Evaluating Beam-Loss Detectors for LCLS-2

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Abstract

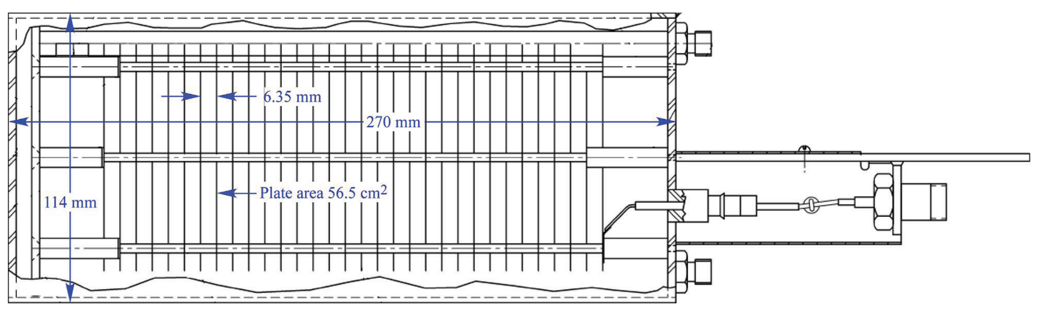
The LCLS x-ray FEL occupies the third km of the 3-km SLAC linac, which accelerates electrons in copper cavities pulsed at 120 Hz. For LCLS-2, the first km of linac will be replaced with superconducting cavities driven by continuous RF at 1300 MHz. The normal-conducting photocathode gun will also use continuous RF, at 186 MHz. The laser pulse rate will be variable up to 1 MHz. With a maximum beam power of 250 kW initially, and eventually 1.2 MW, the control of beam loss is critical for machine and personnel safety, especially since losses can continue indefinitely in linacs, and dark current emitted in the gun or cavities can be lost at any time. SLAC protection systems now depend on ionization chambers, both local devices at expected loss sites and long gas-dielectric coaxial cables for distributed coverage. However, their ion collection time is over 1 ms, far slower than the beam repetition rate. We present simulations showing that with persistent losses, the space charge of accumulated ions can null the electric field inside the detector, blinding it to an increase in loss. We also report on tests comparing these detectors to faster alternatives.

Device	Trip Point	Response Time
Point dectector: Protects stoppers and collimators	Detect loss of 25 J in 100 ms, then shut off within 100 µs. Sample at least every 25 µs.	250 kW for 100 µs 25 kW for 1 ms 2.5 kW for 10 ms ≤250 W is safe
Line detector: Measure inside shielding wall for protection outside	Linac: 10 krad/hr over 10 m Beam Transfer Hall: 3 – 20 rad/hr (adjustable) over 5 m	600 ms

Point-Loss Detectors

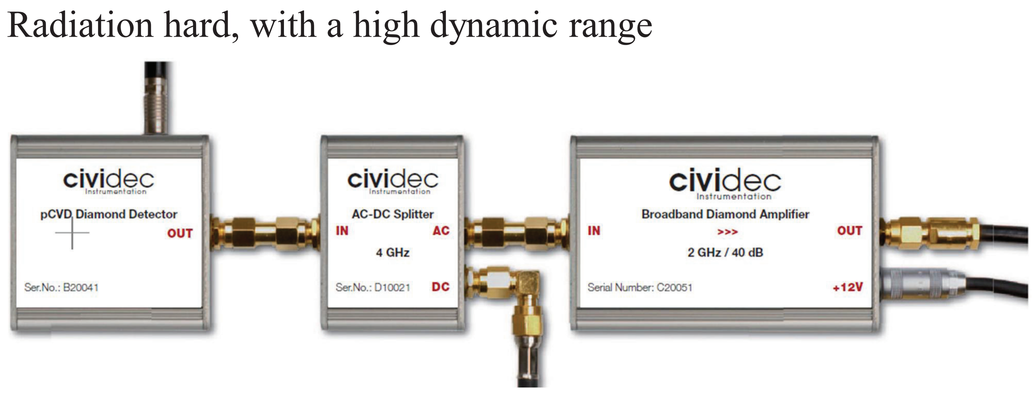
Used for LCLS: Protection Ionization Chamber (PIC)

- Gas-filled stainless-steel cylindrical chamber with 32 electrodes, alternately grounded or connected to a bias of −300 V
- Filled to 125 to 150 kPa with 95% Ar and 5% CO_2
- Typically placed 0.5 m from loss point
- Electrons are collected in 2 µs, but ions take 1 ms.



Alternative for LCLS-2: Diamond Detector

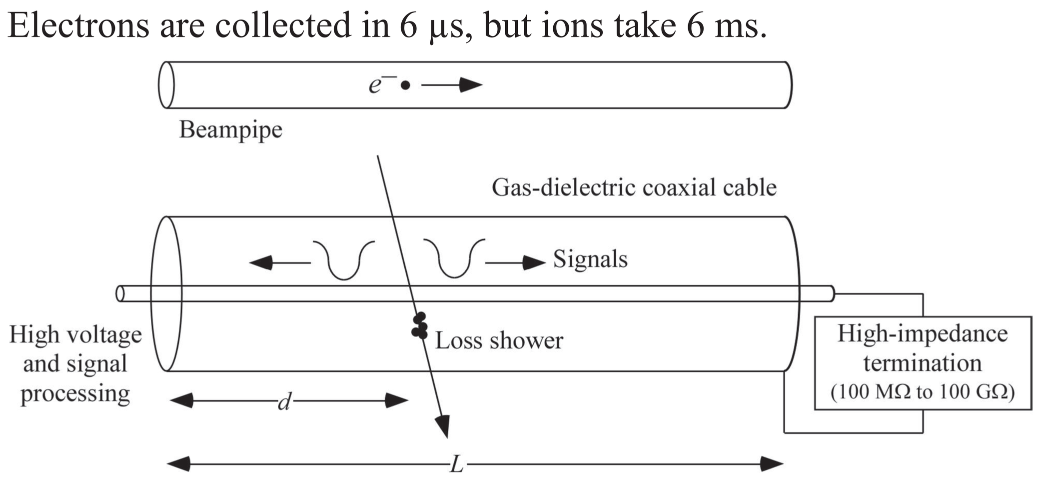
- Radiation creates electron-hole pairs in polycrystalline diamond.
- A 500-V bias between electrodes on faces collects electron-hole pairs.
- 10×10×0.5 mm³: The diamond's volume is 22000 times smaller than the PIC's, but it has 9% of the mass of the PIC gas (for Ar at 100 kPa).
- High electron and hole mobilities and a short distance: 5-ns pulses
  - No accumulation from prior pulses
- Radiation hard, with a high dynamic range



Line Detectors

Used for LCLS: Long Ionization Chamber (LION)

- Gas-dielctric Heliax coaxial cable
  - Conductors made of continuous helically-wound copper strip
  - Diameters of inner and outer conductors: 18.1 and 46.5 mm
  - Length of 30 to 50 m
- Bias of (typically) +250 V collects electrons and ions
- Typically placed 1 m from beamline
- Electrons are collected in 6 µs, but ions take 6 ms.



Alternative for LCLS-2: Optical Fiber

- Detect Cherenkov emission in fiber
- Diameters: 600-µm core, 660-µm cladding, 710-µm buffer, 2000-µm black polyurethane jacket
- Radiation hard: Tested to 1.25 Grad for CERN (CMS end cap)

Parameter	LCLS Linac: Normal Conducting	LCLS-2 Linac: Superconducting
Electron Energy	15 GeV	4 (later 8) GeV
Bunch Charge	20 to 250 pC	20 to 250 pC
Beam Power	450 W	**0.25 (later 1.2) MW**
Linac Frequency	2856 MHz	1300 MHz
Gun Frequency	2856 MHz	185.7 MHz
RF Pulse Rate	120 Hz	Continuous
Electron Bunch Rate	120 Hz	92.9 (later 929) kHz
Photon Energy	0.2 to 5 keV	1 to 15 (later 25) keV

1-D Model of an Ionization Chamber

- Uniform ionization per unit volume $I(t)$ during beam pulse
- Recombination per unit volume proportional to $n_i n_e$
- Argon at 100 kPa: No molecular fragmentation, no slow negative ions
- Mean free path << chamber size: Collision-dominated motion
  - Mobility: $\mathbf{v}_{i,e} = \pm\mu_{i,e}\mathbf{E}$
  - μ_i is constant; μ_e is a weak function of E
- Diffusion: $\mathbf{J}_{i,e} = -D_{i,e}\nabla n_{i,e}$ (particle flux, not current density)
- Electric field evolves self consistently with space charge
- Equations:

$$\mathbf{J}_{i,e} = \pm\mu_{i,e} n_{i,e}\mathbf{E} - D_{i,e}\nabla n_{i,e}$$

$$\frac{\partial n_{i,e}}{\partial t} = -\nabla\cdot\mathbf{J}_{i,e} + I - \beta n_i n_e$$

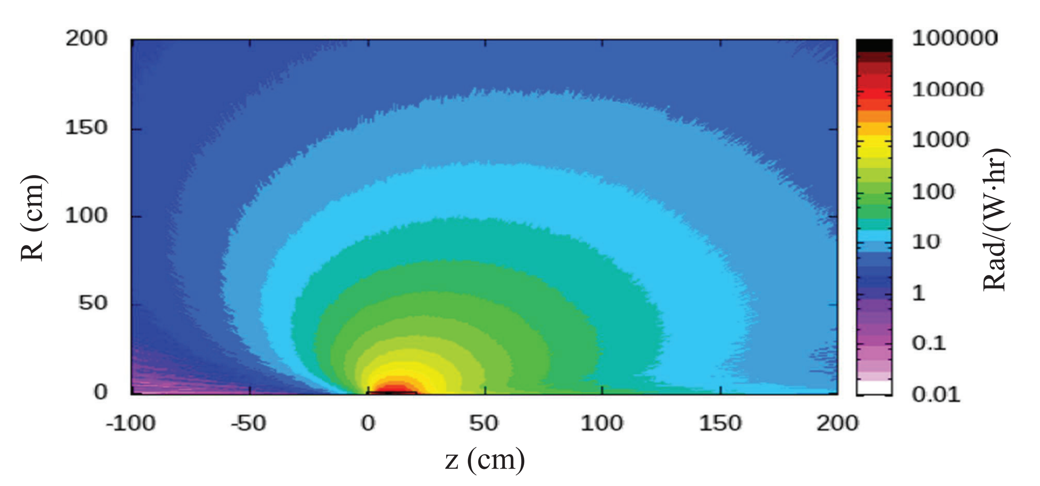
$$\varepsilon_0\nabla\cdot\mathbf{E} = e(n_i - n_e)$$

Boundary Conditions

- Ions or electrons can flow into an electrode, but not out.
- Charge on each electrode: $Q = \varepsilon\int_S \mathbf{E}\cdot d\mathbf{S}$
  - Electrode has surface S and an inward normal $d\mathbf{S}$.
  - Drift and collection of electrons and ions changes $\mathbf{E}$ and so Q.
- Bias supply delivers charge Q_{ext} to maintain the voltage: $V_0 = -\int_a^b \mathbf{E}\cdot d\mathbf{u}$
- Change ΔQ is sum of Q_{ext} and charge collected at electrode:

$$\Delta Q = Q_{ext} \pm e\int_S \mathbf{J}_{i,e}\cdot d\mathbf{S}$$

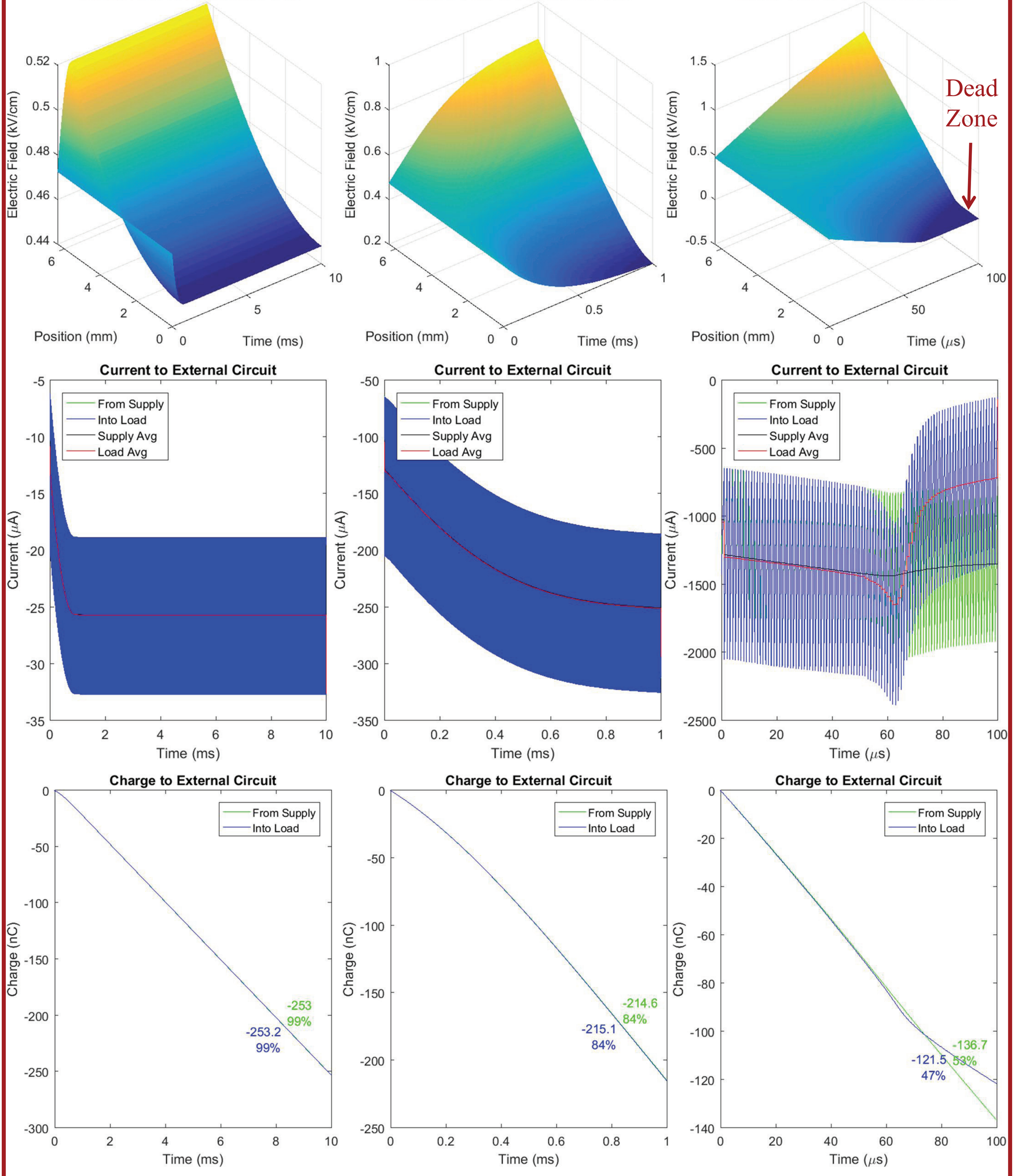
Radiation Dose Modeled with FLUKA

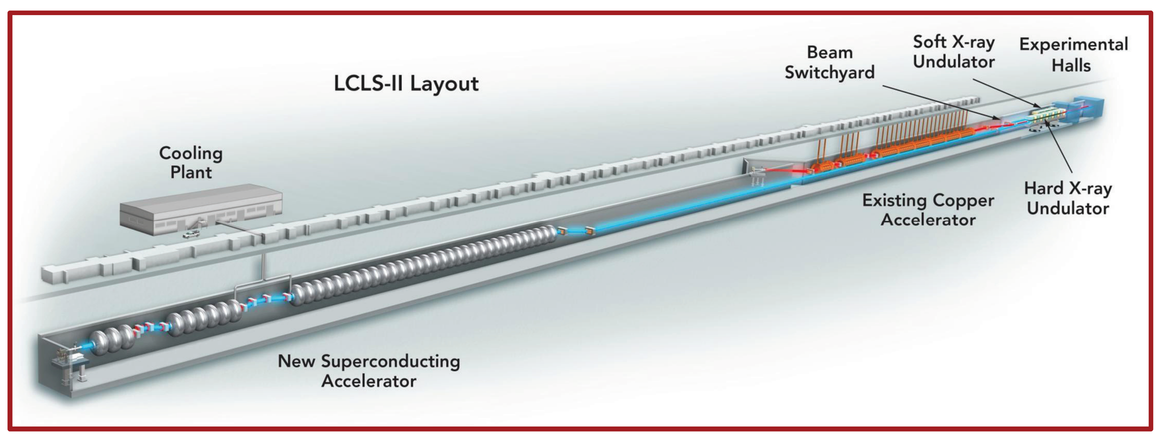


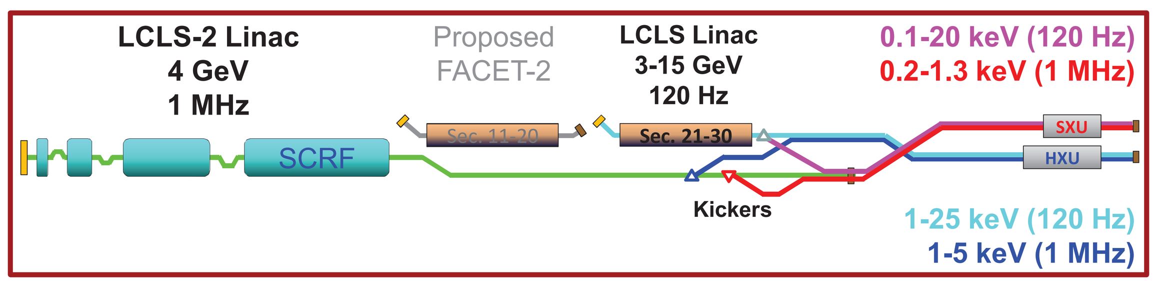
- Beam loss near a stopper, in rad/hour per watt of loss
- Dose limit for point detector >> limit for long detector

PIC at −300 V and 0.5 m with 1-MHz Loss

- Ion space charge cancels the electric field near the positive electrode within 60 µs of the start of high losses, creating a "**dead zone**".
  - No particle transport (except diffusion and recombination)

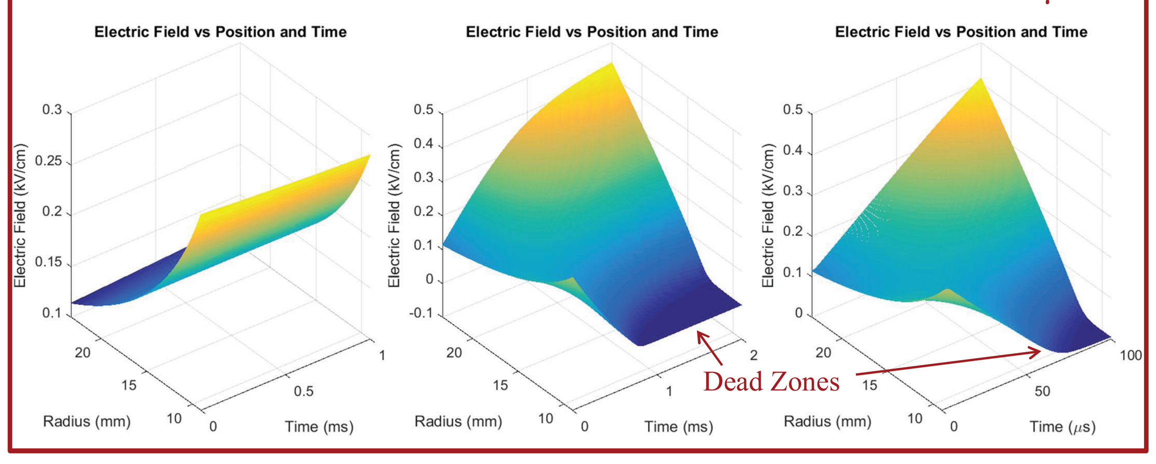




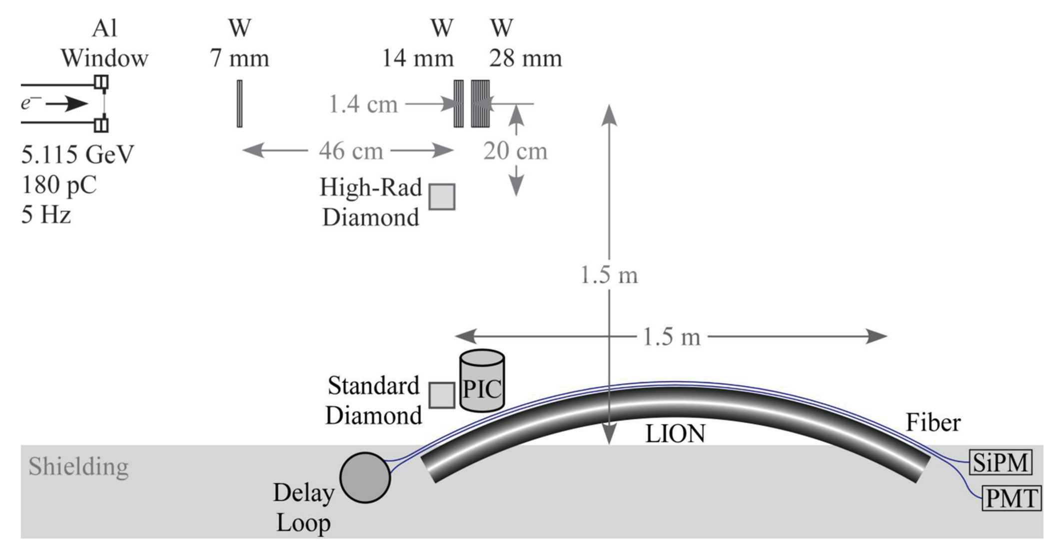


LION at +250 V and 1 m with 1-MHz Loss

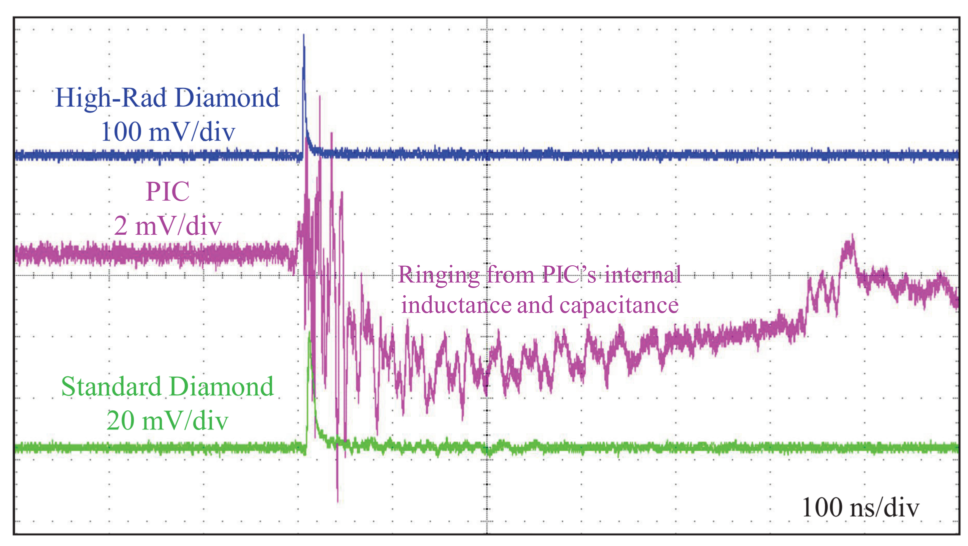
- It's easier to form a dead zone in a LION than in a PIC:
  - Cylindrical electrodes and wide spacing: Low field near outer conductor
- But LIONs have a lower trip threshold and are further from the beam.
  - The linac threshold, 10 krad/hr, corresponds to a loss of only 200 W.
  - No dead zone at this low radiation level—if the LION avoids hot spots.
  - If loss is higher, the 600-ms trip time allows time for ions to acumulate.



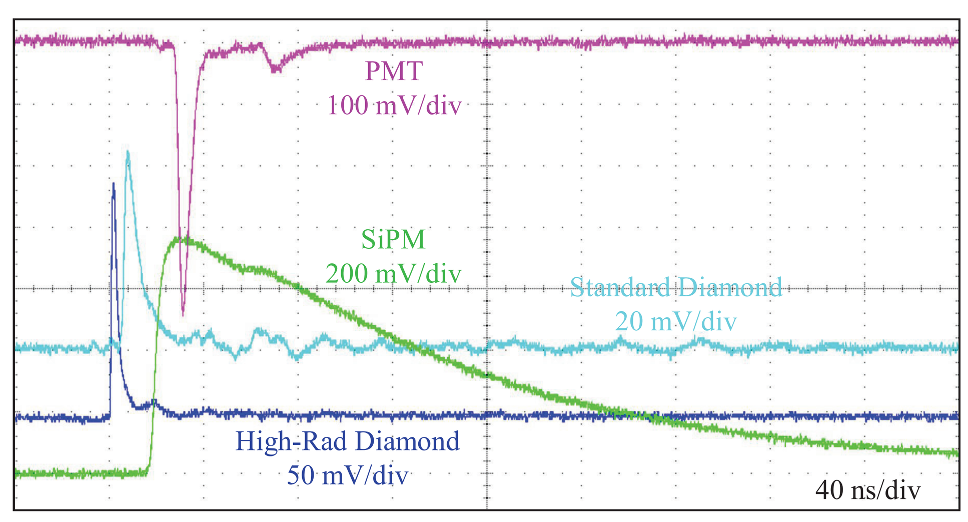
Comparison Tests with Beam



PIC versus Diamonds

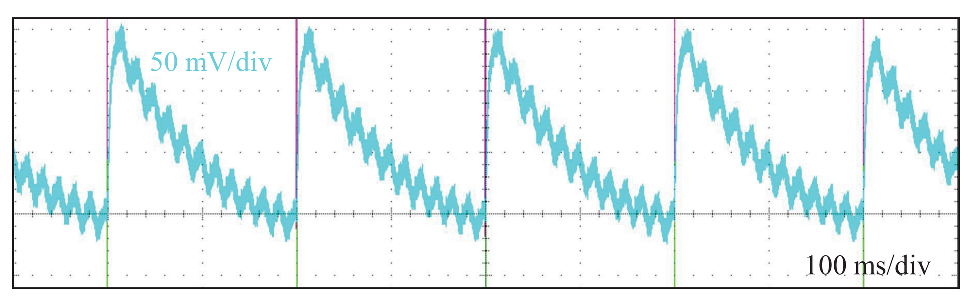


Optical Fiber with PMT and SiPM



LION

- 5-Hz losses with 60-Hz pickup in LION electronics



- Zoom in: 5-ms rise time in LION integrator