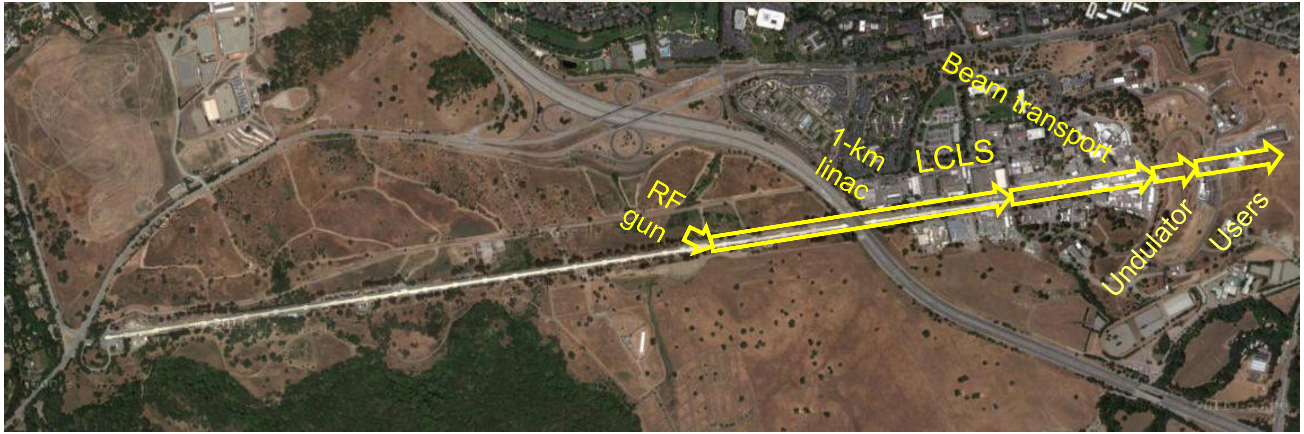
Alan Fisher
SLAC National Accelerator Laboratory

IBIC 2019
Malmö, Sweden
2019-09-10

Sharing the SLAC Linac

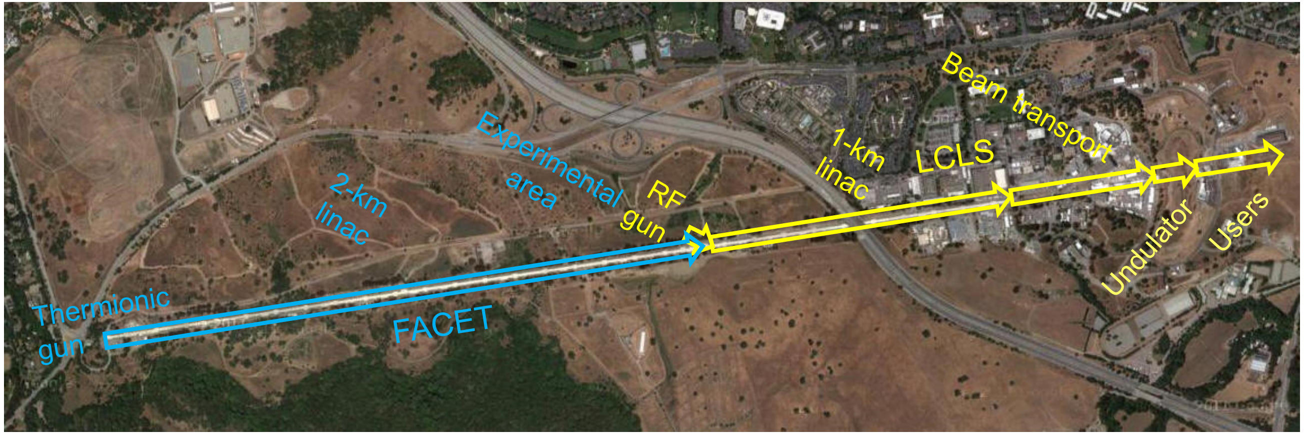
- Linac Tunnel and Klystron Gallery, 3 km 1962–

Sharing the SLAC Linac



- Linac Tunnel and Klystron Gallery, 3 km — 1962–
- LCLS, the first hard x-ray FEL, 3rd km — 2009–2018, 2019–

Sharing the SLAC Linac

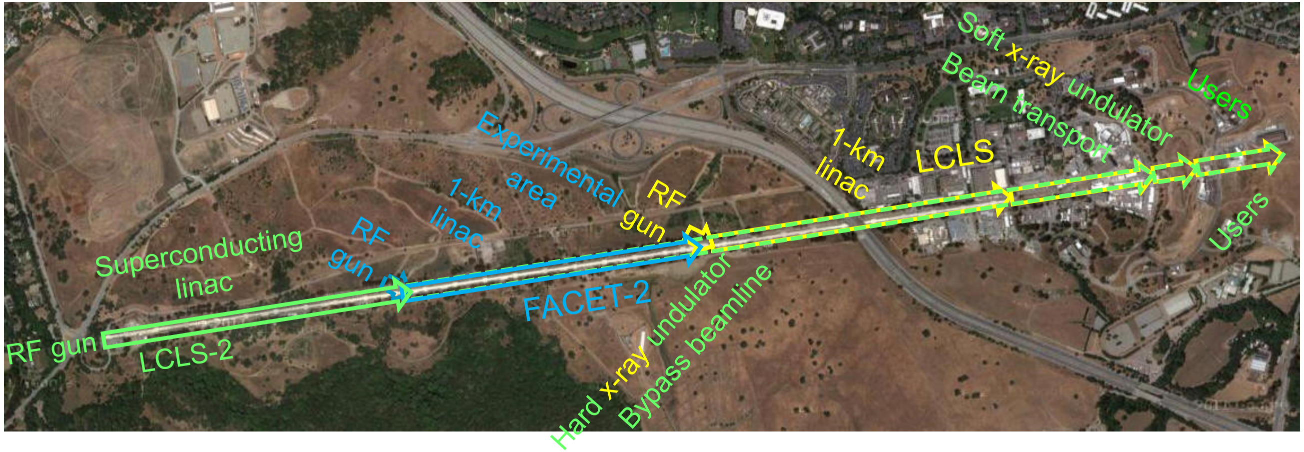


- Linac Tunnel and Klystron Gallery, 3 km — 1962–
- LCLS, the first hard x-ray FEL, 3rd km — 2009–2018, 2019–
- FACET, advanced acceleration tests, 1st and 2nd km — 2010–2016

Sharing the SLAC Linac

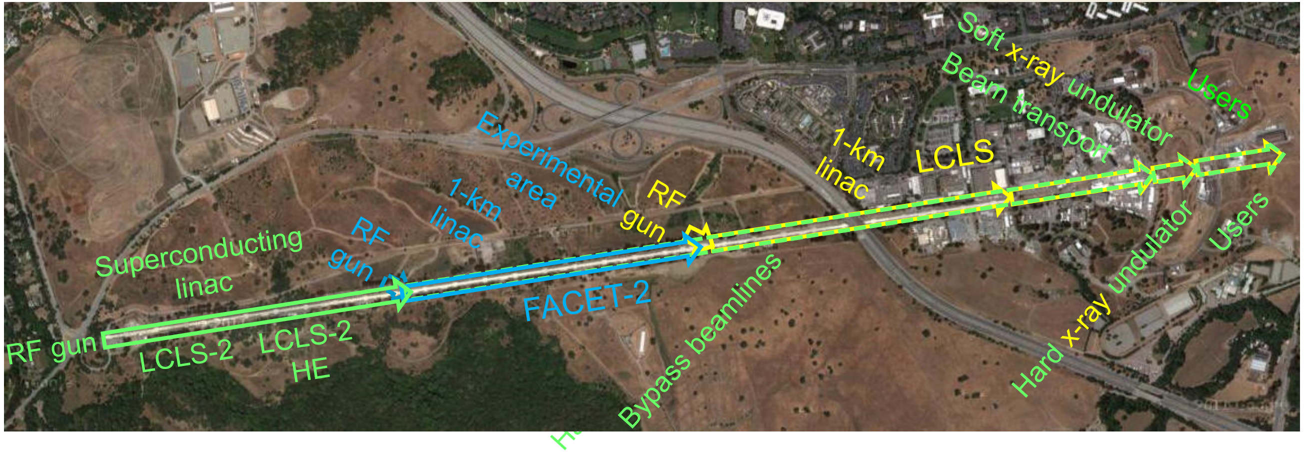
▪ Linac Tunnel and Klystron Gallery, 3 km	1962–
▪ LCLS, the first hard x-ray FEL, 3rd km	2009–2018, 2019–
▪ FACET, advanced acceleration tests, 1st and 2nd km	2010–2016
▪ LCLS-II, 4-GeV superconducting linac, 1st 700 m	2021–

Sharing the SLAC Linac



▪ Linac Tunnel and Klystron Gallery, 3 km	1962–
▪ LCLS, the first hard x-ray FEL, 3rd km	2009–2018, 2019–
▪ FACET, advanced acceleration tests, 1st and 2nd km	2010–2016
▪ LCLS-II, 4-GeV superconducting linac, 1st 700 m	2021–
▪ FACET-II, 2nd km	2020–

Sharing the SLAC Linac



- Linac Tunnel and Klystron Gallery, 3 km — 1962–
- LCLS, the first hard x-ray FEL, 3rd km — 2009–2018, 2019–
- FACET, advanced acceleration tests, 1st and 2nd km — 2010–2016
- LCLS-II, 4-GeV superconducting linac, 1st 700 m — 2021–
- FACET-II, 2nd km — 2020–
- LCLS-II HE, 8-GeV upgrade, 1st km — ≈ 2026–

Point and Long Beam-Loss Monitors

- PBLM Point Beam-Loss Monitor
  - Placed at likely loss sites
  - To prevent damage to collimators, stoppers, dumps
- LBLM Long Beam-Loss Monitor
  - To span the full machine in segments, from gun to beam dumps
    - To detect losses in less likely places
    - To identify loss locations
  - To protect people
    - In the Klystron Gallery, above penetrations from the linac tunnel
    - Outside the linac-to-undulator (LTU) transport line
      - A concrete bunker that is above ground and so less shielded than the linac tunnel

LCLS-II Beam-Loss Monitors Serve Three Functions

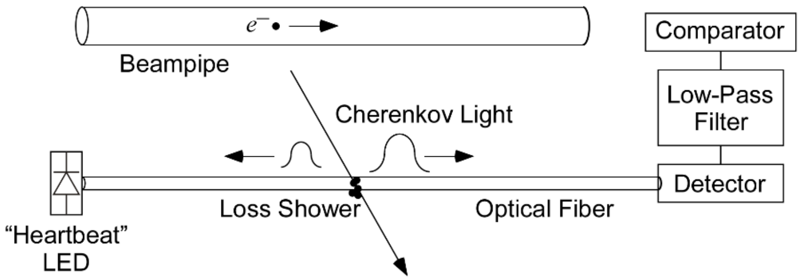
- BCS Beam Containment System
  - Stops the machine if beam goes outside its intended location or power
  - Simple trip logic, without software, without knowledge of timing or rate
- MPS Machine Protection System
  - Halts or rate-limits a beam path if losses exceed the threshold for machine damage
  - Trips before BCS: Threshold generally set 10 times lower
  - More intelligent: Uses software, knows beam timing and beam paths
- Diagnostic Signals
  - Help operators to tune: Display losses below trip threshold, indicate loss location
  - Reduce radiation on beamline components and outside the tunnel
  - Detect loss signals from fast wire scanners

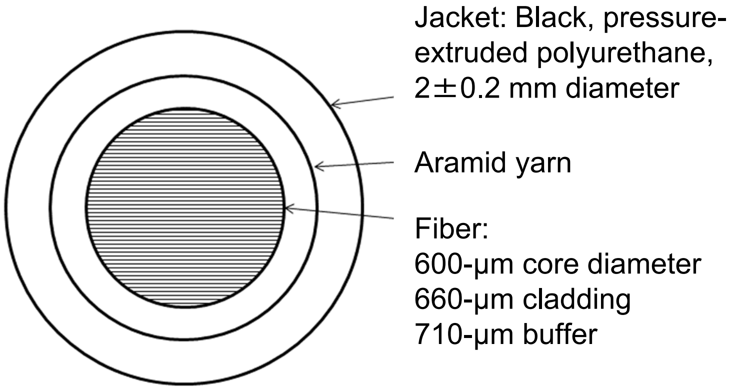
Beam-Loss Requirements for LCLS-II

- Loss detection at SLAC had always used ionization chambers, but:
  - Ionization chambers can have a nonlinear response to high loss power (IBIC 2016)
  - High losses at BCS thresholds: 100 W for PBLMs, and 35 to 1000 W for LBLMs
  - Dynamic range: Continuous RF may cause field-emission with significant power

	LCLS	LCLS-II	LCLS-II HE	
Repetition rate	0.12	929	929	kHz
Allowed beam power	0.5	120	250	kW
"Maximum credible" power	0.5	1100	2200	kW
Loss integration time	1	0.5	0.5	s
Trip time	8.3	0.2	0.2	ms

An Optical Fiber as a Long BLM





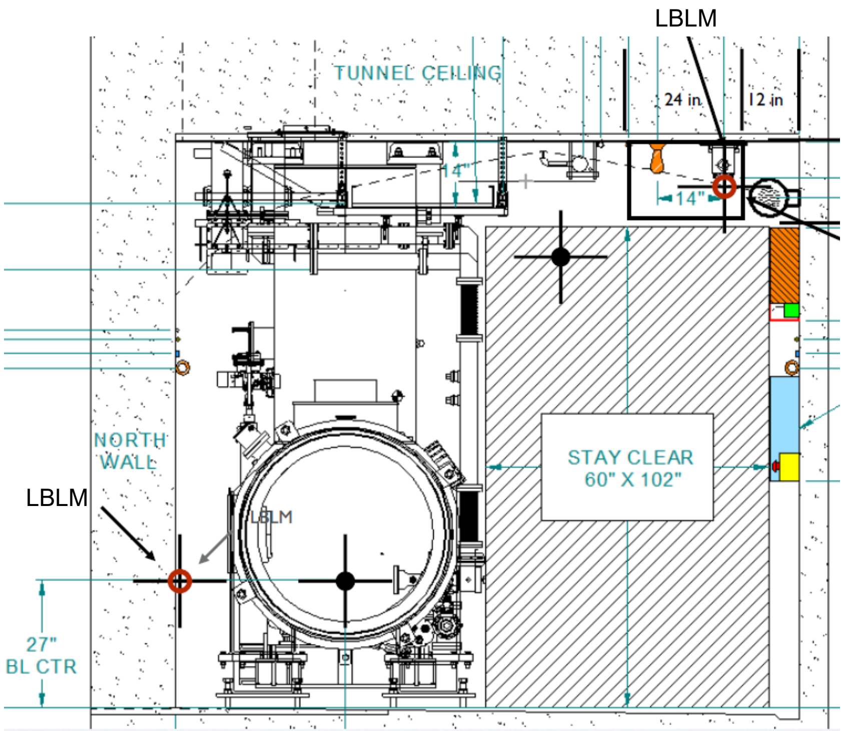
Polymicro
FPB-600660710

- Cherenkov light is emitted as a loss shower crosses the fiber
- Measure light at the end of the fiber
- Large-core fiber is used for a strong signal
- Radiation hard
  - Tested at up to 12.5 MGy for CERN
  - Used in the CMS end cap
- Unlike long gas-filled coaxial cables used as ionization chambers (SLAC's old LBLMs):
  - No pile-up from prior pulses
  - No gas: low maintenance, high reliability

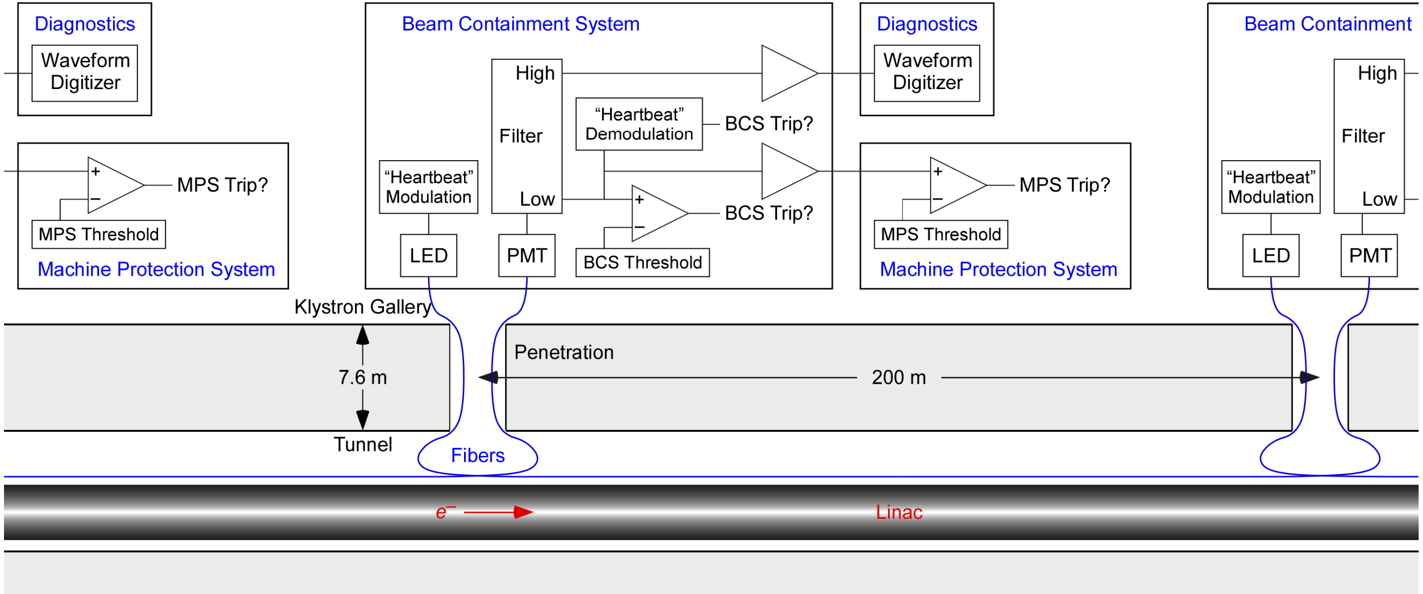
LBLMs Locations

- Divide the 4 km from gun to the beam dumps into sections of 200 m
  - But conform to functional zones:
    - Injector and L0 (linac 0)
    - Linacs L1, L2 leading to bunch compressors BC1, BC2
    - L3, dogleg, bypass…
- Usually 2 fibers, for redundancy and for different viewing angles

LBLMs in the Linac



Fiber Layout in Linac



- Fibers start and end in Klystron Gallery
  - No cables
  - PMTs are upstairs: no radiation, easy access
- Fibers are in 6-mm polyethylene tubes
  - Blown through tube by N_2 in a few minutes
  - Tube protects and allows easy replacement

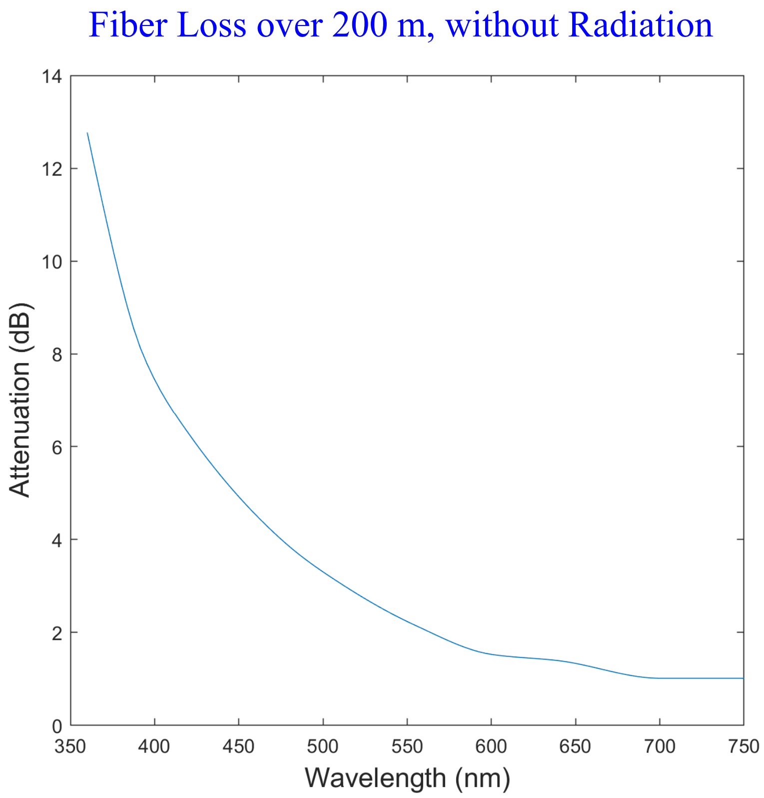
Installing the Fiber Tubes

On the Wall by the Linac

On the Ceiling above the Linac

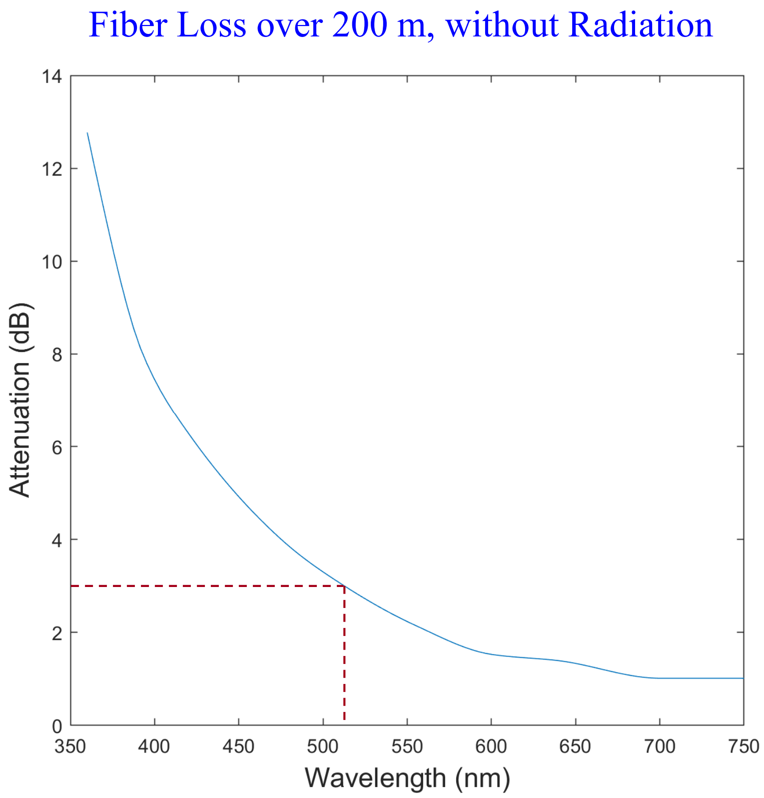
Attenuation in a 200-m Fiber

- Signals from losses near the two ends of the fiber should differ by ≤ 3 dB
  - For uniformity of calibration



Attenuation in a 200-m Fiber

- Signals from losses near the two ends of the fiber should differ by ≤ 3 dB
  - For uniformity of calibration
  - Too much attenuation for λ < 510 nm

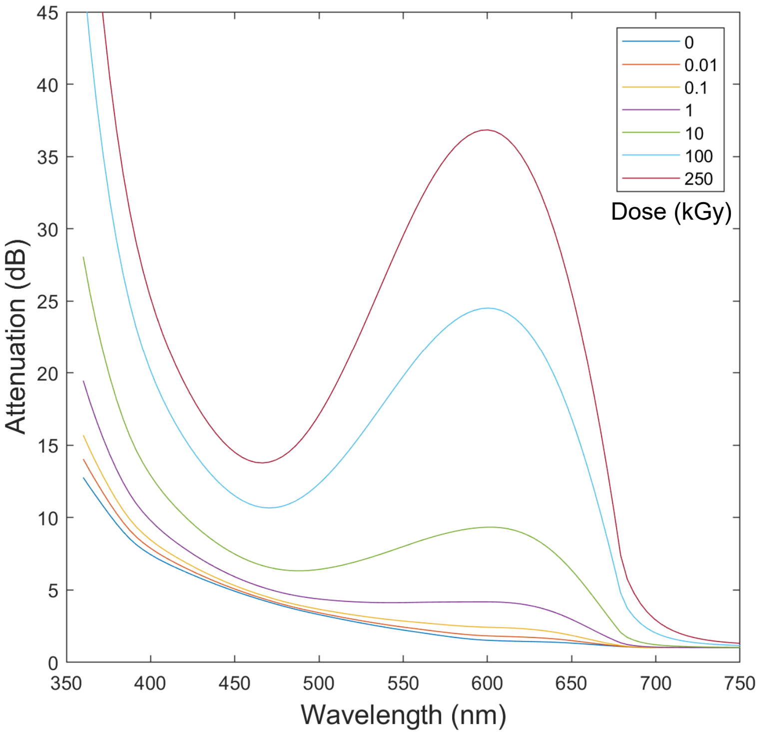


Radiation-Induced Attenuation in a 200-m Fiber

SLAC

- Signals from losses near the two ends of the fiber should differ by ≤ 3 dB
  - For uniformity of calibration
  - Too much attenuation for λ < 510 nm
- Add radiation-induced attenuation:
  - Assume 10 m of fiber sits 1 m from a hot spot and receives a steady loss at the MPS limit, but never trips

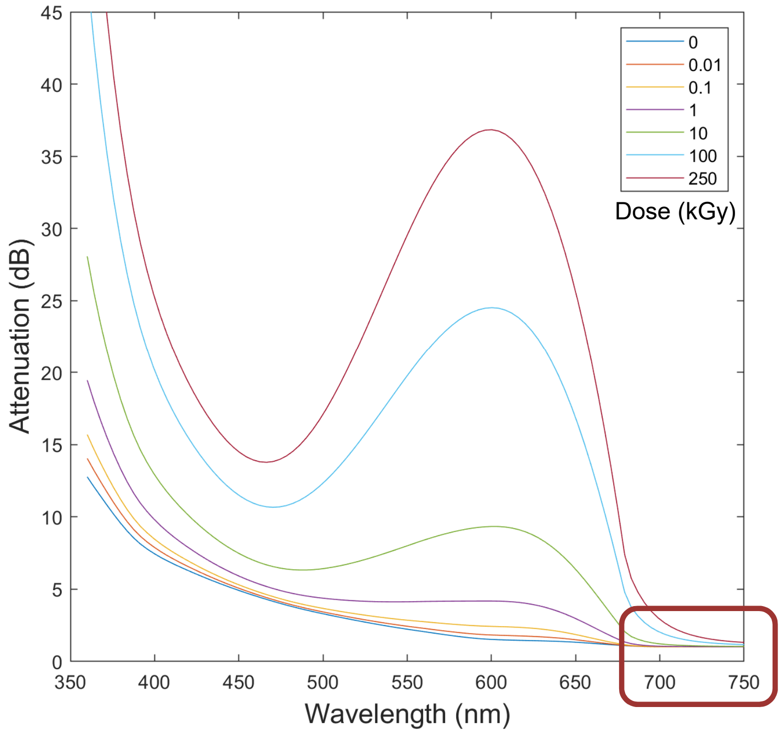
Fiber Loss with Different Doses (kGy) to 10 of 200 m



Radiation-Induced Attenuation in a 200-m Fiber

- Signals from losses near the two ends of the fiber should differ by ≤ 3 dB
  - For uniformity of calibration
  - Too much attenuation for λ < 510 nm
- Add radiation-induced attenuation:
  - Assume 10 m of fiber sits 1 m from a hot spot and receives a steady loss at the MPS limit, but never trips
- Use a red-sensitive photomultiplier
  - Use an optical filter to remove short wavelengths

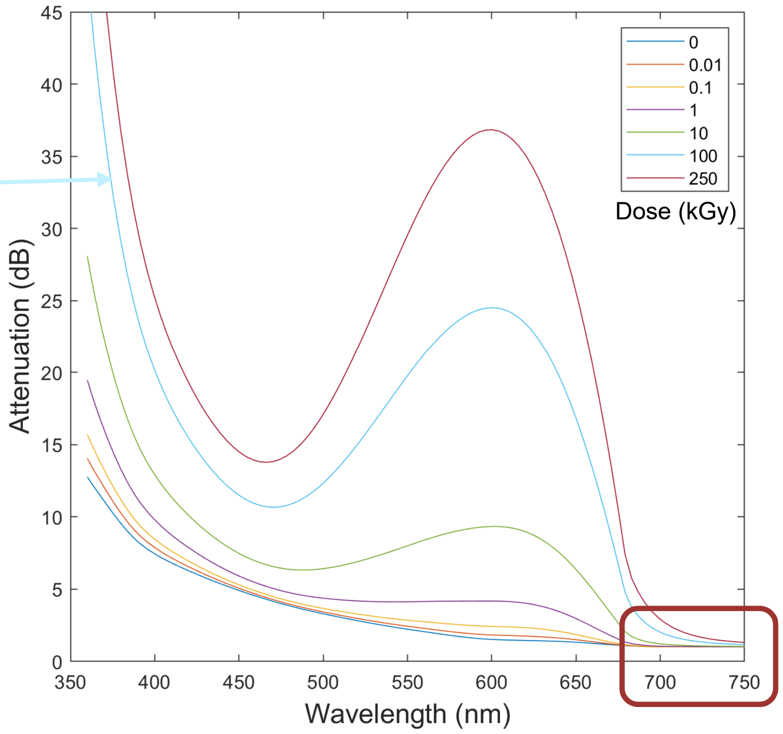
Fiber Loss with Different Doses (kGy) to 10 of 200 m



Radiation Dose versus Spectral Bandwidth

- Regions tolerating high radiation
  - Linac or beam switchyard (BSY)
  - High trip threshold
  - Fiber may get a high dose: 100 kGy
  - Optical filter passes only $\lambda \geq 675$ nm

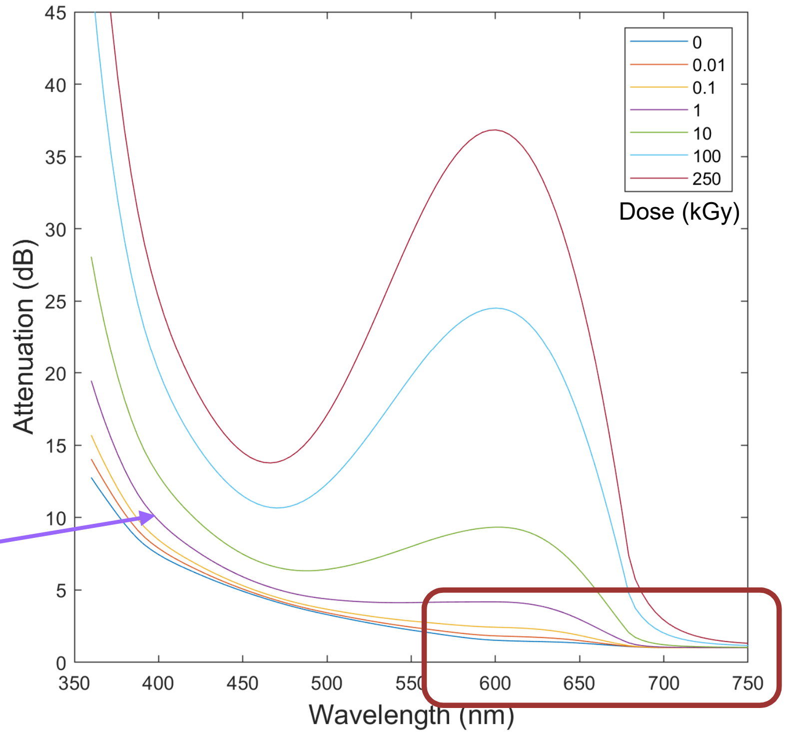
Fiber Loss with Different Doses (kGy) to 10 of 200 m



Radiation Dose versus Spectral Bandwidth

- Regions tolerating high radiation
  - Linac or beam switchyard (BSY)
  - High trip threshold
  - Fiber may get a high dose: 100 kGy
  - Optical filter passes only λ ≥ 675 nm
- Regions requiring low radiation
  - Linac-to-Undulator (LTU) transport hall
  - Low trip threshold
  - Fiber will not get a high dose: 1 kGy
  - Extend filter to λ ≥ 555 nm to get more signal from smaller losses

Fiber Loss with Different Doses (kGy) to 10 of 200 m



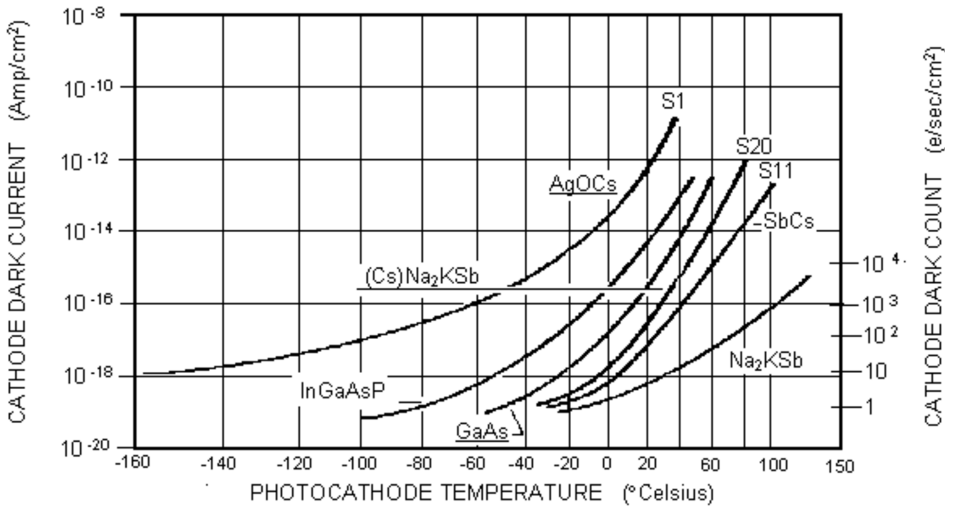
Red-Sensitive Photomultipliers and Dark Current

- Red-sensitive photocathodes also emit more dark current
  - Electrons are less tightly bound
  - Raises level of minimum detectable loss

Red-Sensitive Photomultipliers and Dark Current

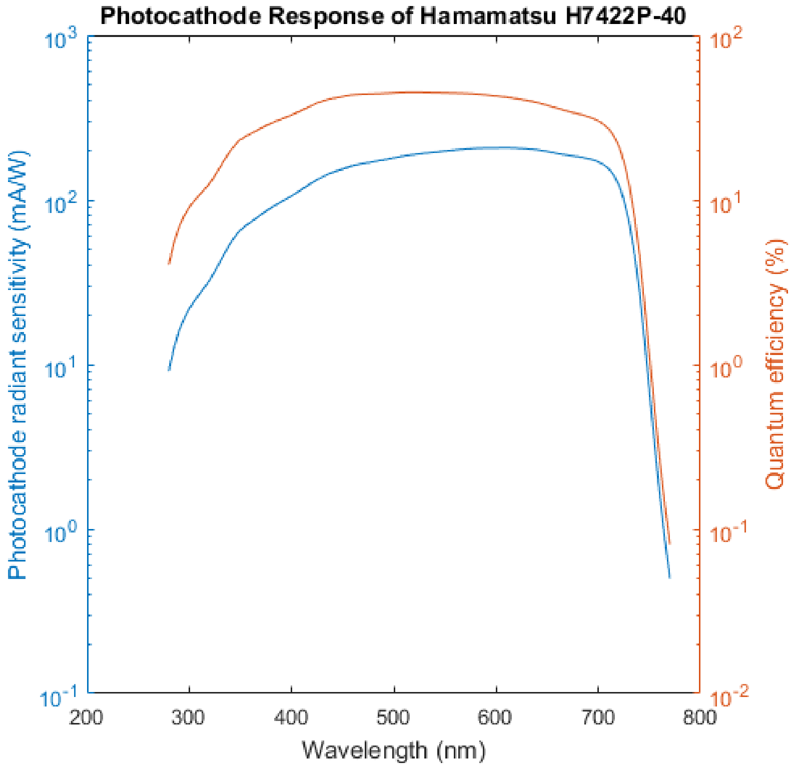
- Red-sensitive photocathodes also emit more dark current
  - Electrons are less tightly bound
  - Raises level of minimum detectable loss
- Dark current is thermal
  - Cool the PMT
  - Dark current drops by about a factor of 2 for every 5°C of cooling
    - Less benefit from cooling below 0°C

Dark Current vs. Temperature for Various Photocathodes



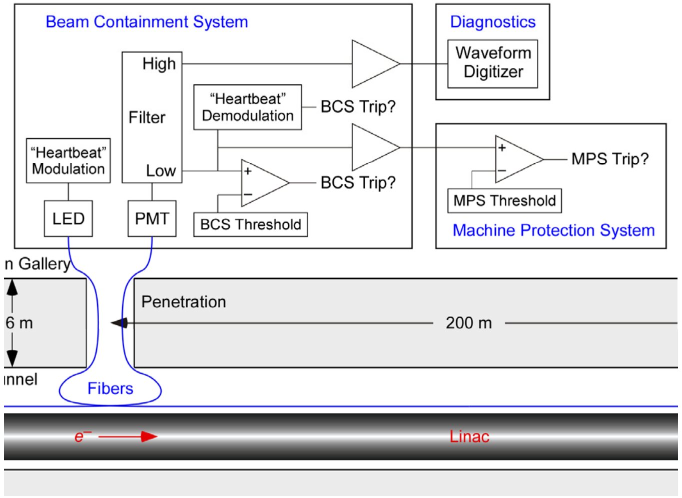
Choosing a Red-Sensitive PMT

- Hamamatsu module that combines:
  - Red-sensitive PMT
    - GaAsP photocathode
    - Quantum efficiency of 30% at 700 nm
  - Peltier cooler
    - Lowers PMT to 0°C
  - HV supply
    - +12 VDC and control voltage input provides HV for PMT

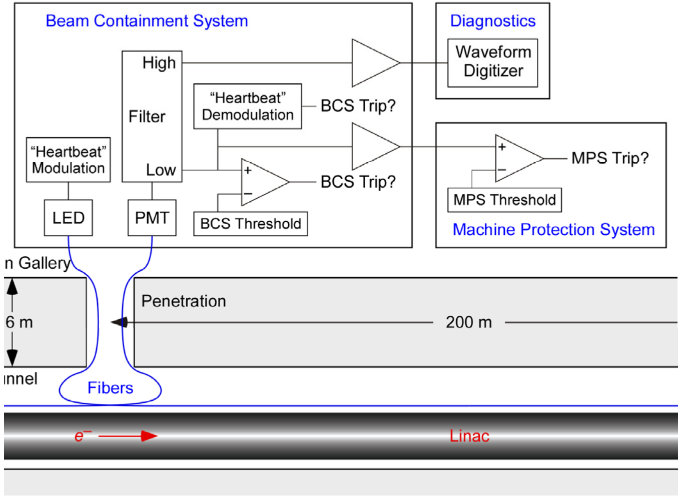


Low-Pass, High-Pass Filter/Splitter

- PMT current enters a passive *RC* filter/splitter:
  - Low frequencies integrated on a capacitor
    - 500-ms time constant
      - Determined by radiation safety and machine protection
    - BCS halts beam if capacitor voltage exceeds trip level
    - Voltage is buffered and sent to MPS
      - Trips at typically 10% of BCS level
  - High frequencies go to a 370-Msample/s digitizer
    - Waveform of loss signal versus time
    - Loss location: Indicated by arrival time of loss peak at PMT
    - Wire scans: Integrated loss peak from successive waveforms correlated with wire position



Continuous Self-Check: The Heartbeat



- BCS and MPS, as safety systems, require testing
  - An LED is at the upstream end of fiber
    - Drive LED with a small sinusoidal current at 0.8 Hz
  - Light reaches PMT at downstream end of fiber
  - Detect 0.8-Hz component from PMT with a DSP
    - Algorithm of a digital lock-in amplifier
      - Narrow-band filter, sensitive to a tiny excitation
    - Trip the beam if this "heartbeat" is missing
    - Archive the demodulated amplitude: Degradation of fiber or PMT over time
      - Blow in a new fiber if needed
  - 0.8 Hz was chosen because it passes through the 500-ms *RC* integration
    - AC power line synchronizes LED drive and DSP detection over 200 m: 0.8 Hz = 60 Hz / 75

Testing the Fibers

- Tests with 100 m of fiber along copper linac and 150 m along BSY
  - Created losses with corrector magnets and with collimator: Localization to ≈3 m
  - Measured wire scans (with old LCLS electronics)
  - Tested new LCLS-II electronics

Testing the Fibers

- Tests with 100 m of fiber along copper linac and 150 m along BSY
  - Created losses with corrector magnets and with collimator: Localization to ≈3 m
  - Measured wire scans (with old LCLS electronics)
  - Tested new LCLS-II electronics
- BSY fiber had a PMT at both ends, to compare forward and backward signals
  - Backward signal: 5 times larger difference in arrival time for losses from two points
    - Simple compensation for the forward signal: Zoom in
    - Zoom limited by PMT rise time and digitizer bandwidth, but sufficient for 3-m localization
  - Forward signal: 4 times larger since loss showers are mostly forward directed
    - Our PMT will go at the downstream end of the fiber

Testing the Fibers

- Tests with 100 m of fiber along copper linac and 150 m along BSY
  - Created losses with corrector magnets and with collimator: Localization to ≈3 m
  - Measured wire scans (with old LCLS electronics)
  - Tested new LCLS-II electronics
- BSY fiber had a PMT at both ends, to compare forward and backward signals
  - Backward signal: 5 times larger difference in arrival time for losses from two points
    - Simple compensation for the forward signal: Zoom in
    - Zoom limited by PMT rise time and digitizer bandwidth, but sufficient for 3-m localization
  - Forward signal: 4 times larger since loss showers are mostly forward directed
    - Our PMT will go at the downstream end of the fiber
- Dark current seen in a section of LCLS copper linac and in a JLab cryomodule

Modeling the Fibers

- We use FLUKA to model particle fluences from beam-loss showers
  - Added a routine modeling Cherenkov emission and light capture by fiber
- Capture is most efficient when shower crosses fiber at an angle near 45°
  - Part of Cherenkov cone then aligns with the fiber axis
  - Rising edge of loss signal is captured by fiber near the source point

A Diamond Detector as a Point BLM

- Metallized diamond chip, 4×4×0.5 mm^3 for the single-crystal (B1) type
- Radiation creates electron-hole pairs, which are collected by a bias voltage
  - Electrons and holes have high mobilities and cross the thin chip quickly
    - Like a solid-state ionization chamber, but fast: Few-ns pulses
- Large dynamic range
  - 1 to 10^6 MIPs (minimum ionizing particles)
- Unlike ionization chambers (SLAC's old PBLMs):
  - No pile-up from prior pulses
  - No gas: low maintenance, high reliability

Civided B1HV

Low-Pass Filter/Splitter

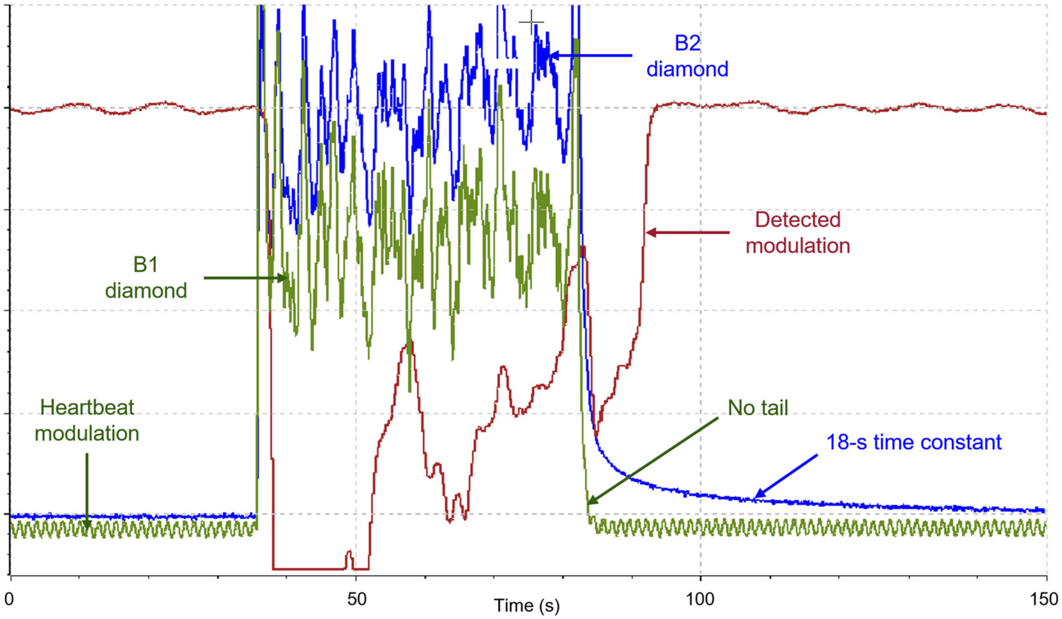
- As with LBLM, current from a diamond enters a passive *RC* filter/splitter:
  - Low frequencies integrated on a capacitor
  - High-frequency output is not needed
    - Loss localization is not useful for a point detector

Continuous Self-Check: The Heartbeat

- Like the LBLM, the PBLM is a safety system and requires full-system testing
  - Modulate the bias voltage sinuosidally at 0.8 Hz
    - We use −250-V bias for the B1, modulated by ±2.5 V
    - Full charge is always collected, with a slight change in the few-ns collection time
  - Capacitance of diamond (3 pF) gives a small current at this frequency
  - As with the LBLM, we detect the 0.8-Hz component of signal with a DSP

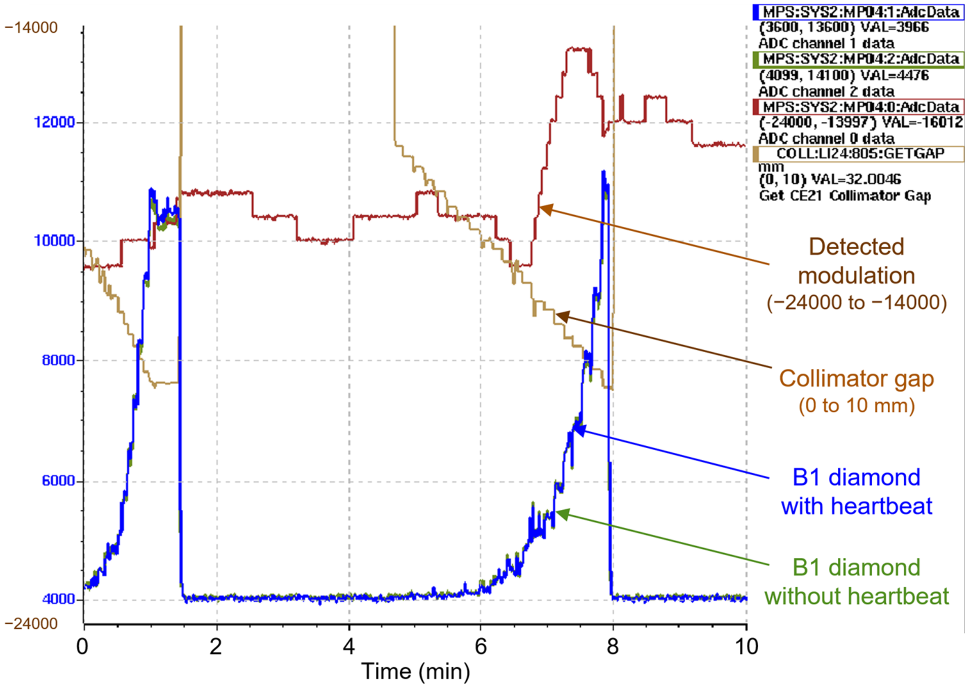
Polycrystalline versus Single-Crystal Diamond Detectors

- ≈1 W of beam (<< MPS trip level) scraped at energy collimator (LCLS BC2)
- Beam rate quickly toggled between 0 and 120 Hz
- Cividec B2, polycrystalline
  - 18-s decay tail
- Cividec B1, single crystal
  - Much better: No tail
- Also, first test of heartbeat
  - Modulating B1 bias voltage



Improved Heartbeat

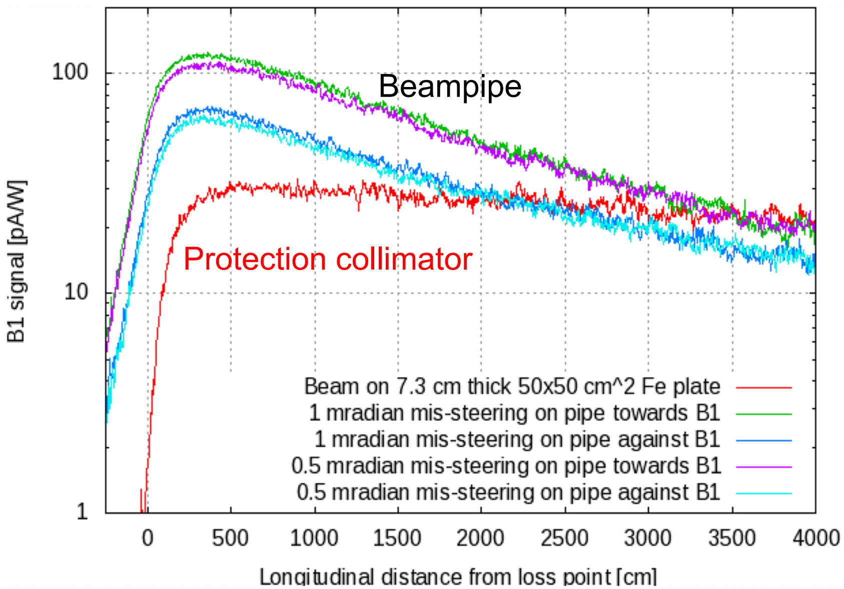
- Improved analog and digital filtering now makes the heartbeat invisible
  - Two B1s, side by side on beamline
    - Blue has heartbeat modulation
    - Green has no modulation
- Robust detection of the heartbeat
  - Settling time of 1 to 2 minutes
    - Suitable for the self-check



Modeling the Diamonds: Area Coverage

- Protection collimators are used after the linac and transport lines, where two or more beamlines are close together
- Extension to FLUKA computes B1 diamond signal from a loss shower
  - Uses Cividec data on creation of *e-h* pairs
- Signal is nearly constant downstream of loss on protection collimator, for >20 m
  - Diamond is 1.5 to 2 m from beamline
  - Experimental test in End Station A
- Each diamond can cover an area, rather than a single protection collimator

Beam-Loss Model



Summary

- SLAC has depended on ionization chambers for its beam-loss safety systems
- For LCLS-II, beam-loss monitors using newer technology have been approved after extensive testing:
  - Long BLMs: Optical fibers with photomultipliers
  - Point BLMs: Diamond detectors
- Electronics have been developed to share these signals for three functions:
  - Beam Containment System
  - Machine Protection System
  - Diagnostics