Simulation and Shot-by-Shot Monitoring of Linac Beam Halo

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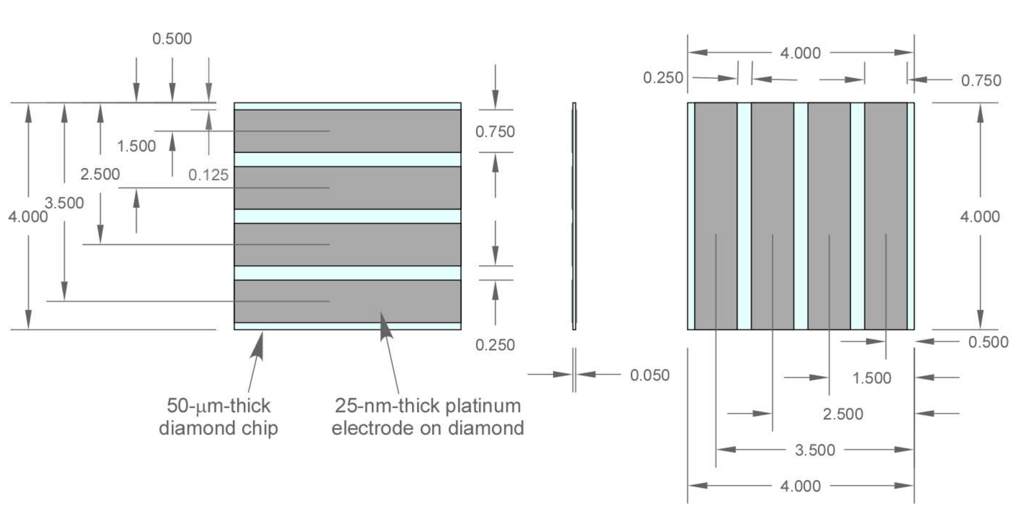
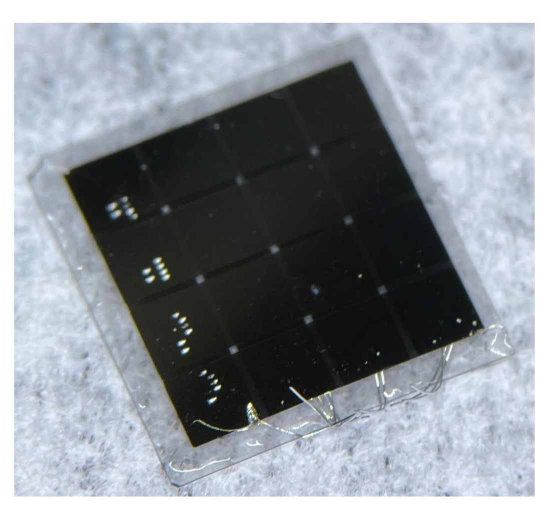
Abstract

FELs require a reproducible distribution of the bunch core at the undulator entrance for robust and reliable lasing. However, various mechanisms drive particles from the core to form a beam halo, which can scrape the beampipe of the undulator and damage its magnets. Collimators can trim the halo, but at the 1-MHz repetition rate of SLAC's LCLS-II superconducting linac, the collimator jaws can be activated and damaged. The Machine Protection System (MPS) can detect excessive radiation and halt the beam, but repeated MPS trips lead to significant downtime. Halo control begins by studying its structure, formation, and evolution, using a sensitive halo monitor. To that end, we are developing a pixellated diamond sensor. Diamond offers a dynamic range of up to 7 orders of magnitude, extending from the edge of the core to the faint halo expected at greater distances. Nalu Scientific has developed fast electronics for high-rate shot-by-shot readout. Initial tests are starting with a prototype 16-pixel sensor at the beam dump of SLAC's FACET-II test facility. The tests and simulations will guide more elaborate sensor designs.

Pixellated Diamond as a Beam-Halo Detector





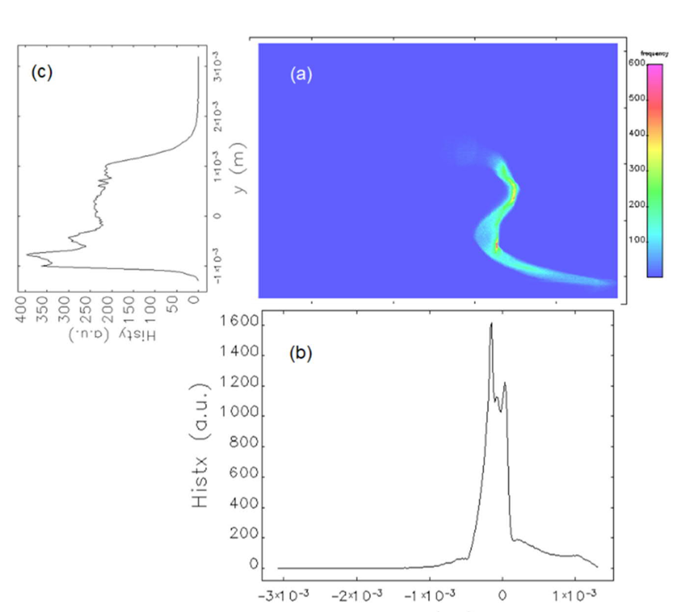
Diamond Sensor for Initial Test

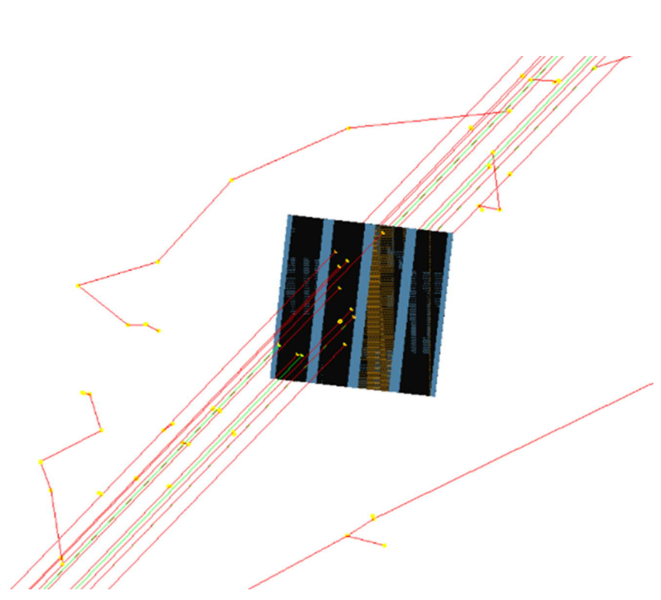
- Chip of single-crystal diamond
  - 4-mm square
  - 50-µm thick
- 4 parallel platinum electrode strips cross each face
  - 750-µm wide
  - 25-nm thick
  - 1-mm period
- Electrode strips are horizontal on one face and vertical on the other
  - Intersections form a 4×4 grid of pixels
- Charge is collected by 30-V bias between electrodes on the two faces.
- Diamond has excellent thermal conductivity and radiation tolerance.
- Low Z makes it less sensitive than other semiconductors to bremsstrahlung photons, which create background.
- As a halo electron passes through the diamond, each 13.3 eV of energy deposited creates an electron-hole pair.
  - Expected loss of 35 keV for a 10-GeV electron at FACET-II → 2600 pairs
  - We anticipate being sensitive to 10 electrons/pixel.
- Linear dynamic range of 11 orders of magnitude has been demonstrated with photons.
  - We anticipate at least 7 orders of magnitude with electrons.
- Future sensors: Several chips with different pixel distributions.
  - Non-invasive: Chips will surround the bunch core but remain outside the stay-clear radius.

Simulating the Halo Test

Simulation with ELEGANT

- Finds essential parameters such as particle position, direction, and energy entering the FACET-II exit flange
- Computes transverse distribution as beam enters flange
  - x and y projections show long tails of halo electrons
- Parameters passed to GEANT4





CIVIDEC FUNCTIONS			
5.9E-05	2.9E-02	4.0E-03	2.4E-05
1.2E-04	7.4E-02	8.5E-04	1.0E-05
1.9E-03	7.9E-02	6.6E-03	1.1E-05
2.7E-02	1.4E-02	5.9E-05	4.9E-06

EDEP FUNCTIONS			
1.0E-04	3.8E-02	5.3E-03	4.0E-05
1.9E-04	9.9E-02	1.2E-03	2.6E-05
2.6E-03	1.1E-01	9.0E-03	2.6E-05
3.7E-02	2.0E-02	9.5E-05	1.4E-05

Relative difference			
40%	25%	24%	41%
36%	26%	28%	60%
28%	27%	27%	56%
27%	27%	38%	66%

Y ⇧ X ⇦

Simulation with GEANT4

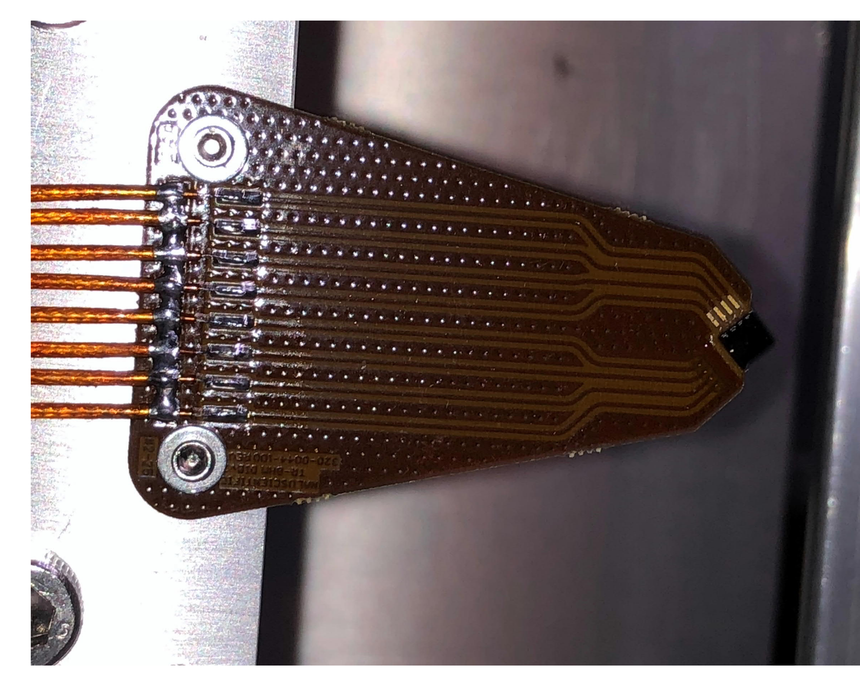
- Accurate model of setup from window through detector
- Beam passes through aluminum window flange and 185 cm of air
- Calculates the energy deposited and the charge collected in the diamond.
- Comparison of two scoring approaches
  - Cividec provided transfer functions with interaction probabilities and charge generated.
    - Only considers electrons, photons, protons and neutrons
  - GEANT4 computes energy deposited in diamond.
    - Each 13.3 eV creates one electron-hole pair
    - Also has deposition by alphas, deuterons, pions and ions
      - Found to be negligible
- Table shows relative differences of 20% to 60%
- Supports the accuracy of the predicted response
- Should provide a good benchmark with the upcoming measurements.

Testing the Halo Monitor at the Beam Dump of FACET-II

FACET-II

- FACET-II is SLAC's test facility for advanced accelerator research, primarily plasma-wakefield acceleration.
- The vertical bend into the beam dump serves as a spectrometer for the resulting wide energy changes from the initial 10 GeV
- The beam passes through >2 m of air, over an optical table and into the dump.
  - The beam exits the vacuum through a 5-mm-thick aluminum window in a flange.
  - The dump table provides a convenient place for a first look at halo.
- After a long shutdown, the beam is about to return to the dump.

FACET-II dump table



A printed circuit connects the 8 electrodes on the diamond (right) to 8 coaxial cables that run to a nearby amplifier box covered in shielding.

Test Setup

- The diamond is mounted at beam height, 185 cm from the window.
- The diamond mounting post is on a 50-mm translation stage
  - Moves the chip into and away from the beam.
- Long coaxial cables connect the amplifier outputs to a digitiser.
  - Digitiser output goes to a computer upstairs, outside the tunnel.
- Nalu Scientific provided electronic and software
  - AARD-VARC digitiser hardware
  - *Naluscope* software for viewing and control.

Test Plan

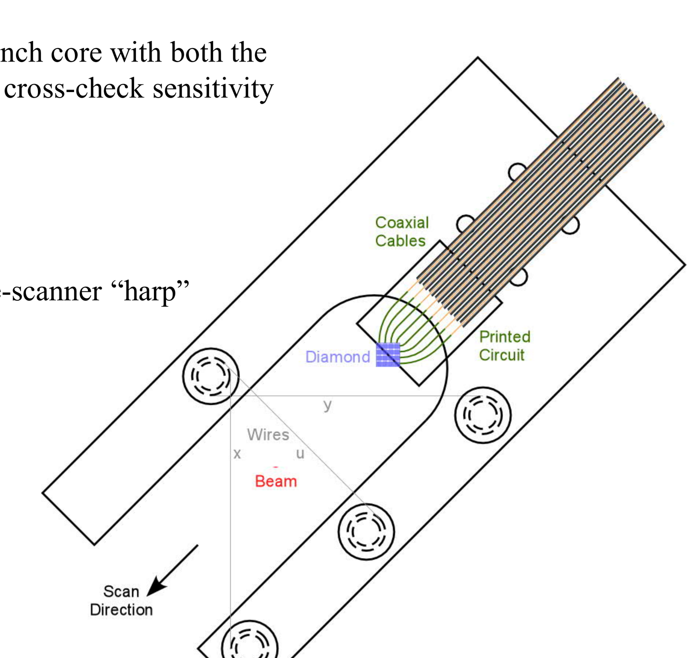
- Translate the diamond slowly toward the beam while monitoring the signals.
  - Look for increase as diamond enters halo.
  - Continue until the beam is approaches within perhaps 2σ of the bunch centre.
  - Avoid saturation and radiation on the simple FR4 circuit board.
- Scan the dump bend vertically across the diamond to shift the halo.
- Scan with a horizontal corrector or with the translation stage (which has a less precise control).
- Dynamic range extends at least between the noise floor when the diamond is fully retracted and the highest level that seems safe.
- Look for changes in halo from adjusting the spectrometer quadrupoles.
- Image the collimator upstream onto the diamond and look for the moving image of the jaws.
- Pixel readout:
  - Ground the horizontal strips on one side. Bias only one vertical strip on the other., which selects an x coordinate.
    - Strip readouts then give a y profile for this x coordinate.
  - Move the bias to the next strip.

Plans for an In-Vacuum Test

Mount Diamond on a Wire Scanner

- Translate the detector in vacuum by modifying a spare LCLS wire scanner
  - Mount the diamond on the "harp"(or "wire card") that moves the 3 wires
  - Diamond can be scanned slowly toward the beam.
- Wire scanner first measures the profile of the bunch core.
  - Find coordinates of centroid relative to diamond pixels to map halo distribution along axis of motion
  - Measure the tail of the bunch core with both the wires and the diamond to cross-check sensitivity

A modified wire-scanner "harp"



Old "slow" wire scanner in LCLS