Beam Containment and Machine Protection for LCLS-2

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IBIC 2017 — Grand Rapids
2017-08-24

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

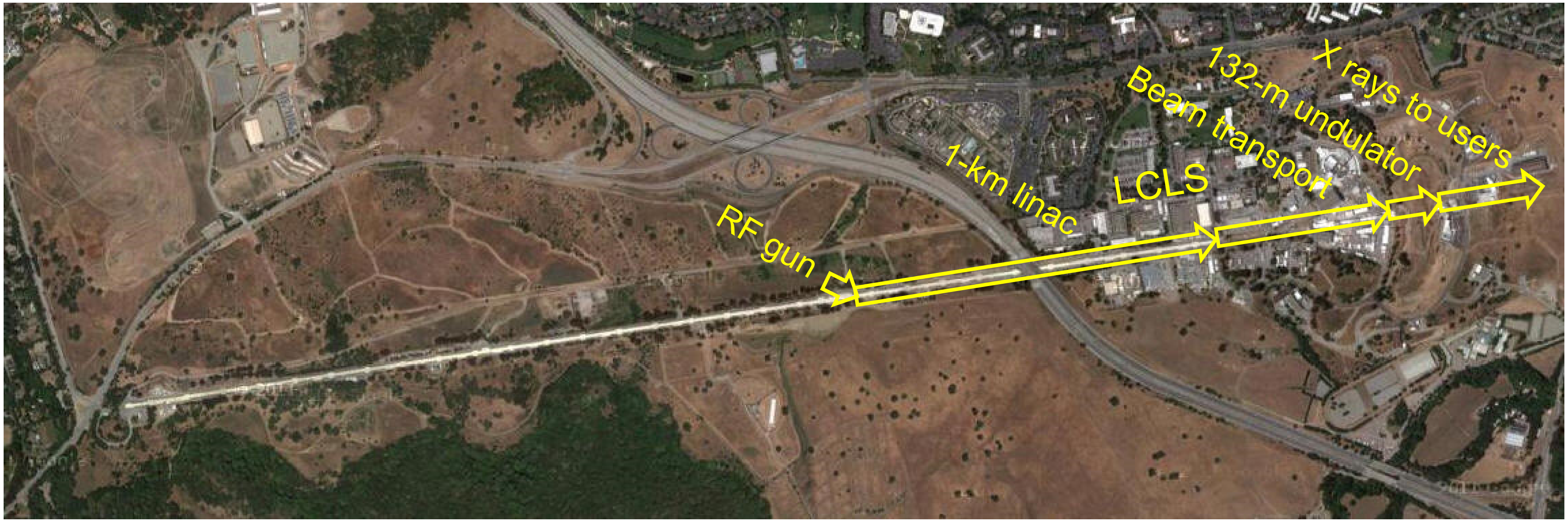
SLAC and San Francisco Bay

Sharing the SLAC Linac

Sharing the SLAC Linac

- SLAC, Klystron Gallery and Linac Tunnel, 3 km: 1962–

Sharing the SLAC Linac



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- LCLS, 3rd km: 2009–

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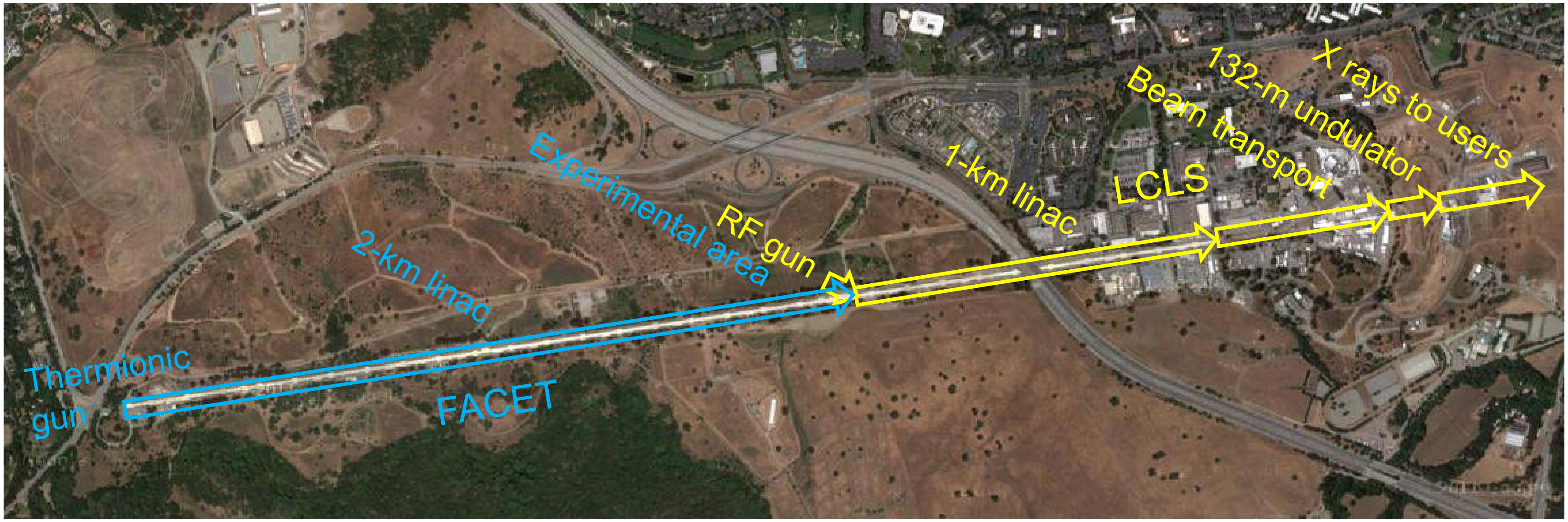

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- FACET, 1st and 2nd km: 2010–2016

Sharing the SLAC Linac

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- LCLS-2, 1st km: ≈ 2019–

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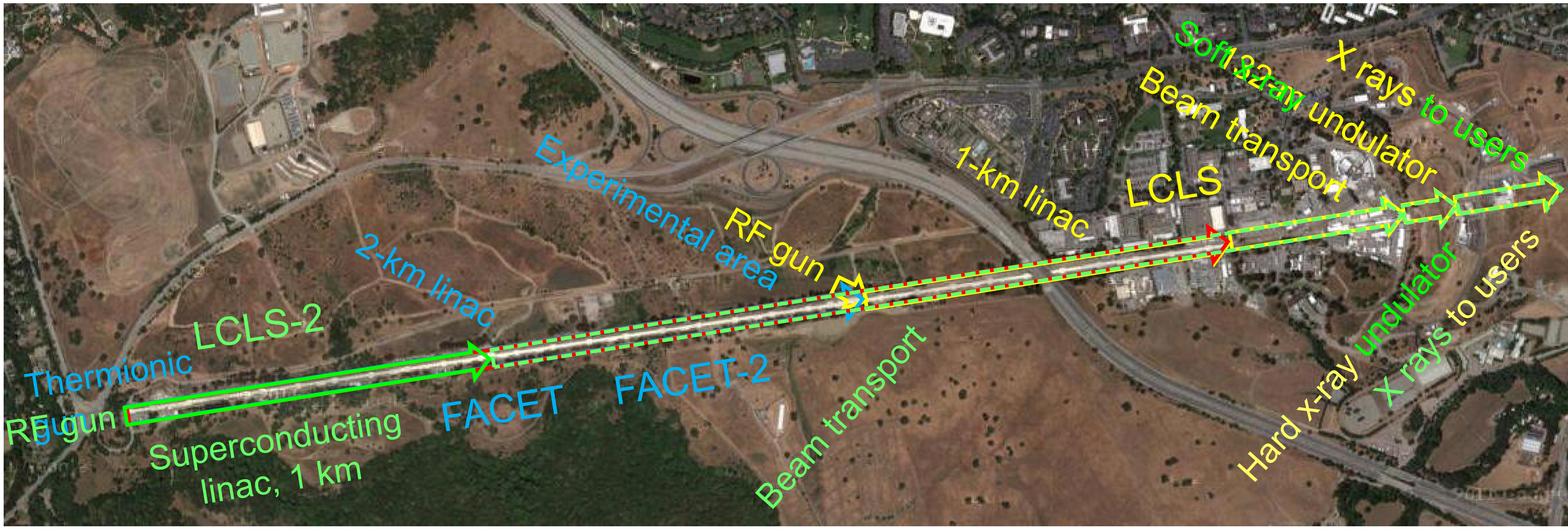


- SLAC, Klystron Gallery and Linac Tunnel, 3 km: 1962–
- LCLS, 3rd km: 2009–
- FACET, 1st and 2nd km: 2010–2016
- LCLS-2, 1st km: ≈ 2019–
- FACET-2, 2nd km: ≈ 2020–

Beam-Loss Monitoring for LCLS-2

- LCLS-2:
  - 1st km of SLAC's 3-km copper linac was removed last year.
  - New superconducting linac
    - Continuous RF at 1300 MHz
    - 4 GeV initially, with an upgrade to 8 GeV in planning
  - New normal-conducting RF photocathode gun
    - Continuous RF at 1300/7 = 186 MHz

- LCLS-2 parameters require a fresh look at loss detection:
  - Much higher repetition rate: up to 1 MHz
  - Much higher beam power: up to 250 kW initially, later 1.2 MW
    - Requires a much faster response (≥ 100 μs)
  - Continuous RF may lead to continuous dark current with significant power.

Beam-Loss Monitoring and SLAC Safety Systems

LCLS-2 Beam-Loss Monitors (BLMs) will serve three functions:

- BCS: Beam Containment System
  - Trips the whole machine when a beam-containment threshold is exceeded
  - Simple trip path, without software, without knowledge of timing or rate
- MPS: Machine Protection System
  - Halts or rate-limits a beam path exceeding a machine-protection threshold
  - Trips before BCS: Lower thresholds
  - More intelligent: Uses software, knows beam timing and beam paths
- Diagnostics
  - Guidance for operators in tuning the machine
    - Displaying losses below trip thresholds and identifying their locations
  - Radiation control
    - Minimizing radiation outside the tunnel
    - Reducing radiation damage to, and activation of, beamline components

Point and Long BLMs

- PBLM: Point detectors at known loss sites
  - To prevent damage to collimators, stoppers, dumps, undulators
- LBLM: Long detectors spanning the full machine in segments
  - To look for losses in less likely places
  - To identify the location of such losses
  - To protect people outside the linac-to-undulator (LTU) transport line
    - Above ground, and so less shielded than the tunnel

Thresholds, Response Times, and Locations

- Required limits are specified in joules of lost beam within 500 ms.
  - Once limit is exceeded, the response is required within 100 μs.
- Typical BCS limits:
  - LBLMs:
    - 500 J in the linac tunnel
    - 17.5 J in the LTU
  - PBLMs:
    - 50 J
- MPS thresholds are set at 10% of BCS thresholds.
  - Recovery from an MPS trip is faster, since the RF stays on
- Radiation modeling (FLUKA) computes the radiation dose near these losses.

LIONs, PLICs, and PICs

- SLAC has always measured beam loss with ionization chambers.
  - Losses ionize gas between electrodes.
  - Bias voltage collects electrons on anode and positive ions on cathode.
- Protection Ion Chambers (PICs) for Point BLMs
  - Cylindrical chamber with 16 interleaved pairs of electrodes
- Long Ionization Chambers (LIONs) for Long BLMs
  - Gas-dielectric Heliax-cable spanning a region
- Panofsky's Long Ionization Chambers (PLICs) for Diagnostics
  - Similar to a LION, but the cable is longer and thinner, with more voltage
  - Named for SLAC's founder, Wolfgang Panofsky

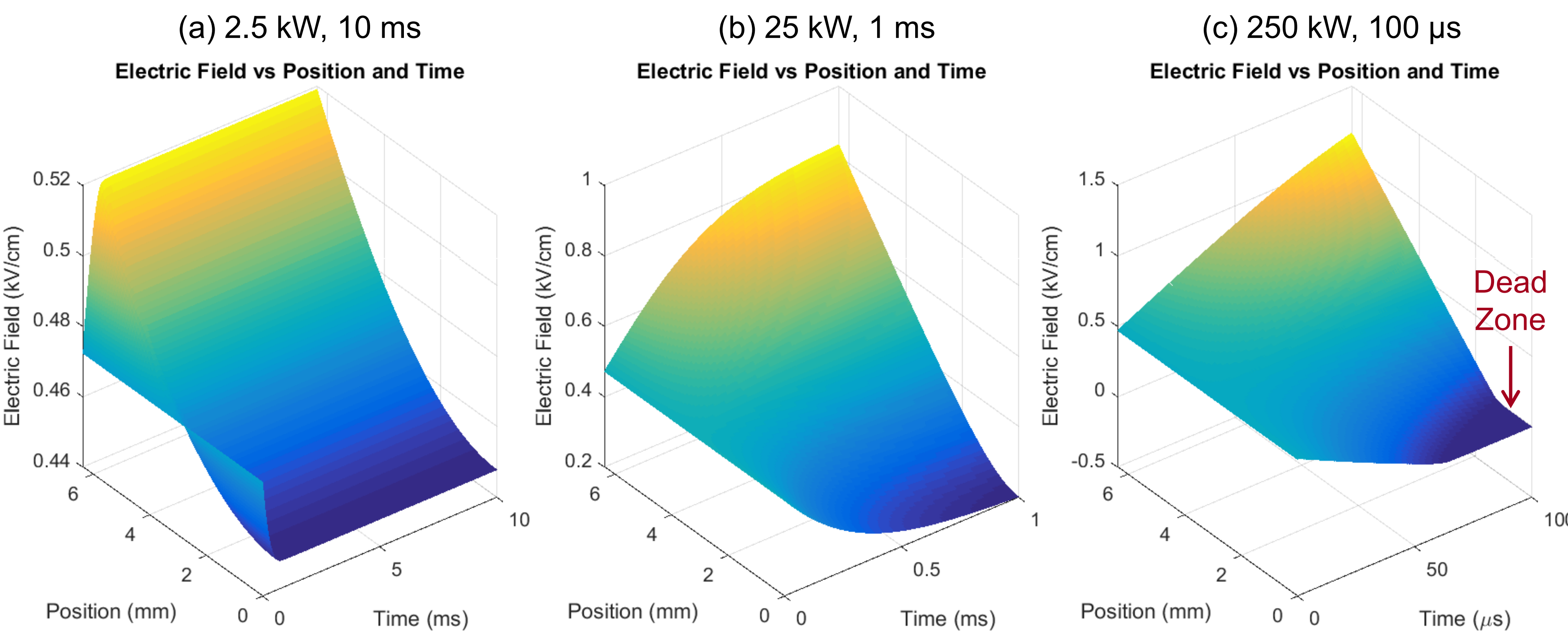
Ionization Chambers and High-Power Losses

- Electrons move quickly, but ions are slow, with a transit time > 1 ms.
- I modeled PICs and LIONs to see how they would respond to beam losses at 1 MHz.
  - Ion space charge can accumulate and alter the field in the chamber.
  - With high losses, a field-free “dead zone” can form between the electrodes.
- The following examples show losses of 2.5 kW to 250 kW, continuing in each case for just long enough to integrate to **25 J**.
  - That’s **half the MPS threshold** for LBLMs in the linac.

PIC at −300 V, 0.5 m, 1-MHz Loss: Electric Field

SLAC

- As the ions build up, the power supply maintains a constant voltage, but the field becomes nonuniform.
- In (c), with high loss, the ion space charge nulls the electric field near the positive electrode after 60 μs, creating a "**dead zone**".

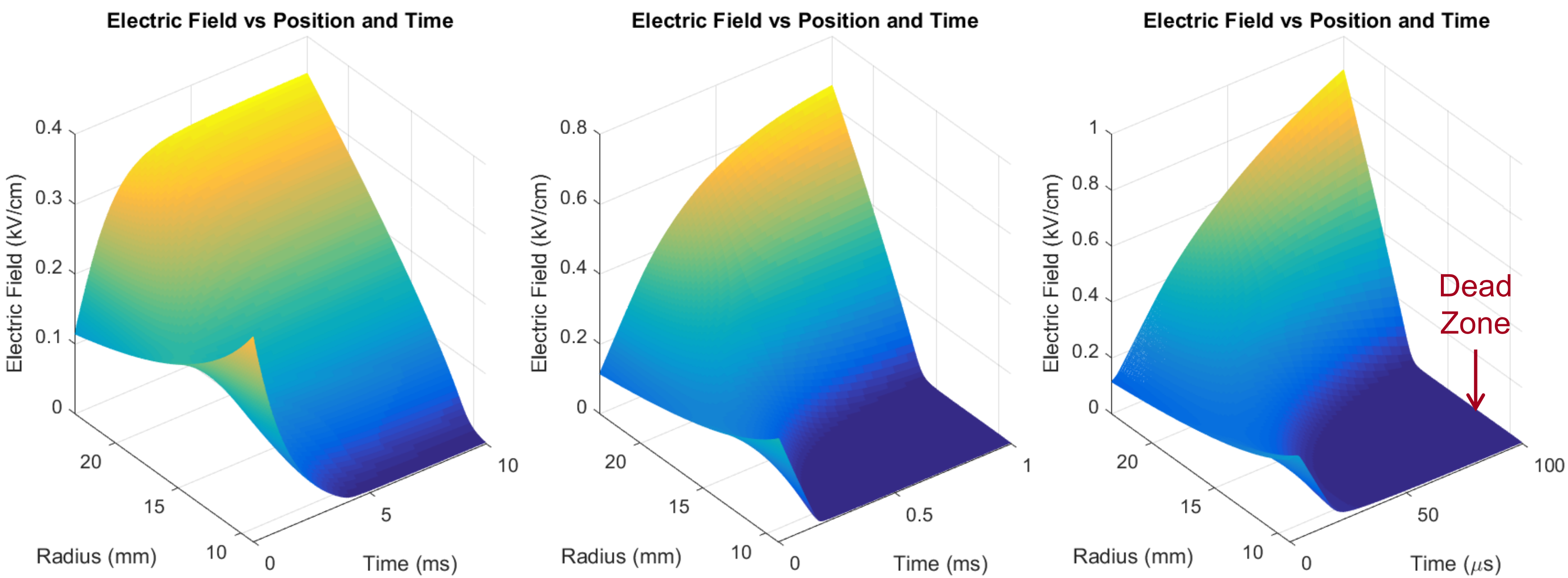


LION at +250 V, 0.5 m, 1-MHz Loss: Electric Field

SLAC

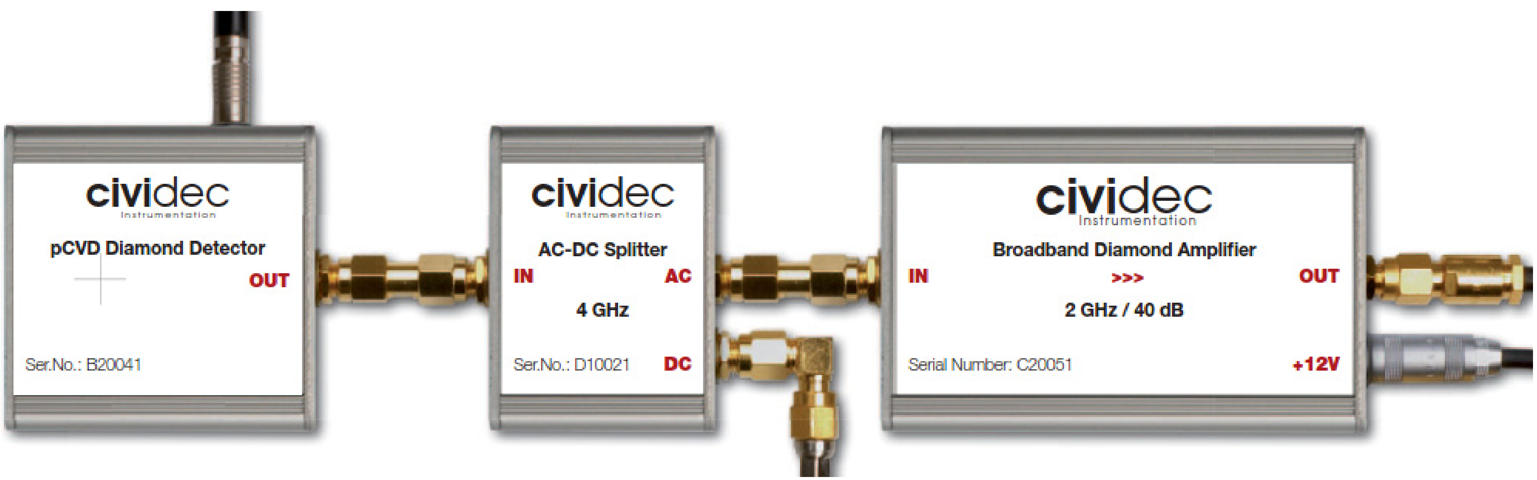
- (a) Field reverses slope. Dead zone forms at inner conductor in 4 ms.
- (b) Dead zone in 200 µs. (c) Dead zone in only **30 µs**.
- Dead zone forms faster in LIONs than in PICs because:
  - Larger distance between electrodes, 1/*r* field, lower voltage

(a) 2.5 kW, 10 ms (b) 25 kW, 1 ms (c) 250 kW, 100 µs



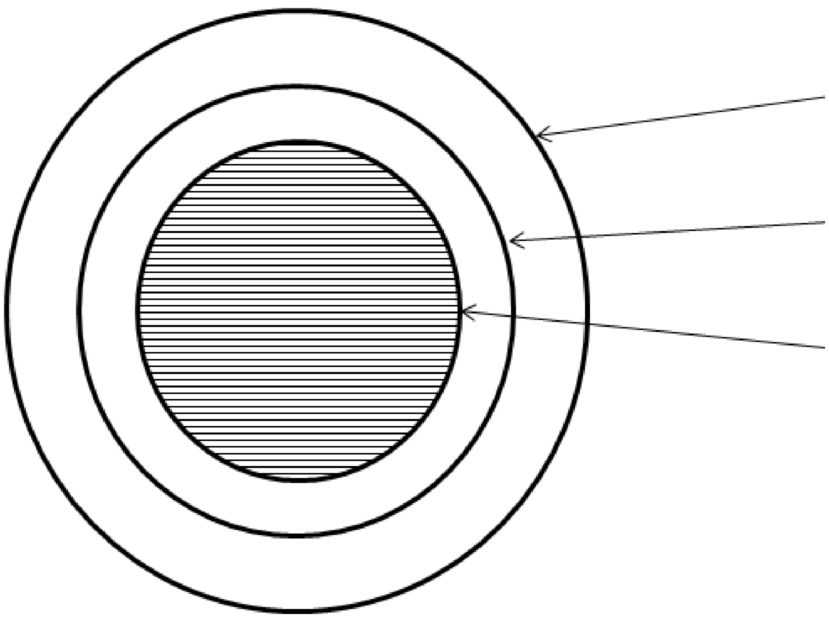
PBLMs: Diamond Detectors instead of PICs

- Metallized diamond chip, $8 \times 8 \times 0.5$ mm^3 for B2 (standard) type
  - Much smaller than a PIC, but some compensation since it's a solid.
    - Active volume is 35,000 times smaller, but 6.1% of mass (vs. PIC, 1 atm of Ar)
- Radiation creates electron-hole pairs collected by a 500-V bias
  - Thin chip with high electron and hole mobility: Few-ns output pulses
    - No accumulation from prior pulses
- B2 has dynamic range of 1 to 10^6 MIPs (minimum ionizing particles)
  - 10^9 possible by using the standard (B2) type, the high-radiation (B4) type, and perhaps a splitter and amplifier on one arm



LBLMs: Optical Fibers instead of LIONs

- Cherenkov light is emitted as loss shower passes through optical fiber
- Photomultiplier (PMT) at end of fiber measures the loss
- Radiation-hard fiber: Tested to 1.25 Grad for CMS end cap at CERN

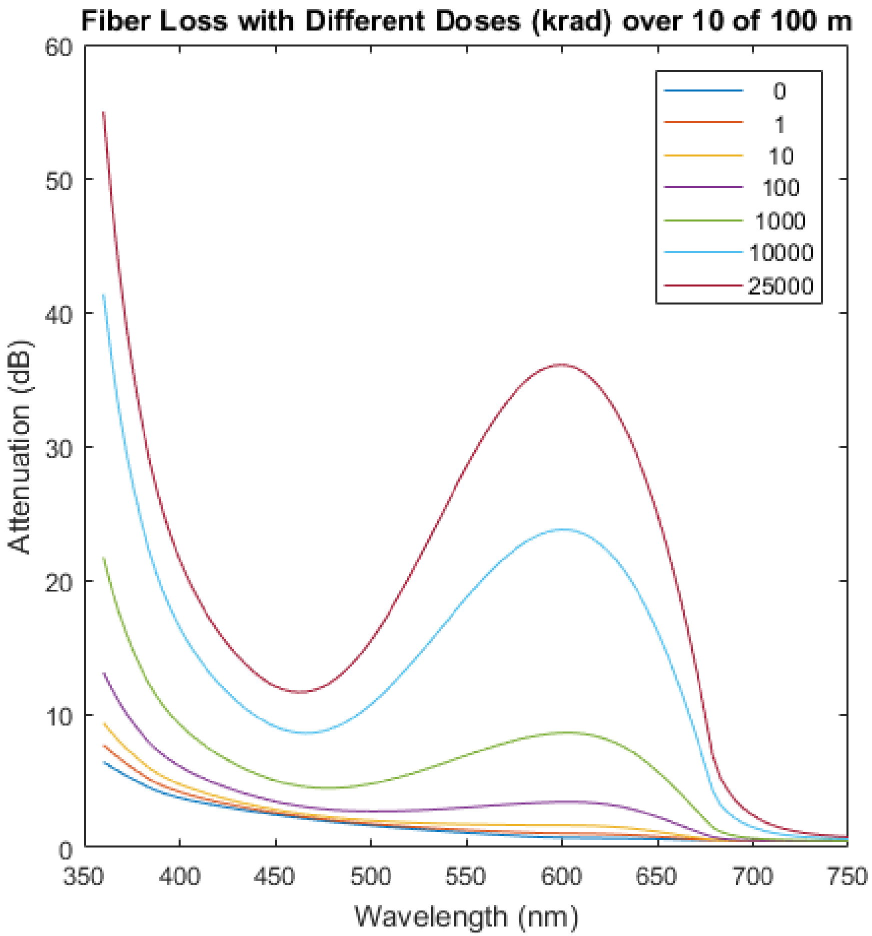


- What length would work for LCLS-2? How long would it last?

Fiber Attenuation with Radiation at MPS Limit

- Assumptions:
  - **100 m** of fiber, most of which is not exposed to high radiation
  - But a **10-m section receives a steady loss all year** (5000 hours) slightly below **the MPS limit**, so that it never trips.
- FLUKA model gives the radiation field **50 cm** from the loss:
  - LTU MPS: 1.75 J in 0.5 s = 3.5 W → 175 rad/hr = **875 krad/yr**
  - Linac MPS: 50 J in 0.5 s = 100 W → 5 krad/hr = **25 Mrad/yr**
- How does this exposure affect the fiber's attenuation?

Attenuation of 100-m Fiber versus the Dose to 10 m

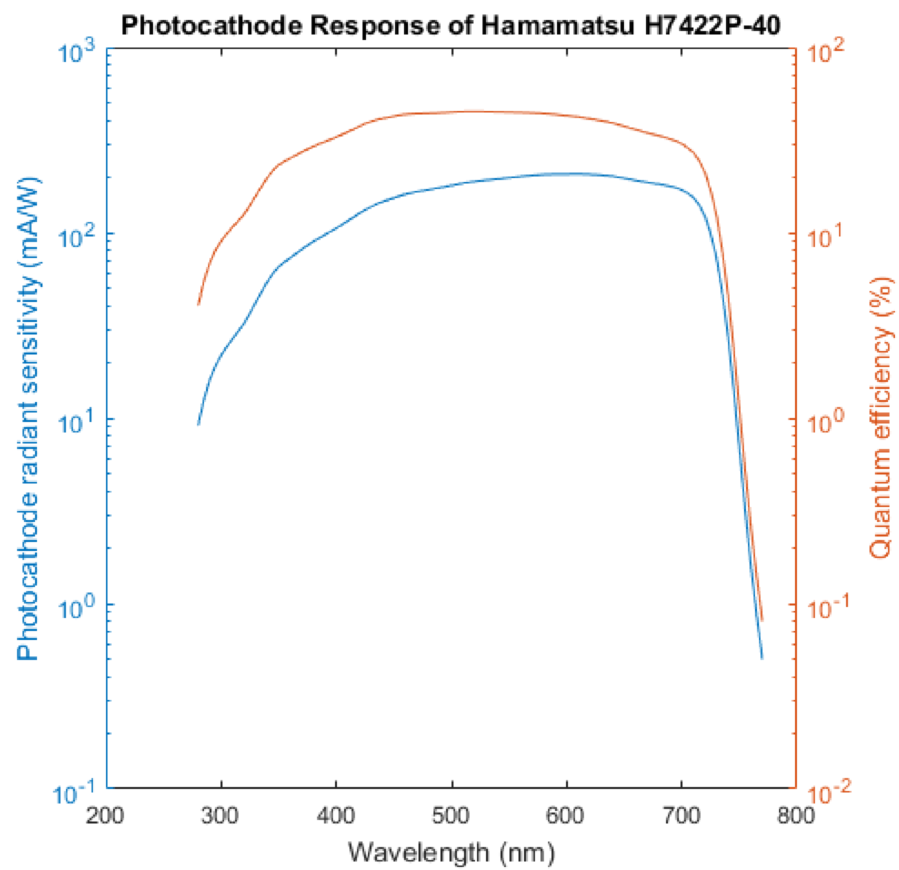


Wavelength (nm)	Attenuation (dB)		
	Initial	After 1 Year	
		LTU	Linac
400	3.7	8.9	21.5
450	2.5	4.9	12.0
600	0.8	8.1	36.1
700	0.5	0.7	2.4

- Red region near 700 nm minimizes loss
- Little growth in attenuation with radiation exposure

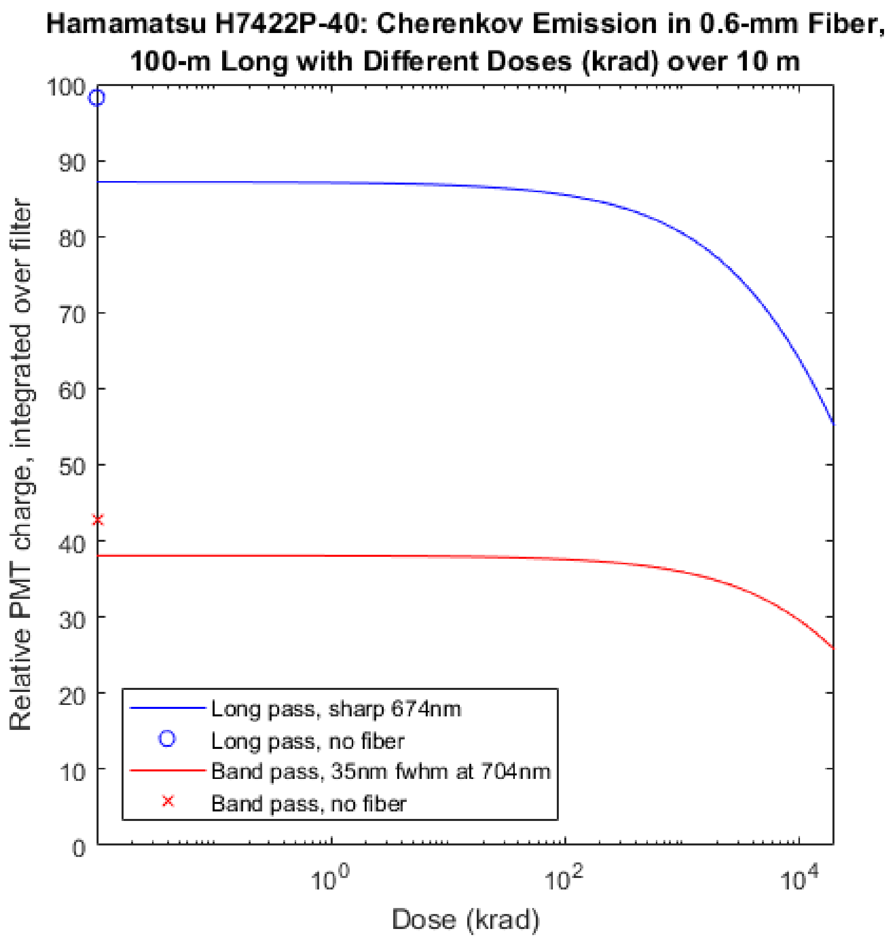
Choice of Wavelength

- Cherenkov intensity $dI/d\omega dx \sim \omega$
  - Photon flux $dN/d\omega dx$ is flat with ω
  - Red can give enough light
- Requires a PMT with a strong response to red light
  - But red PMTs have more dark current
    - PMT with thermoelectric (Peltier) cooling
- How long a fiber is reasonable when using red light?

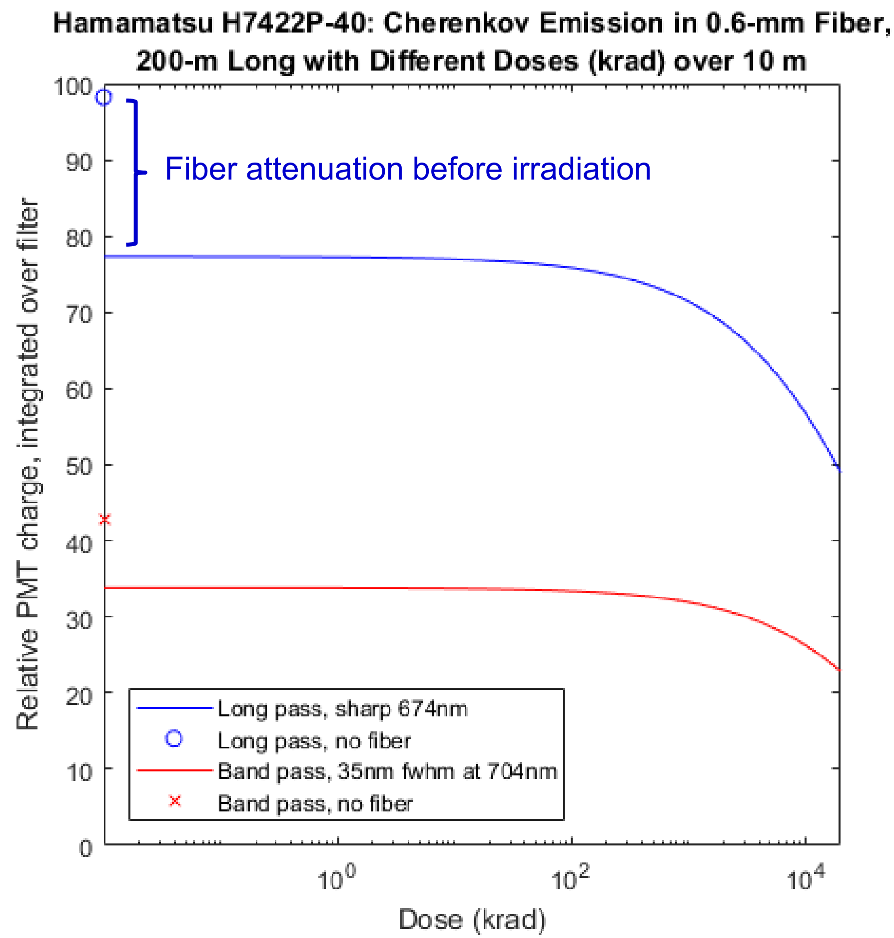


Attenuation versus Dose for 100- and 200-m Fibers

100-m Fiber



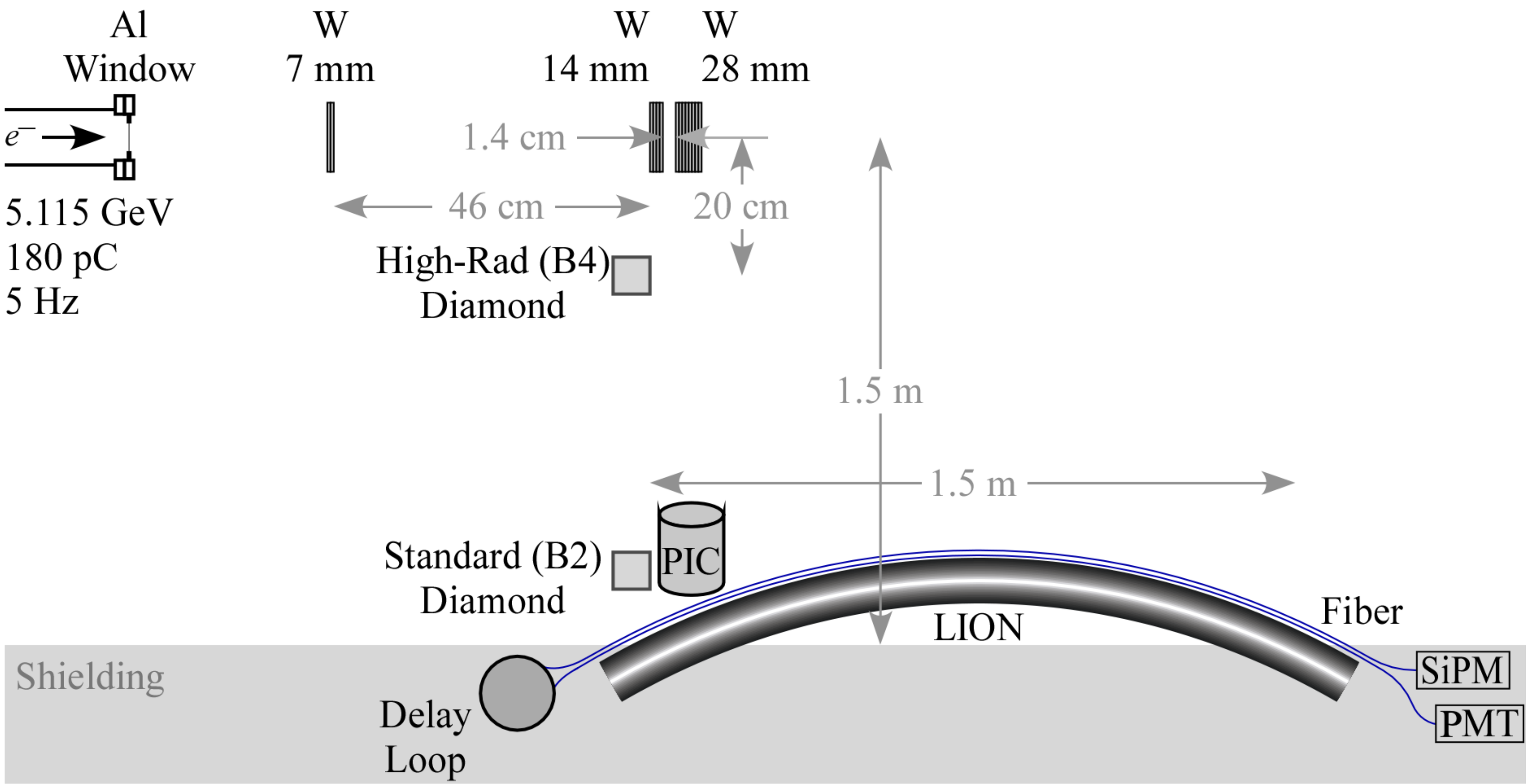
200-m Fiber



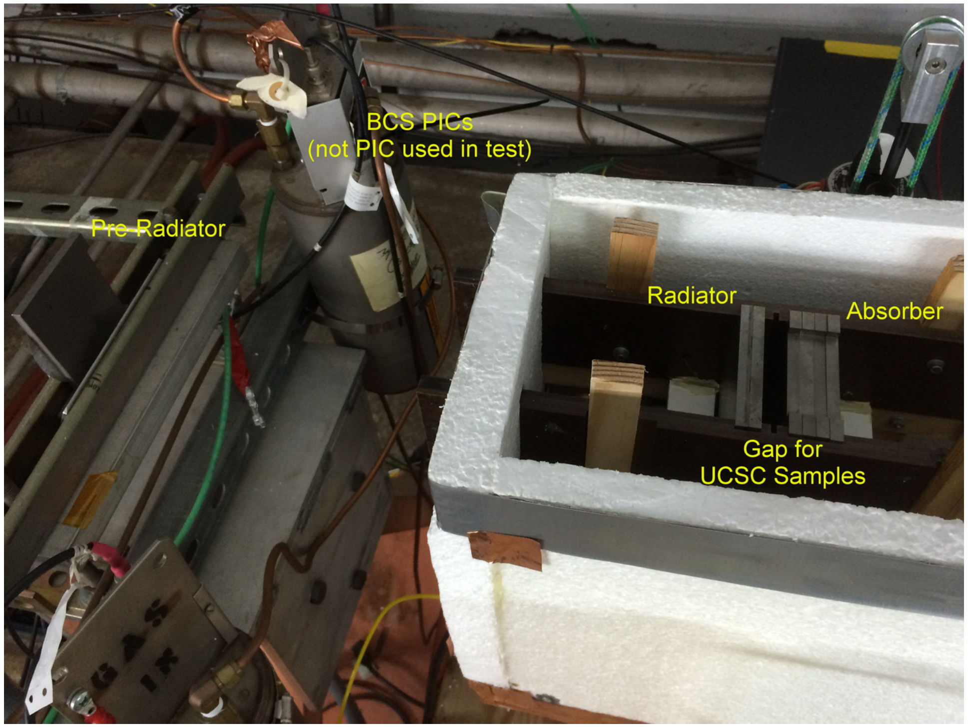
For calibration, losses at the fiber ends near and far from the PMT should produce signals differing by no more than 2.

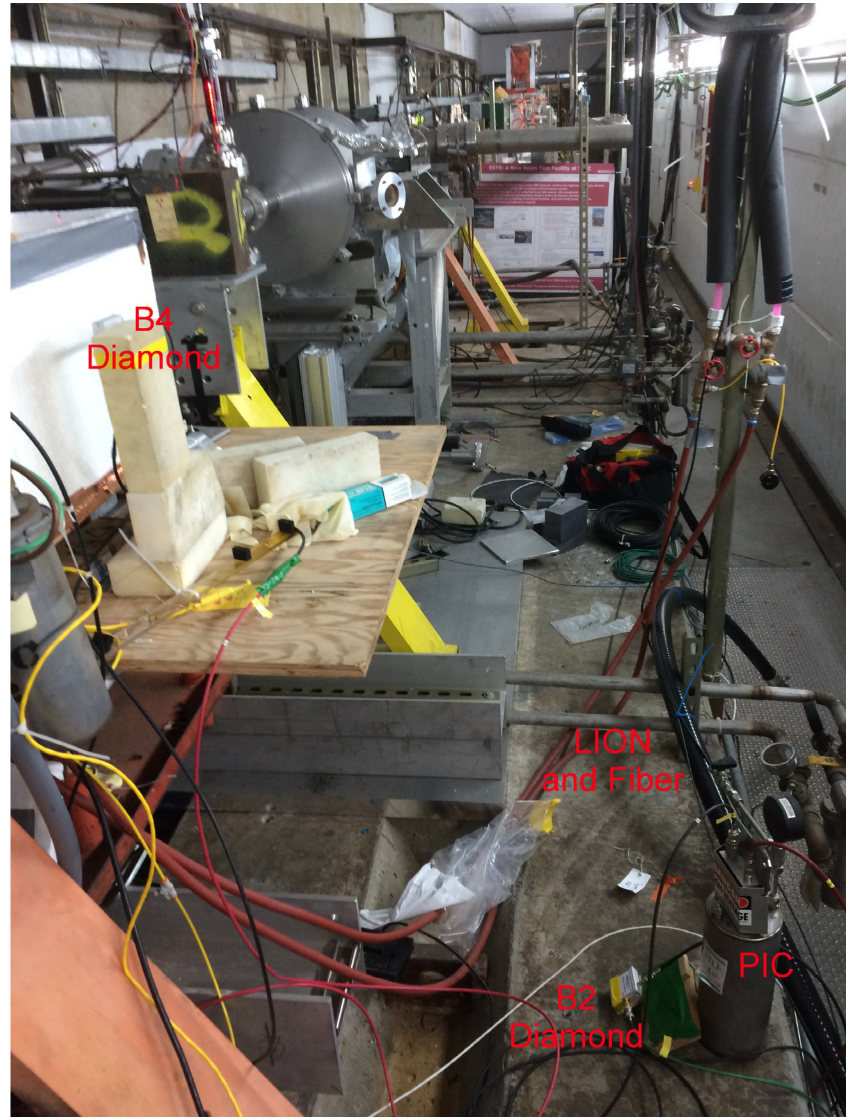
ESTB: Test of Beam-Loss Sensors, 2016-05

- **Goal:** To compare the old and the proposed new loss sensors, using large losses of pulsed beam in the End Station Test Beam area (ESTB) at SLAC

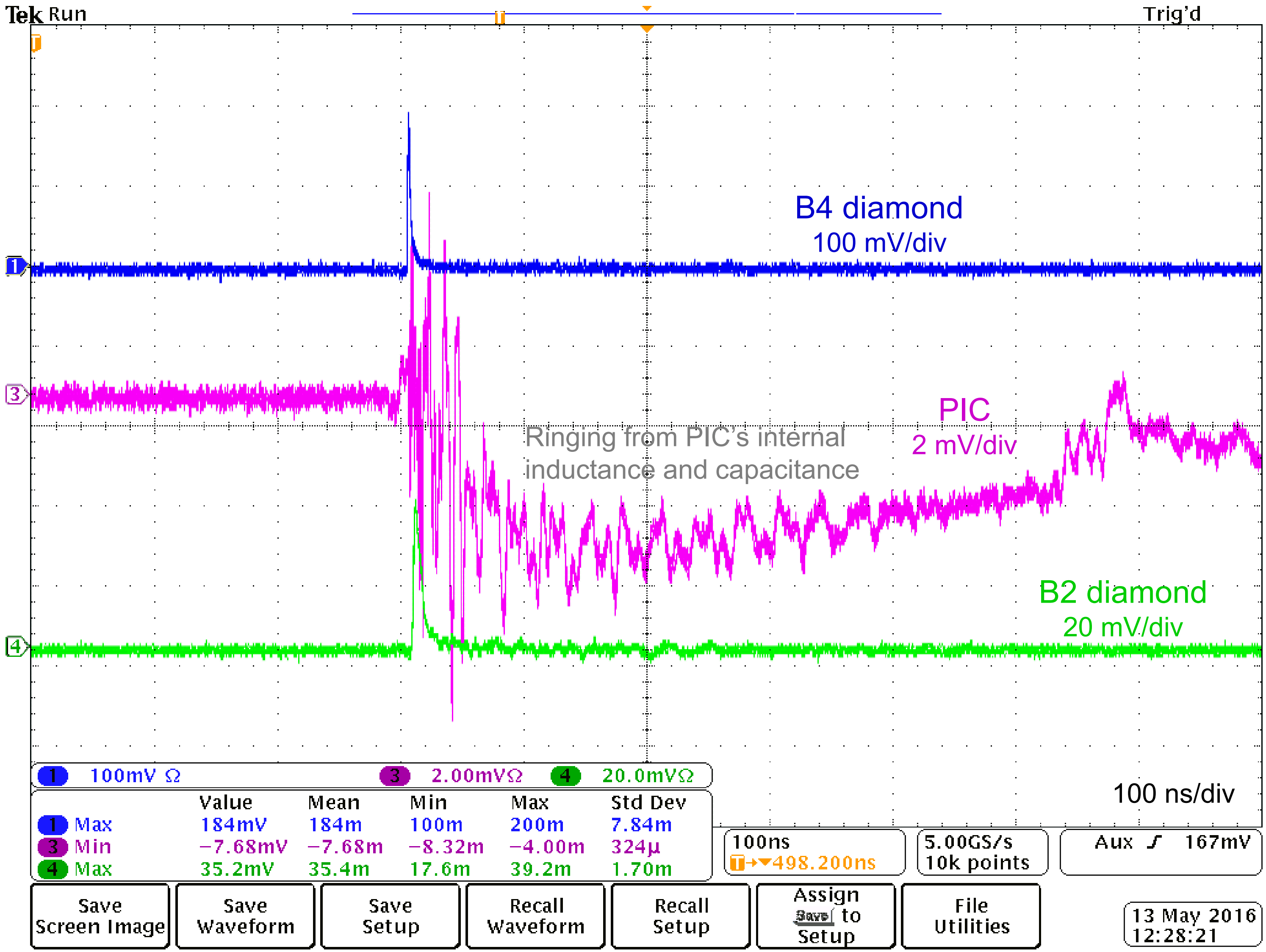


ESTB: Tungsten Blocks and Detectors

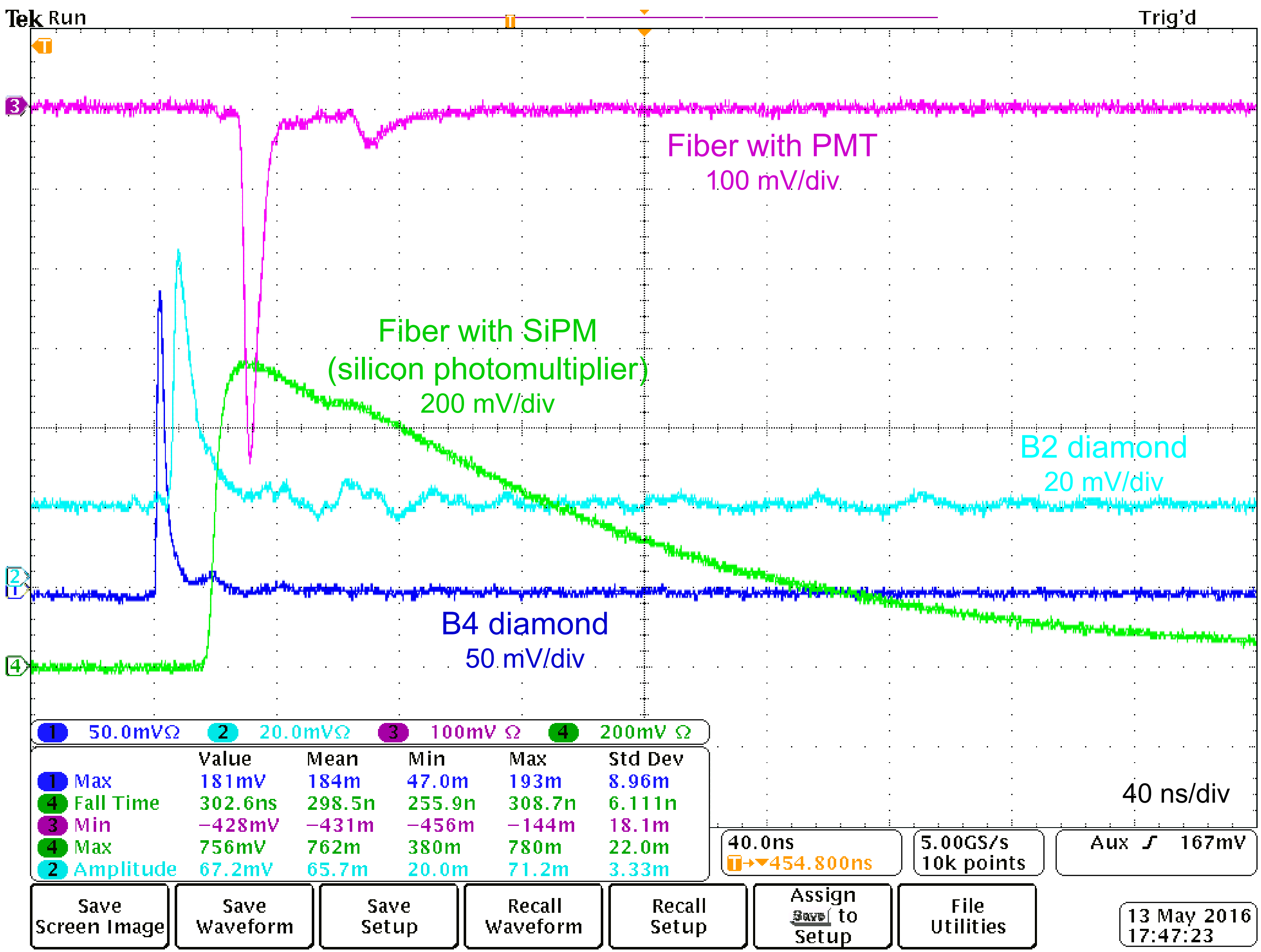




ESTB: Signals from PIC and Diamonds



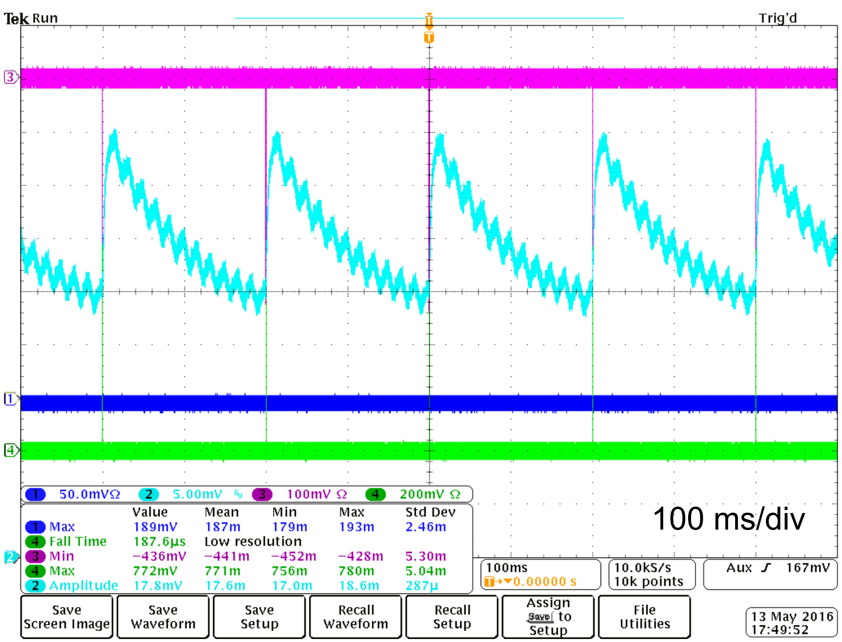
ESTB: Optical Fiber with PMT and SiPM

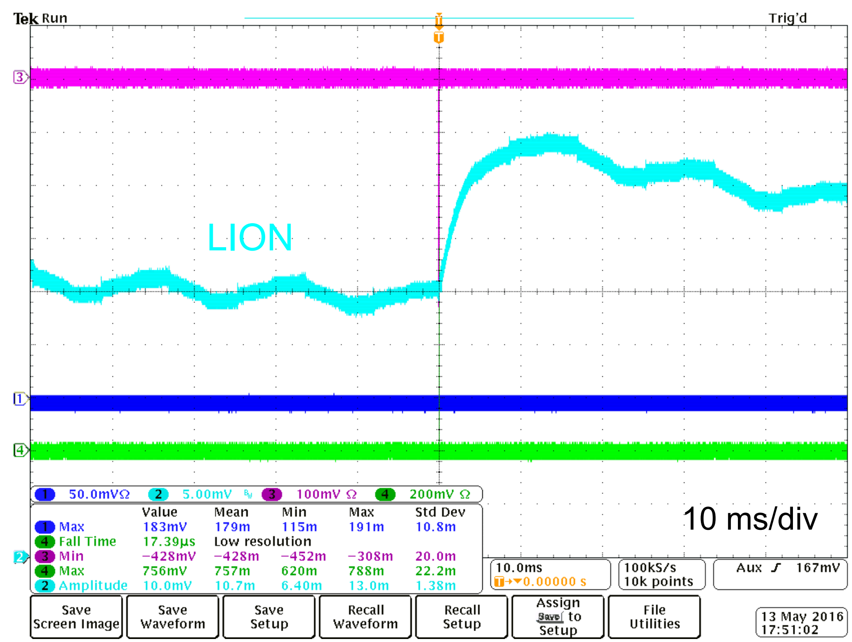


ESTB: LION at +250 V

- LION signal integrated with our standard LION electronics
- Viewed with 10× scope probe
- Beam loss at 5 Hz
- Strong pickup at 60 Hz

- Zoom in: 5-ms rise time
  - Trips would be too slow for LCLS-2 requirements
  - Even without considering the dead zone, the LION electronics would need a thorough redesign.

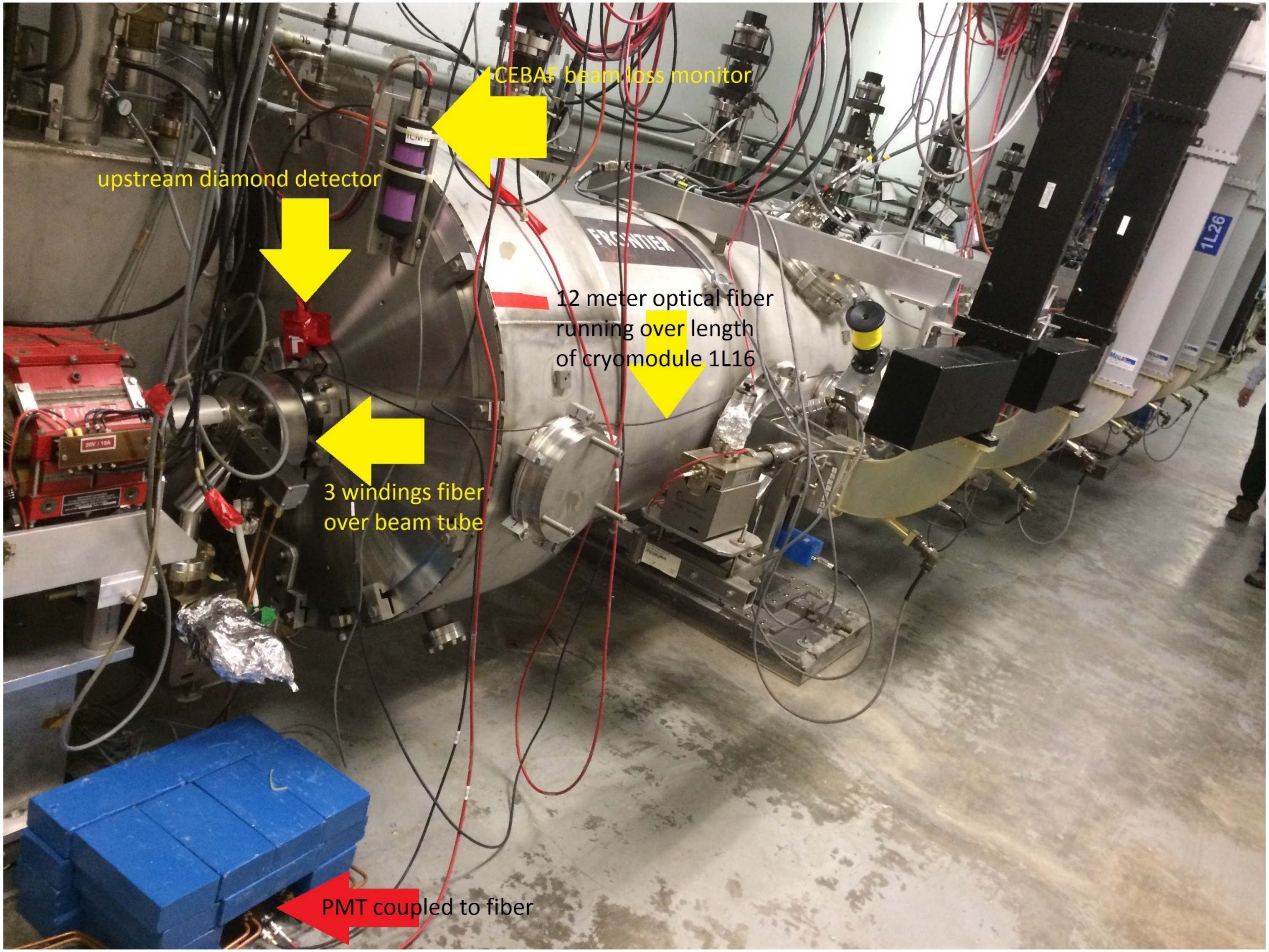




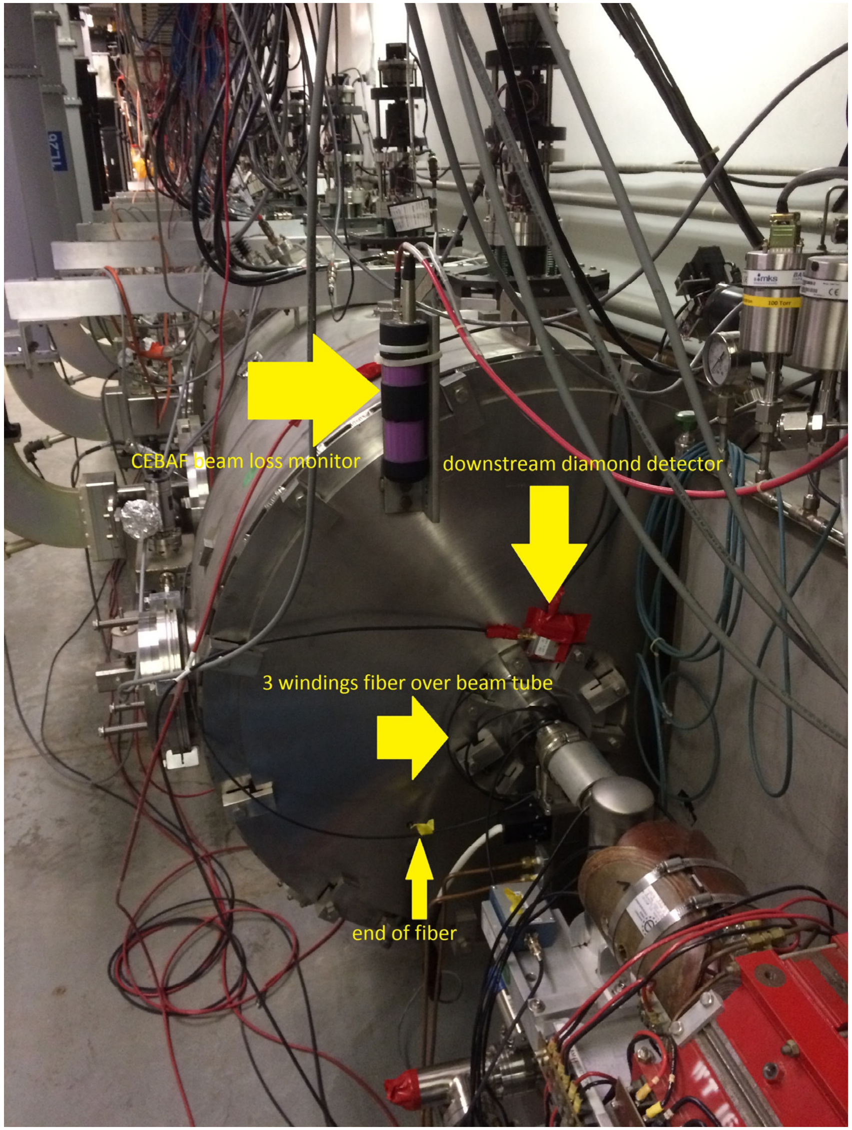
CEBAF: Cryomodule Field Emission, 2017-01

- **Goal:** To measure field emission from a linac cryomodule
- Location: Final cryomodule in CEBAF's north linac
  - Cryomodule 1L26, a high-gradient C100
- RF on, but no photocurrent. Cavity gradients stepped incrementally.
- Diamonds:
  - Cividec diamond detector at each end of the tank, above warm beampipe
    - A known loss point, since the warm pipe has a smaller diameter
- Fiber with PMT:
  - 12 m of fiber along the side of the tank
  - 3 turns around the beampipe at each end
  - PMT at the upstream end, shielded with lead
- JLab BLMs:
  - JLab has a network of their BLMs, using PMTs with scintillation.
  - At the upstream end of each tank, plus one more after 1L26
- Digitizer with high input impedance read diamonds and fiber's PMT.

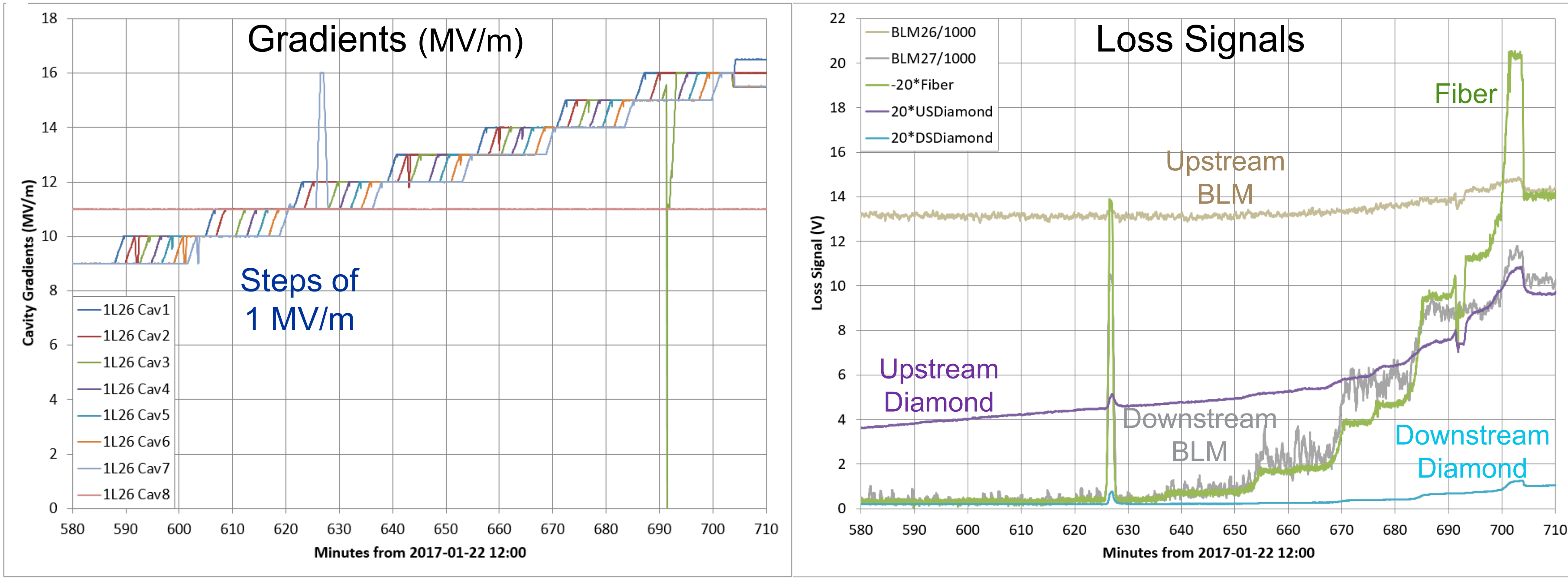
CEBAF: Sensors at Upstream End of Cryomodule



CEBAF: Sensors at Downstream End of Cryomodule



CEBAF: 1L26 Cavity Gradients Raised in Steps



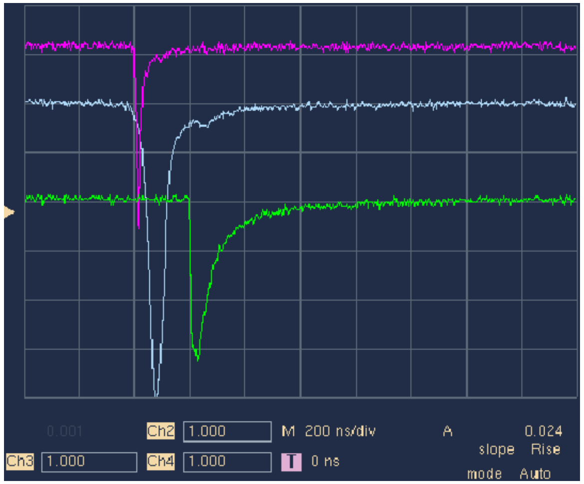
- Fiber signal shows exponential growth of field emission.
- Fiber is far more sensitive to spike of cavity 7 and to drop-out of cavity 3.
- Diamonds are high-rad (B4) types (less sensitive than B2 type).
- Upstream CEBAF BLM dominated by losses from 1L25; weak response to 1L26.
- Upstream diamond also hit (not as hard) from upstream.
- Downstream diamond and BLM show steps of cavity RF.

BSY: 155-m Fiber Tested, 2017-06

- Test in the Beam Switchyard (BSY) at SLAC
- **Goals:**
  - To compare Cherenkov signals in the fiber from the forward- and backward-going loss showers for:
    - Time resolution and loss localization
    - Relative strengths of forward and backward signals
  - To compare attenuation in a 155-m fiber to manufacturer's specifications
    - Using blue light since attenuation is larger
- Two blue-sensitive PMTs, one at each end of fiber

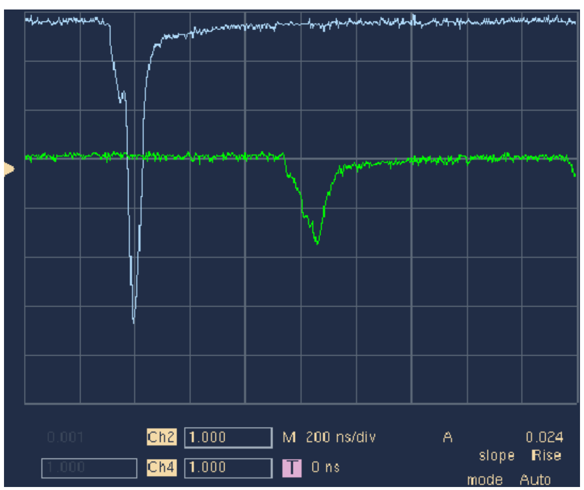
BSY: Loss Localization

XCOR:LI30:802

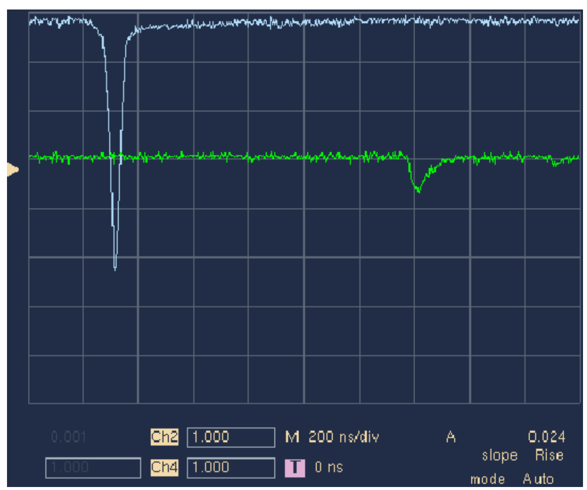


- Correctors steered beam into beampipe
- As loss points move downstream, the peaks move:
  - Rightward for PMT1, at upstream end of fiber
  - Leftward for PMT2, at downstream end
- Peak separation is 5 times larger at PMT1

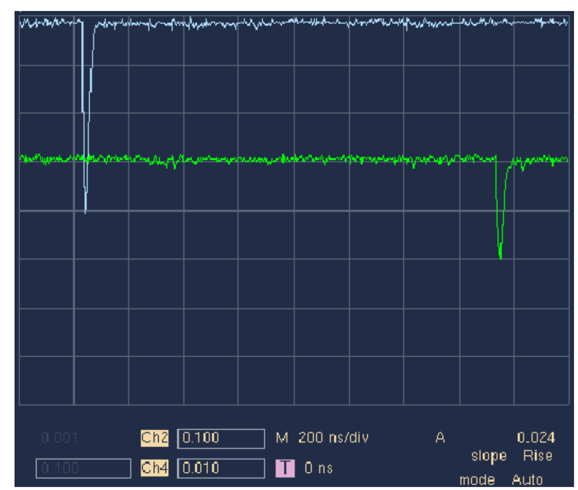
XCOR:CLTH:168 (BSY Q2)



XCOR:BSYH:452 (BSY Q3)

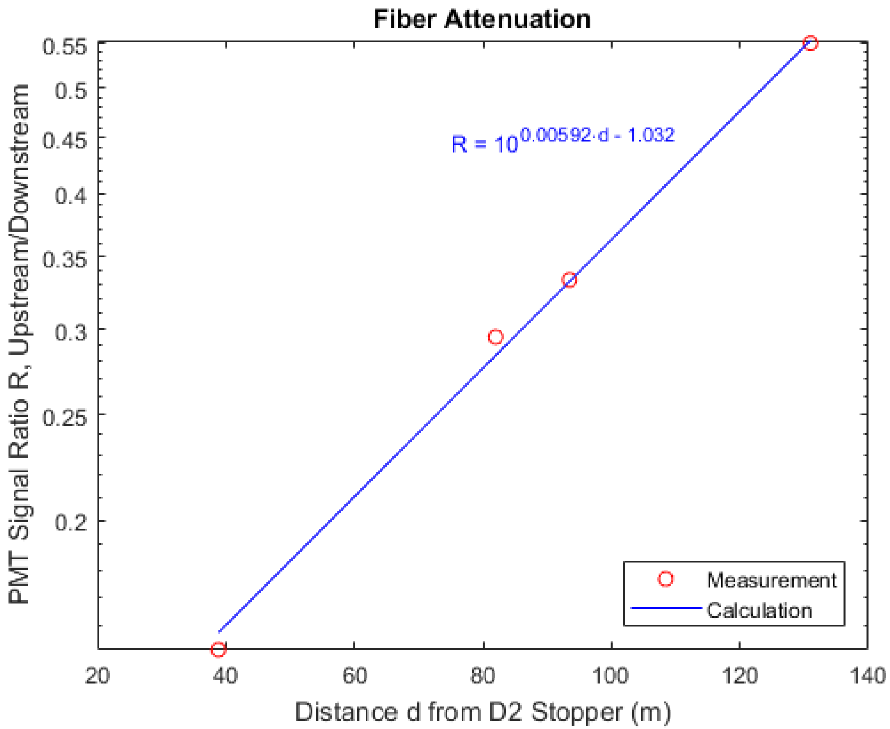


Beam on D2 Stopper



BSY: Upstream and Downstream Loss Measurements

PMT1/PMT2 vs.
Distance from Downstream End of Fiber

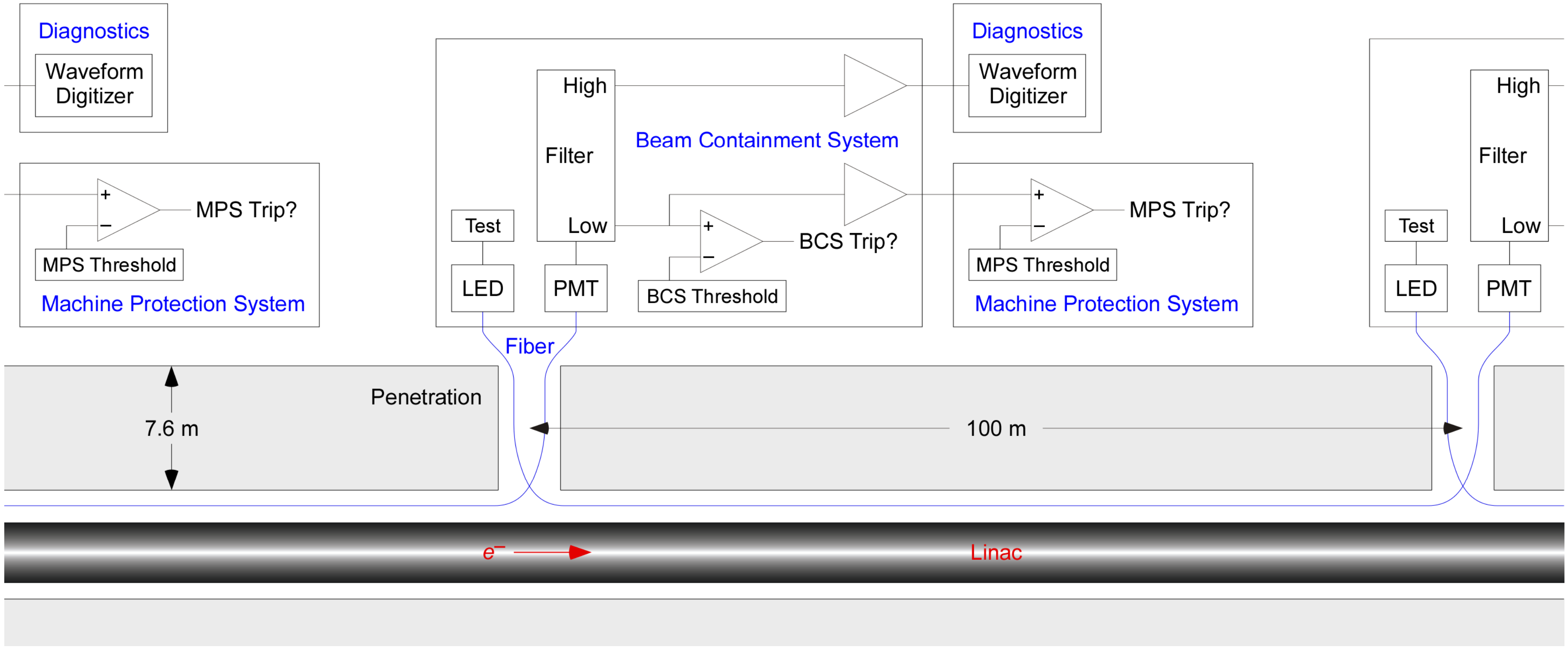


- The slope was calculated only from the known properties of Cherenkov light, fiber, and blue PMTs.
  - Calculated attenuation: 30 dB/km
    - Loss at 700 nm is only 5.1 dB/km
- The vertical offset was then adjusted to fit the measurements.
  - Offset gives the ratio of the upstream-to-downstream capture of Cherenkov light: 27%.

Signal Processing

- Same sensors serve all three functions, but with different processing
- Diamonds and PMTs are current sources:
  - Accumulate charge from loss pulses on a capacitor, in BCS chassis
  - Discharge resistor provides decay path for capacitor's voltage
    - Set time constant to BCS and MPS integration time—500 ms
  - Buffer amplifier relays capacitor voltage to MPS
- If the voltage exceeds the BCS (or MPS) threshold, a comparator trips (or rate limits) the beam.
- For PMT, a filter/splitter integrates low frequencies but terminates high frequencies in 50 Ω
  - Buffered output for diagnostic waveform digitizer, for loss localization
  - Localization isn't needed for diamond point-loss sensors

Planned Fiber Layout



Summary

- LCLS-2 presents some difficult beam-loss challenges:
  - Up to 1.2 MW of photocurrent at 1 MHz
  - Possible steady losses from field emission
- Old SLAC approach: Ionization chambers
  - Ion pile-up can make them unreliable with large persistent losses.
- Instead:
  - Diamonds for point monitors
  - Optical fiber, in lengths of ~100 m, for long monitors
    - Use red light to minimize attenuation, both before and after radiation exposure
    - Signal from forward-going loss shower is 4 times stronger
    - Sensitive to field emission from long LCLS-2 cryomodules
- The detectors will be shared by BCS, MPS and diagnostics.