HIGH-REPETITION RATE DIAGNOSTICS USING DIAMOND SENSORS

RENE PADILLA

SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS, UC SANTA CRUZ

MARCH 15, 2023

INSTITUTIONS INVOLVED IN THE ADVANCED ACCELERATOR DIAGNOSTICS COLLABORATION

- Universities
  - UC Santa Cruz, Santa Cruz Institute for Particle Physics
  - UC Davis, Crocker Nuclear Laboratory
  - UC Santa Barbara
- National Laboratories
  - Los Alamos National Laboratory (LANL)
  - Lawrence Berkeley National Laboratory (LBNL)
  - SLAC National Laboratory (SLAC)

Funded by the University of California Office of the President

MOTIVATION

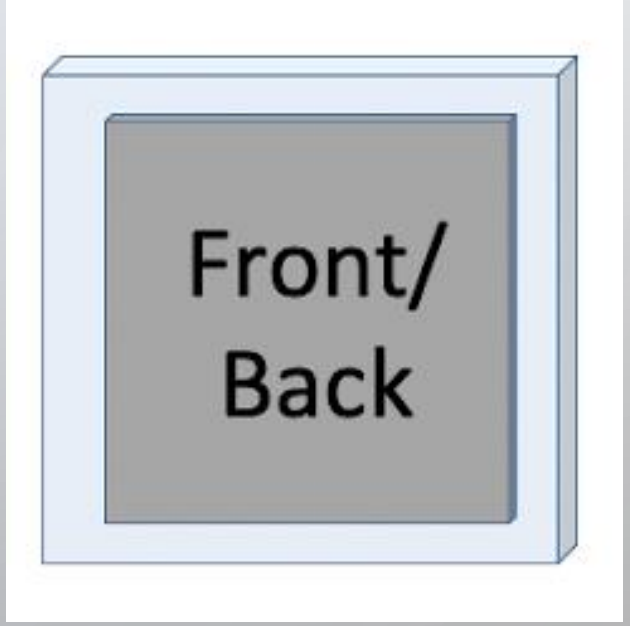
- High frame rate position pass-through diagnostics will be of great use for the accelerator community, and can lead the way to high frame-rate imaging
- Multi-GHz frame rate ionizing particle detection is an underexplored area in detection technology (currently reaching up to 500 MHz)

XFEL motivations (Upcoming upgrades)

- CBXFEL requires position sensitive diagnostics in the 20 MHz range
- Multi-RF-bucket operation (LCLS) → up to 3.5 GHz repetition rate
- Next generation XFELs Facilities (MARIE, …) → 10 GHz repetition rate
- Intrinsic SASE fluctuations will require pulse-by-pulse position sensitive diagnostics operation over a large dynamic range

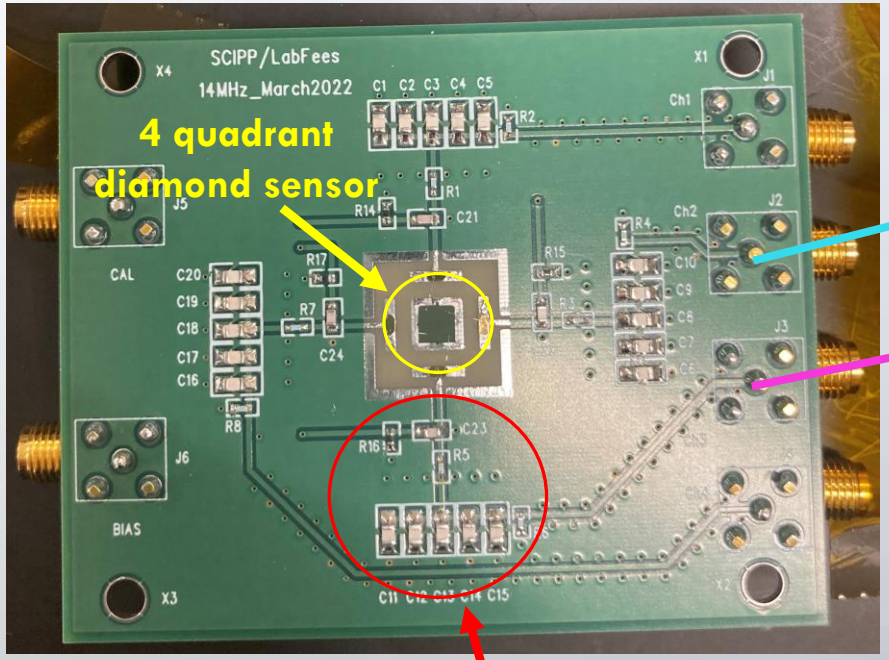
Monocrystalline Diamond Characteristics

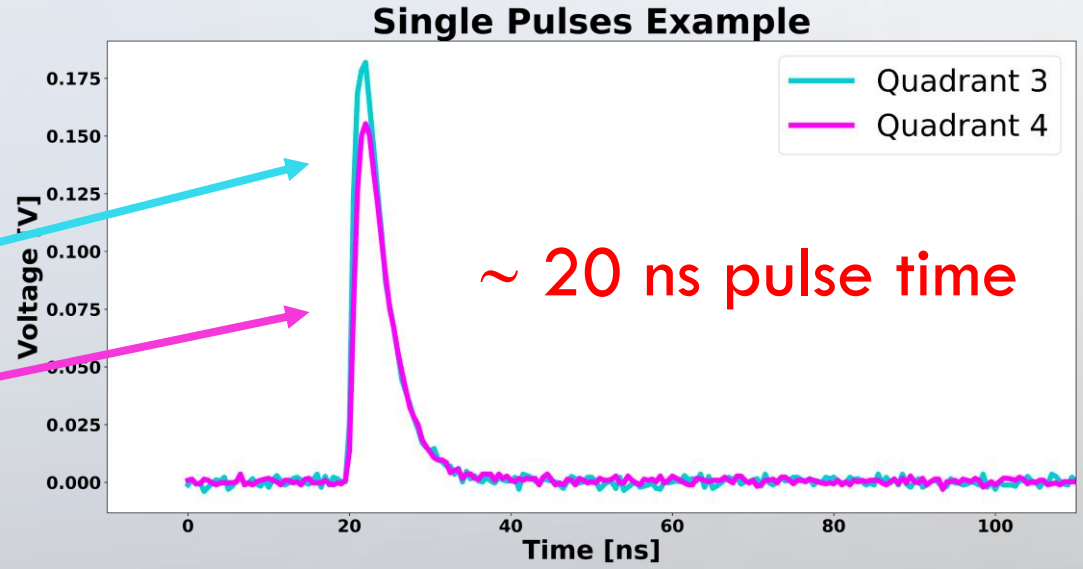
- **Drift velocity saturates at about 3V/µm at 200 µm/ns**
  - For saturated 500 µm sensor charge collected in 2.5 ns
  - For saturated 30 µm sensor charge collected in 150 ps
- **Expected to be highly radiation tolerant**
- **Thermal Conductivity of 2200 W/m-K**
  - Copper has 386 W/m-K
- **Energy bandgap 5.5 eV**
  - Electron/hole rate at 13.3 eV/eh-pair
  - Limiting the production of signal charge
- **Low atomic number leads to small scattering cross section**
  - Limiting the absorption of XFEL beam

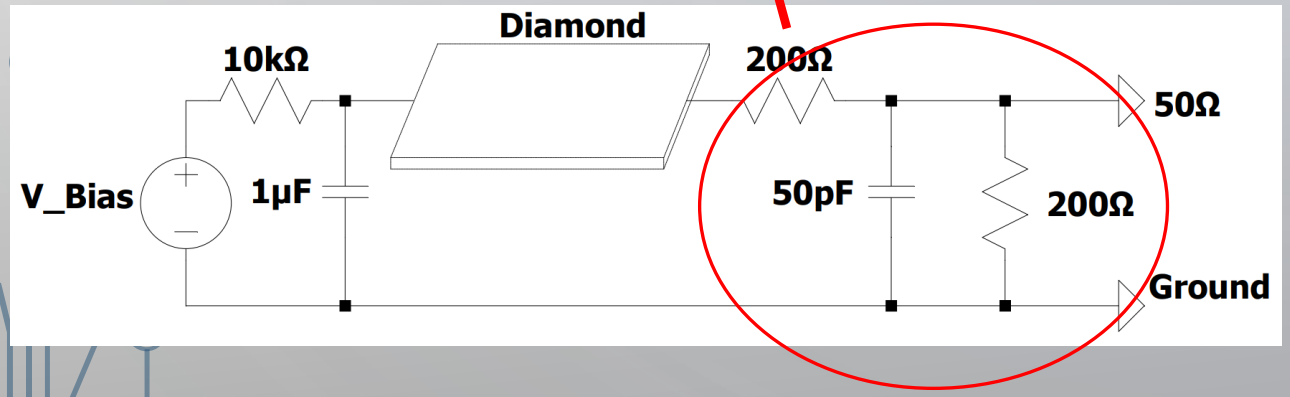


50 MHz POSITION SENSITIVE DIAGNOSTIC (FOR CBXFEL APPLICATION)

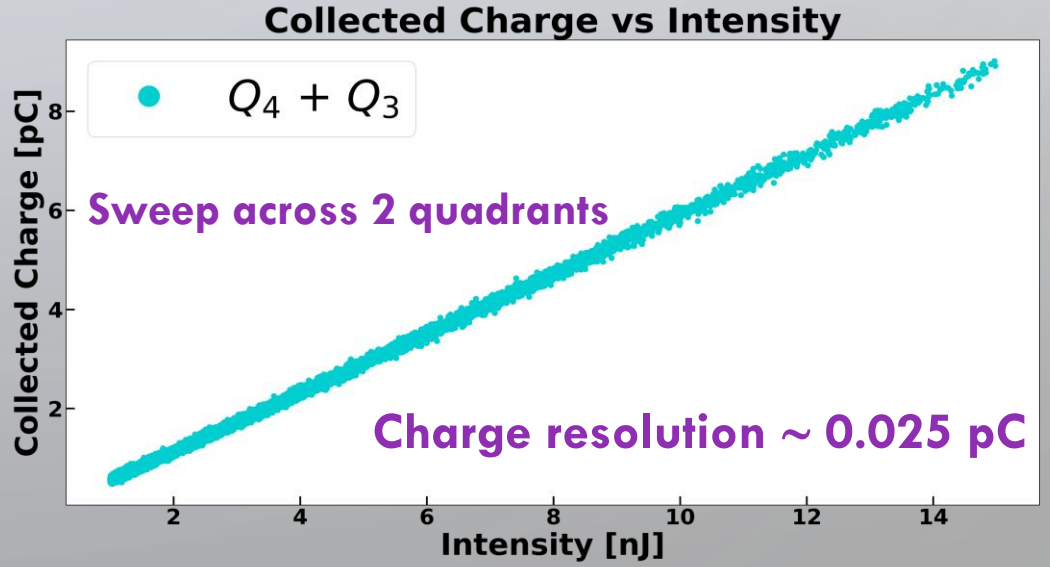
50 MHz POSITION SENSITIVE DIAGNOSTICS



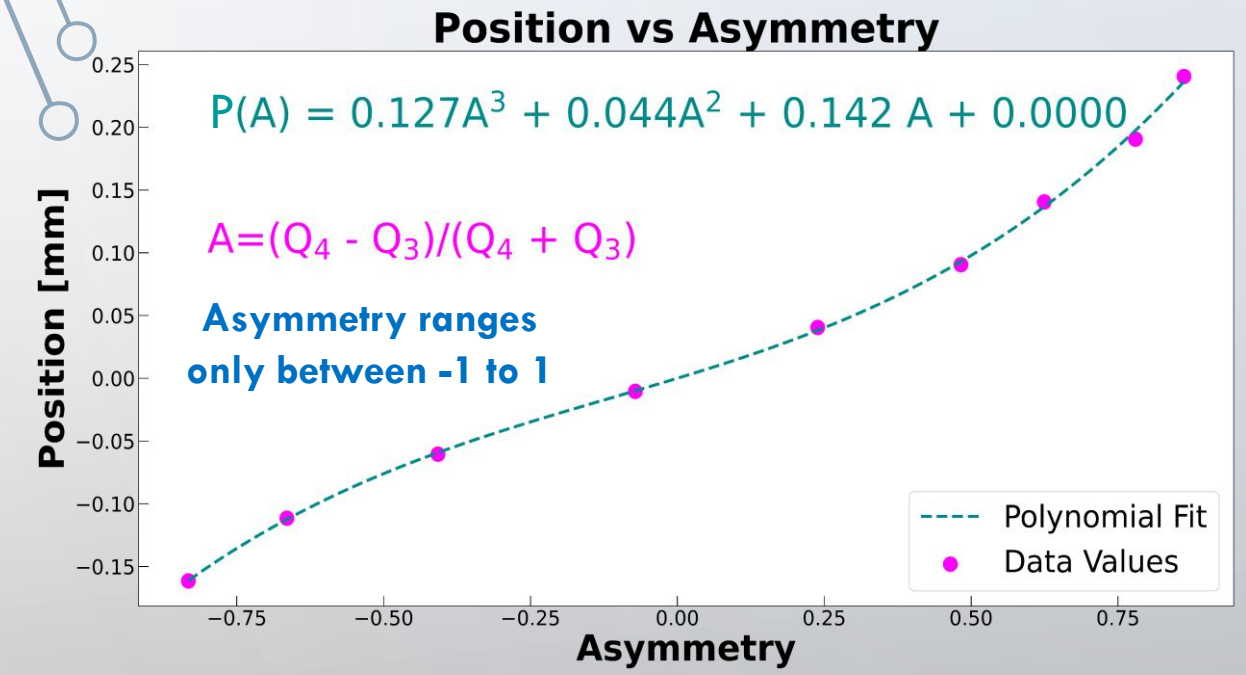




~ 10 ns shaping network



POSITION RESOLUTION RESULTS



$$\sigma_p = \frac{dP}{dA}\sigma_A$$

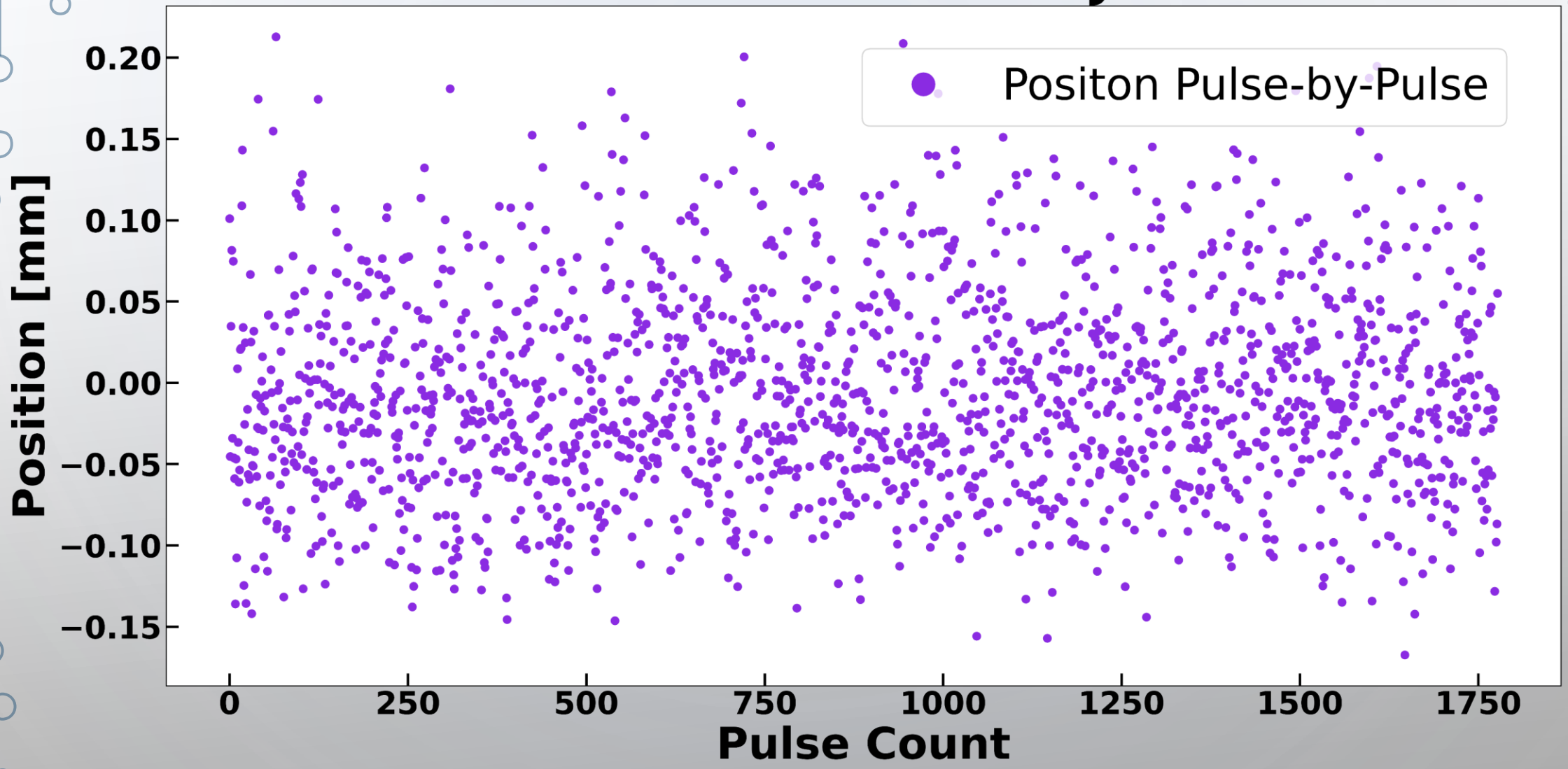
→ Position Resolution

$$\sigma_A = \frac{\sigma_Q}{Q}\sqrt{1 + A^2}$$

→ Asymmetry Uncertainty

For 4 nJ pulse ~ σ_Q of 0.025 pC yields to 2 µm centroid position resolution (pulse-by-pulse)

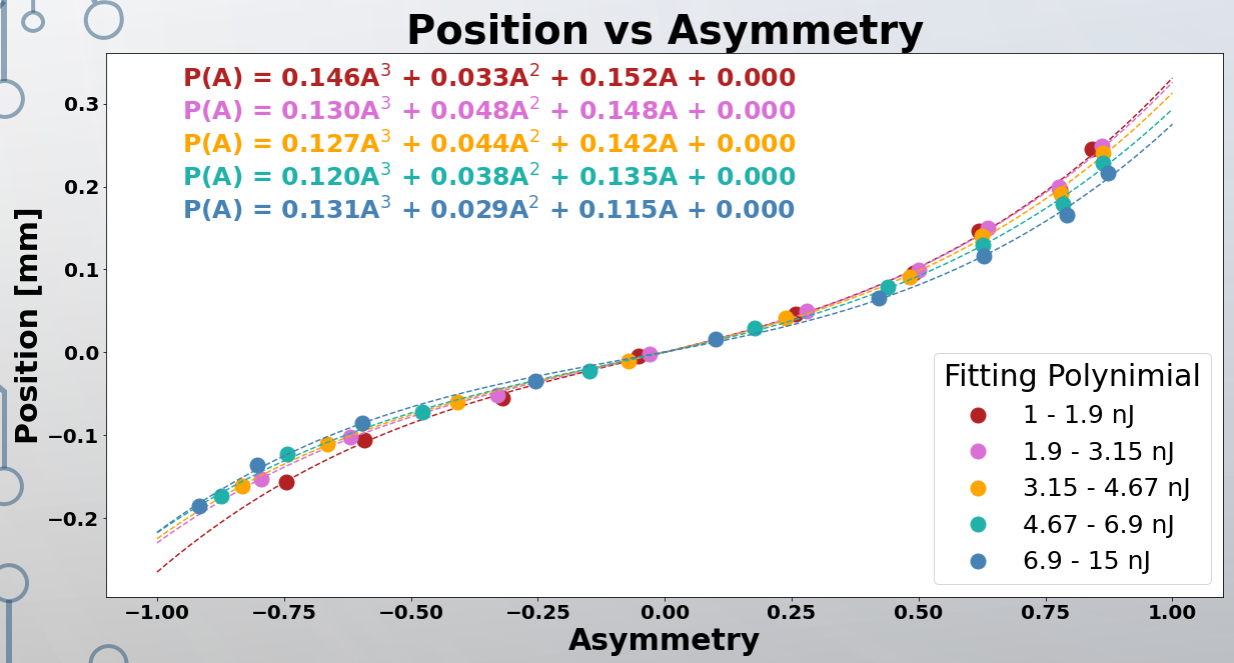
Measured XPP Beam Jitter

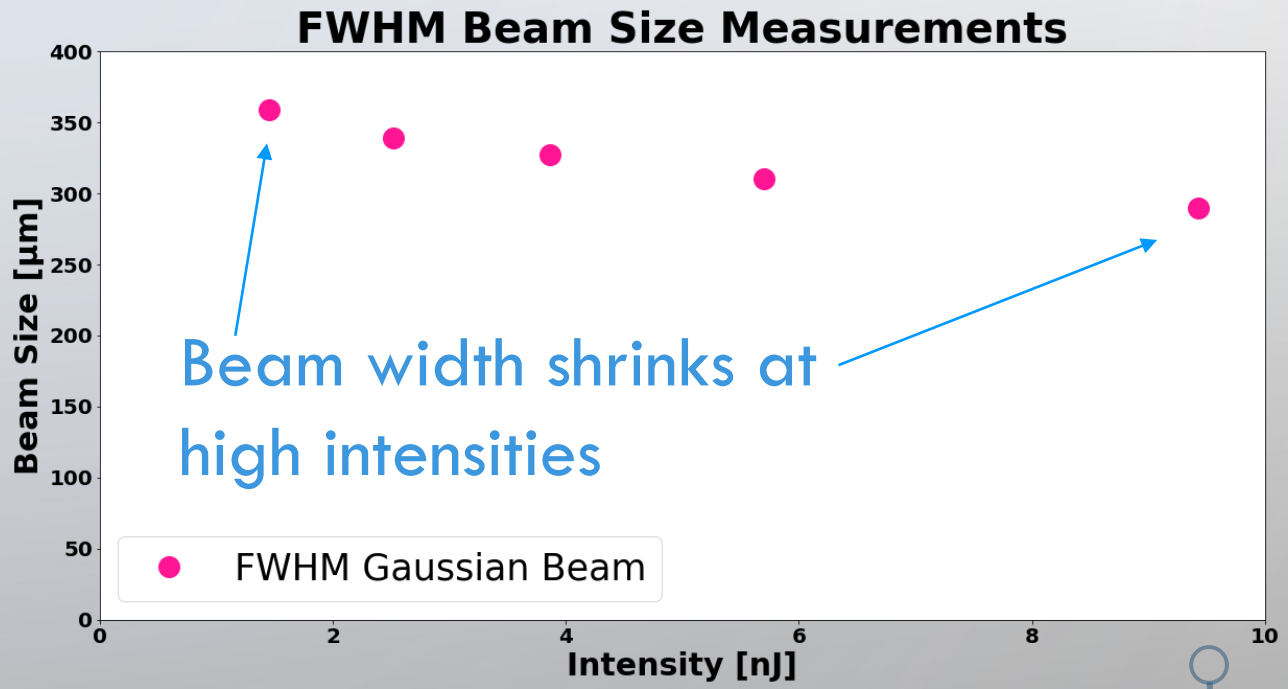


Diagnostic capable of 2 μm resolution at 50 MHz

FWHM BEAM MEASUREMENTS

Shape of measured asymmetry function from the sweep gives FWHM beam size

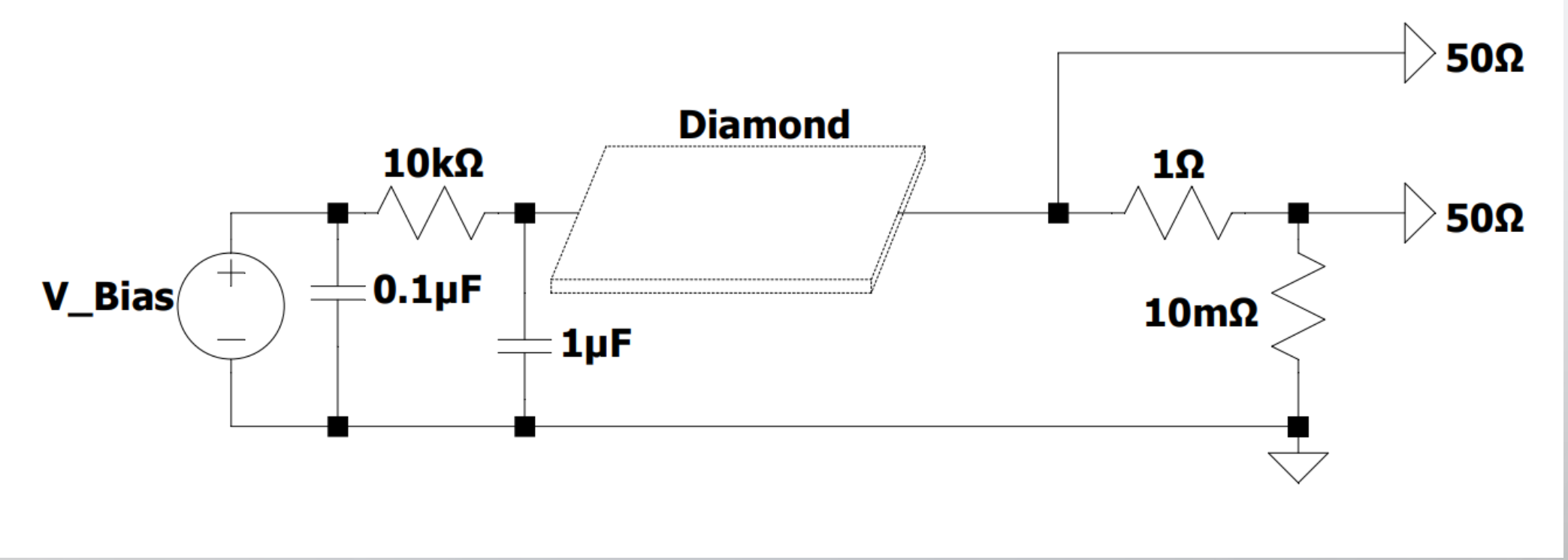




- **Calculations assume a gaussian profile**
- **We were surprised to learn that the spot size shrinks with intensity**

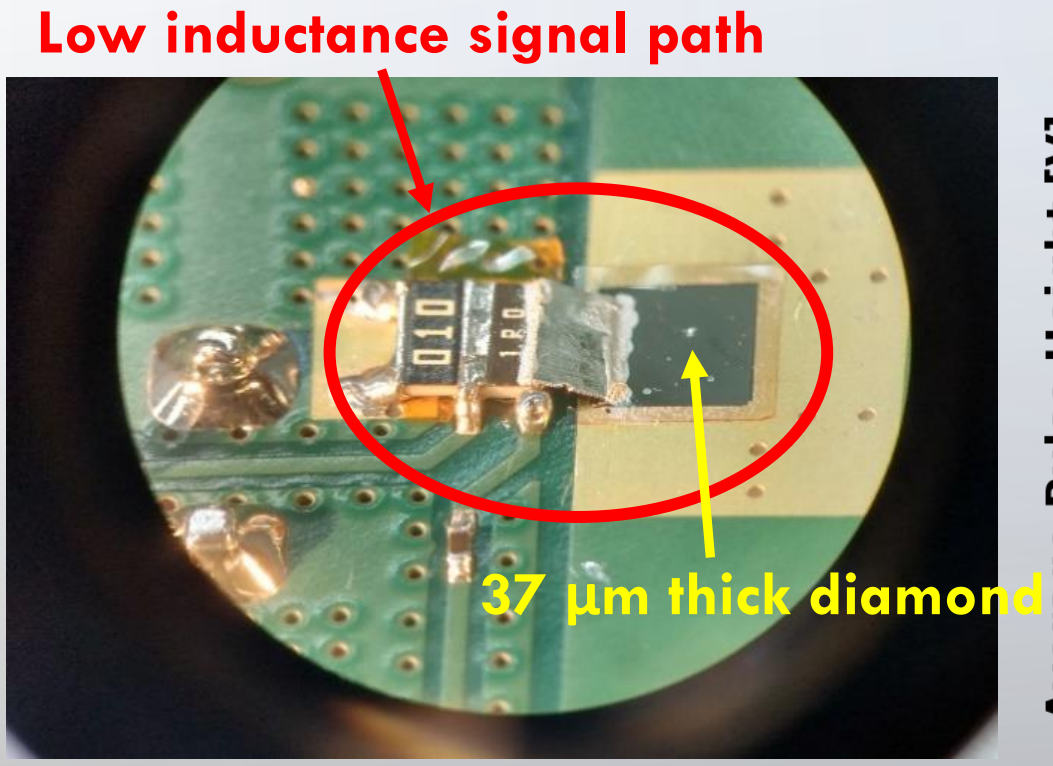
1 GHz PASSTHROUGH DIAGNOSTICS AND CHARGE COLLECTION CHARACTERIZATION

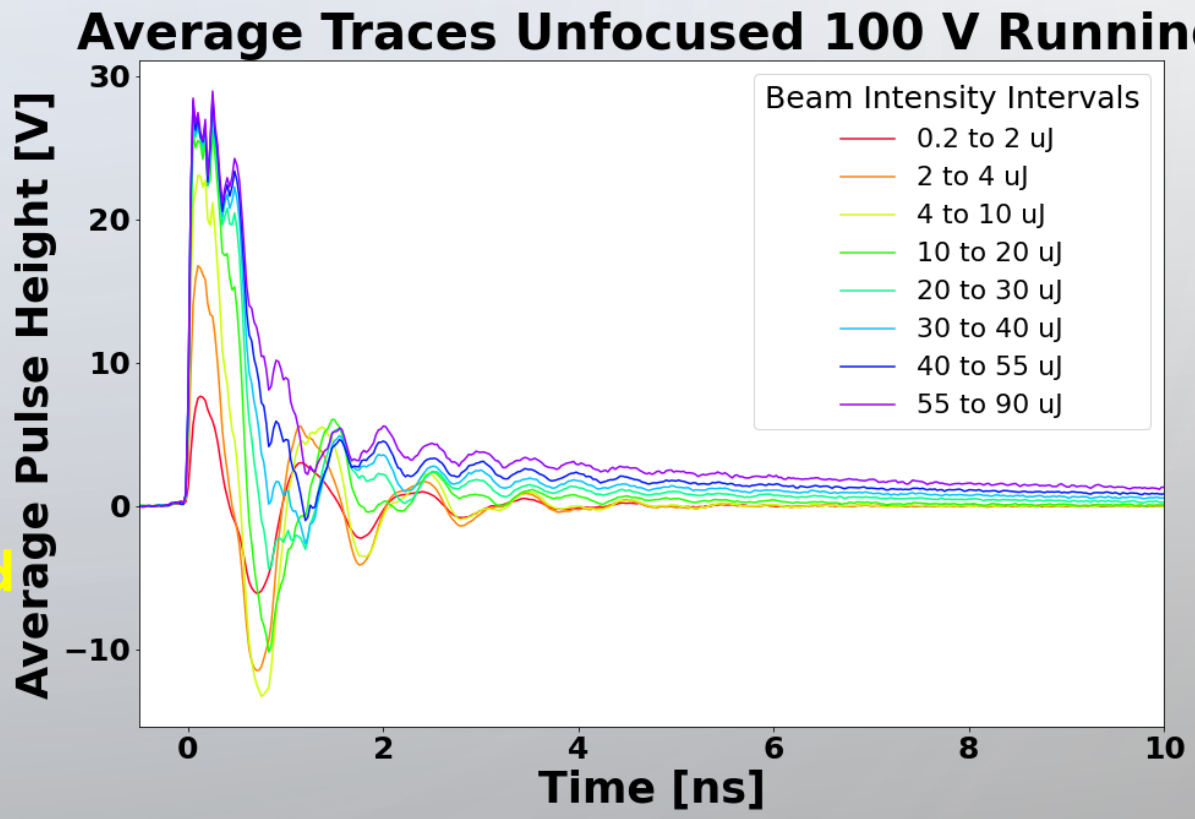
1 GHz BOARD SIGNAL PATH APPROACH



- The μF capacitor provides signal charge for high intensity pulses
- The 1.01 Ω resistor network provides low impedance signal path to ground
- But we need to worry about stray inductance ($Z = \omega L$)

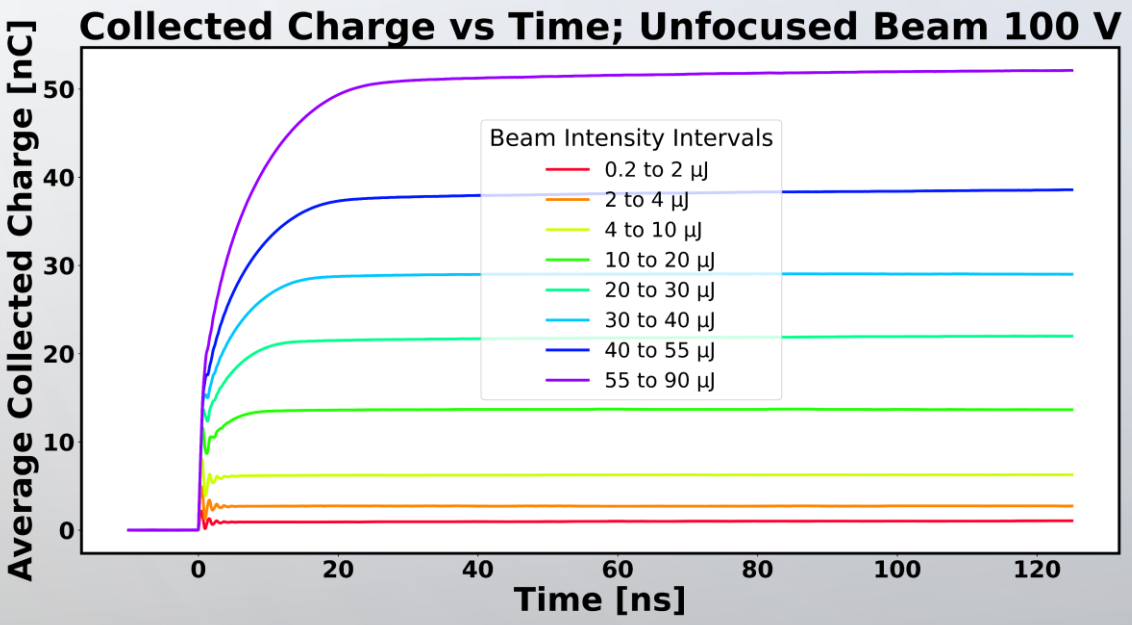
1 GHz BOARD AND PERFORMANCE

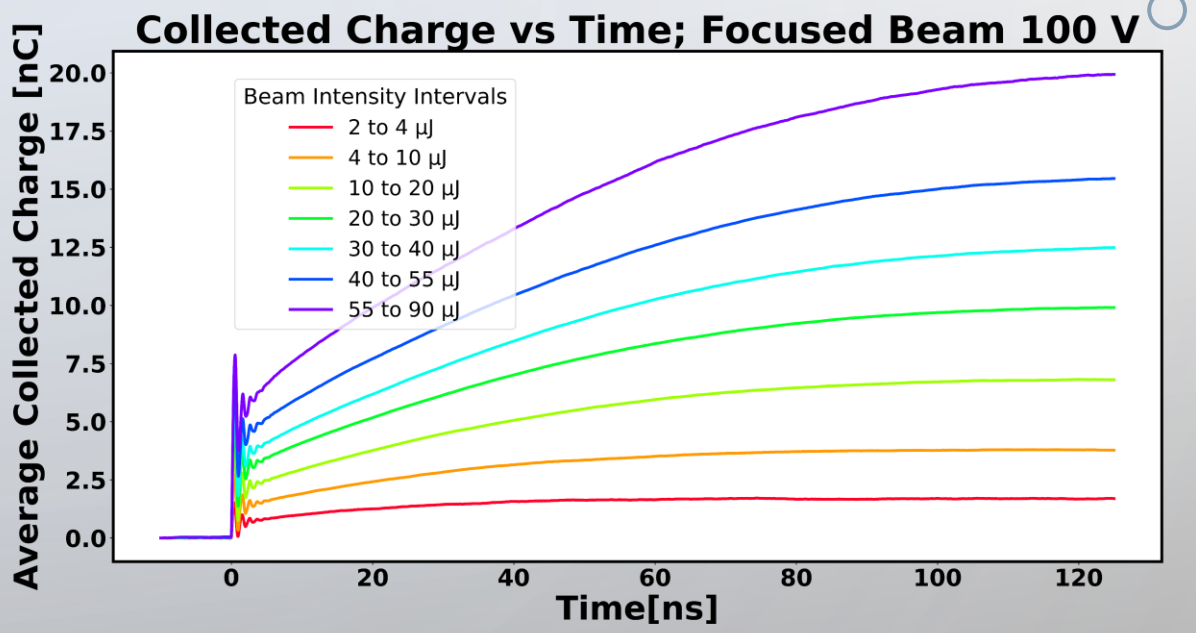




- **Intrinsic charge collection time ~ 200 ps**
- **For low intensity signal duration 1 ns but with some ringing**
- **For higher intensity internal space charge field slows charge collection**

DIAMOND BEHAVIOR UNDER VARYING BEAM SIZE



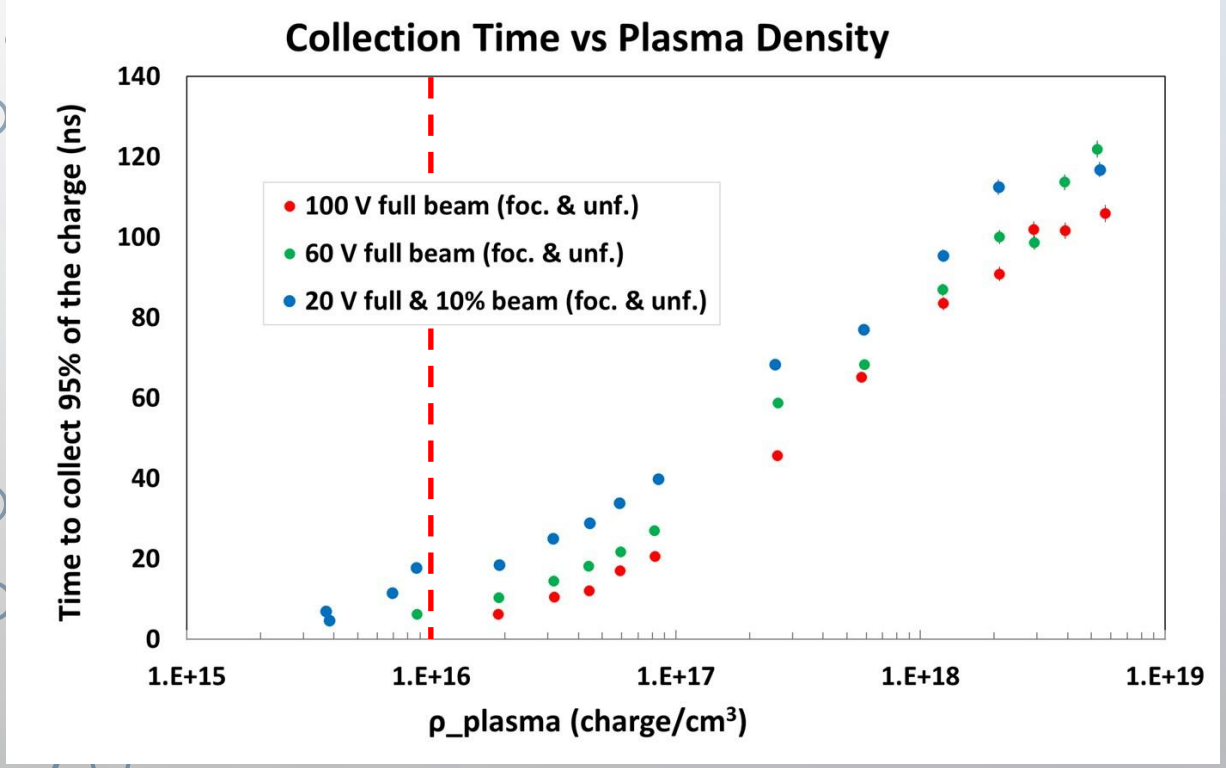


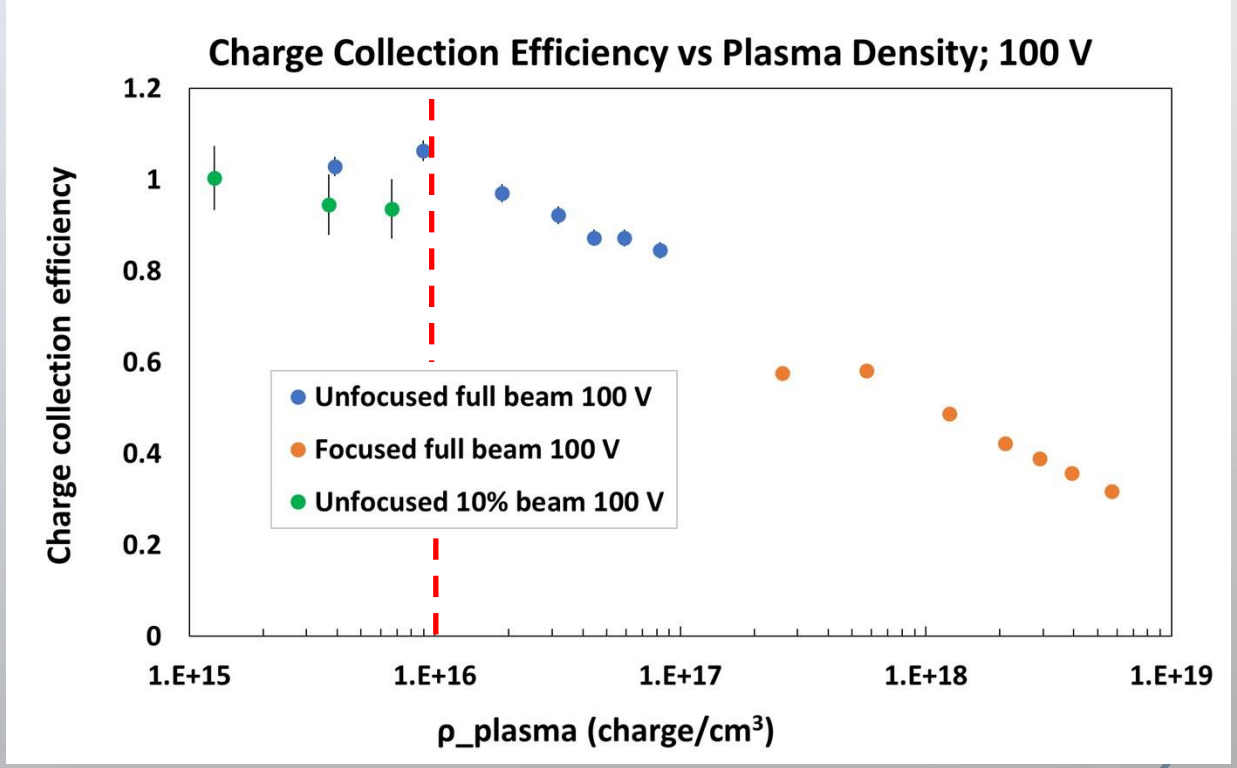
FWHM beam size ~ 350 μm

FWHM beam size ~ 43 μm

Collection rate slows with increasing "plasma" density ρ_{plasma} of released e/h pairs

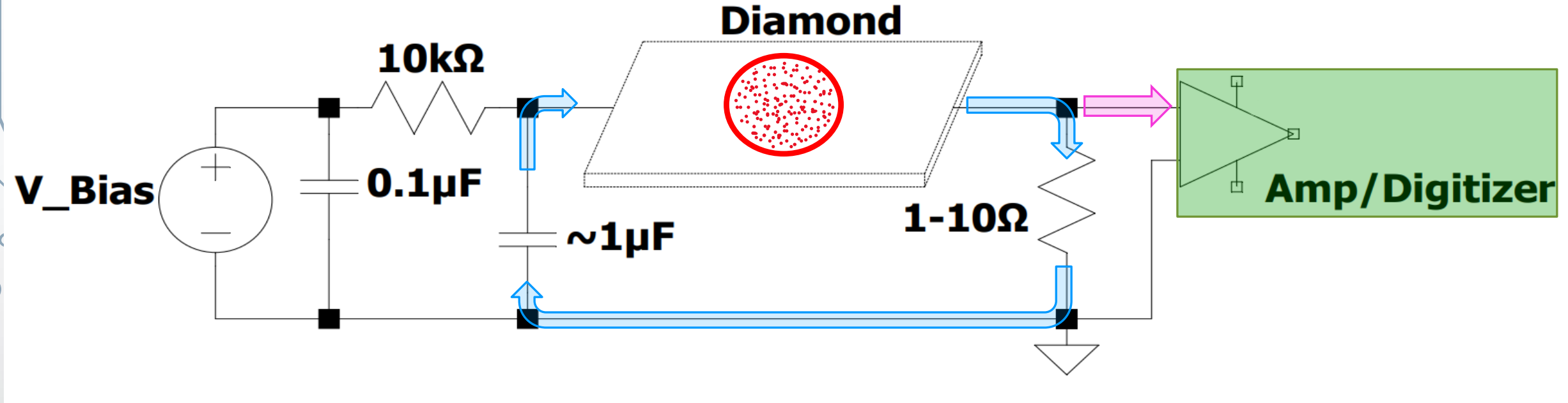
CHARACTERIZATION IN TERMS OF PLASMA DENSITY





Charge collection begins to degrade at densities of 10^{16} charge/cm^3

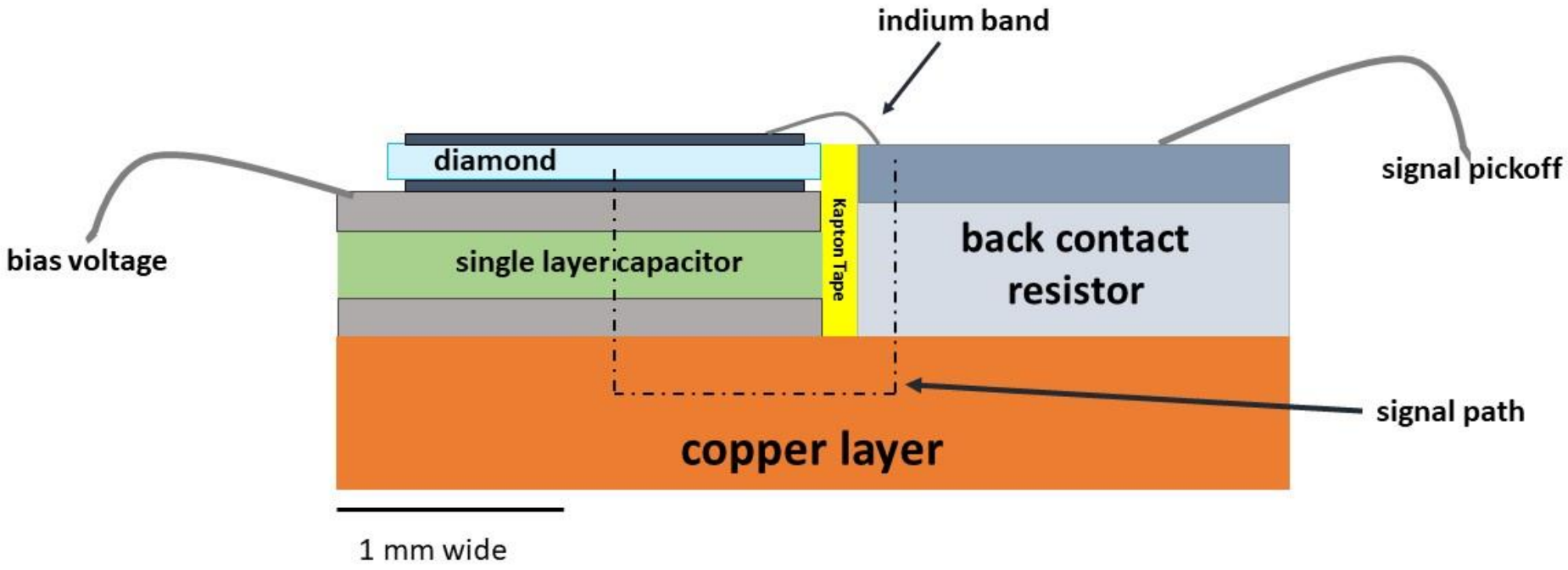
MULTI-GHz DIAGNOSTIC DEVELOPMENT



- **We have divided the challenge into 4 areas**
  - **Charge Collection**
    - Seems fast and efficient up to 10^{16} charges/cm^3
  - **Signal Path**
    - How fast the signal can return to ground without ringing
  - **Signal processing (amplification/buffering and digitization)**
    - High speed electronics development
  - **Interfacing of signal path with signal processing features**
    - RF Engineering

SIGNAL PATH

Limit the effects of induction by making ultra-compact signal path



Under patent review

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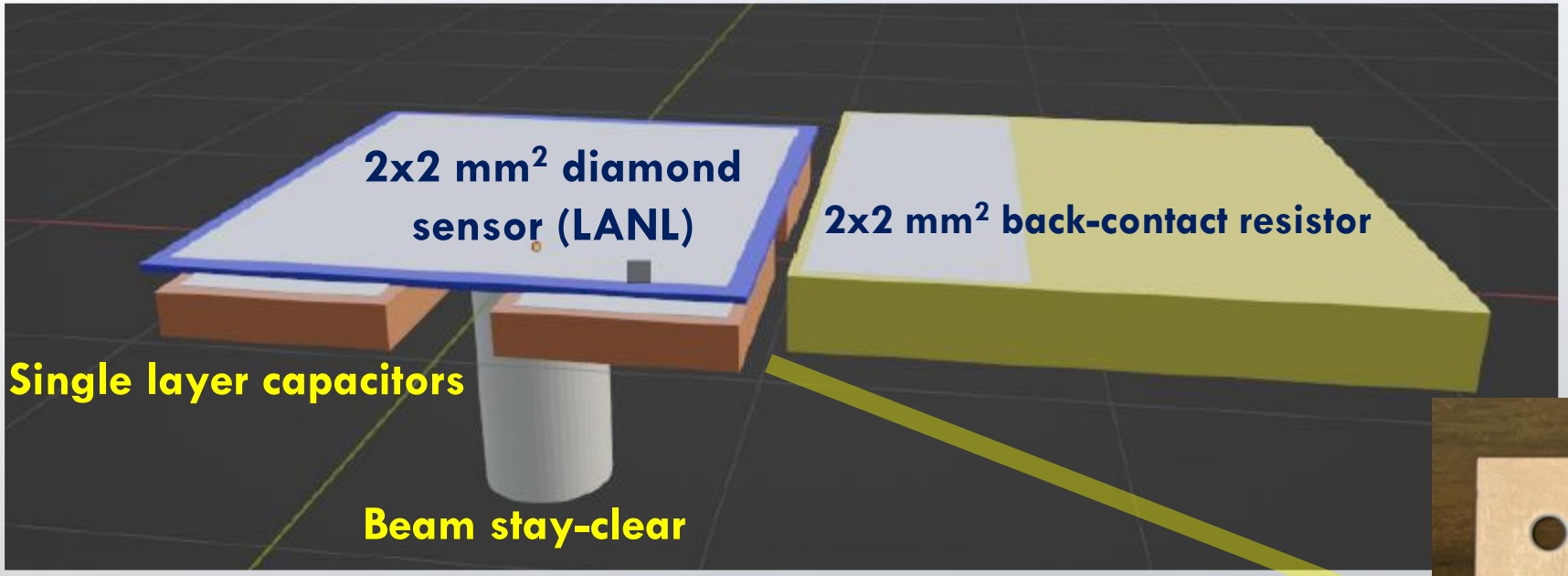
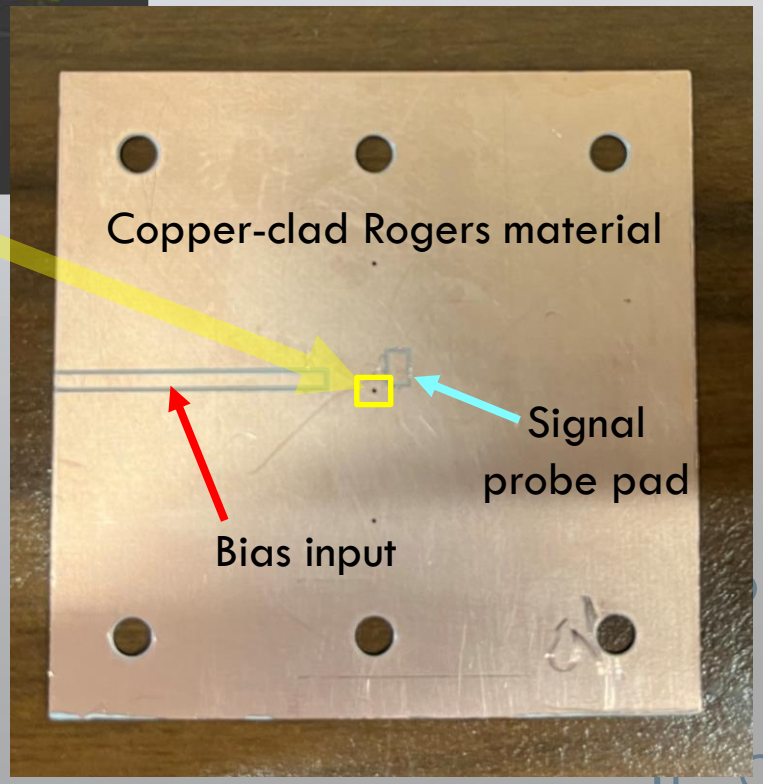
CAD LAYOUT OF SIGNAL PATH SCHEME

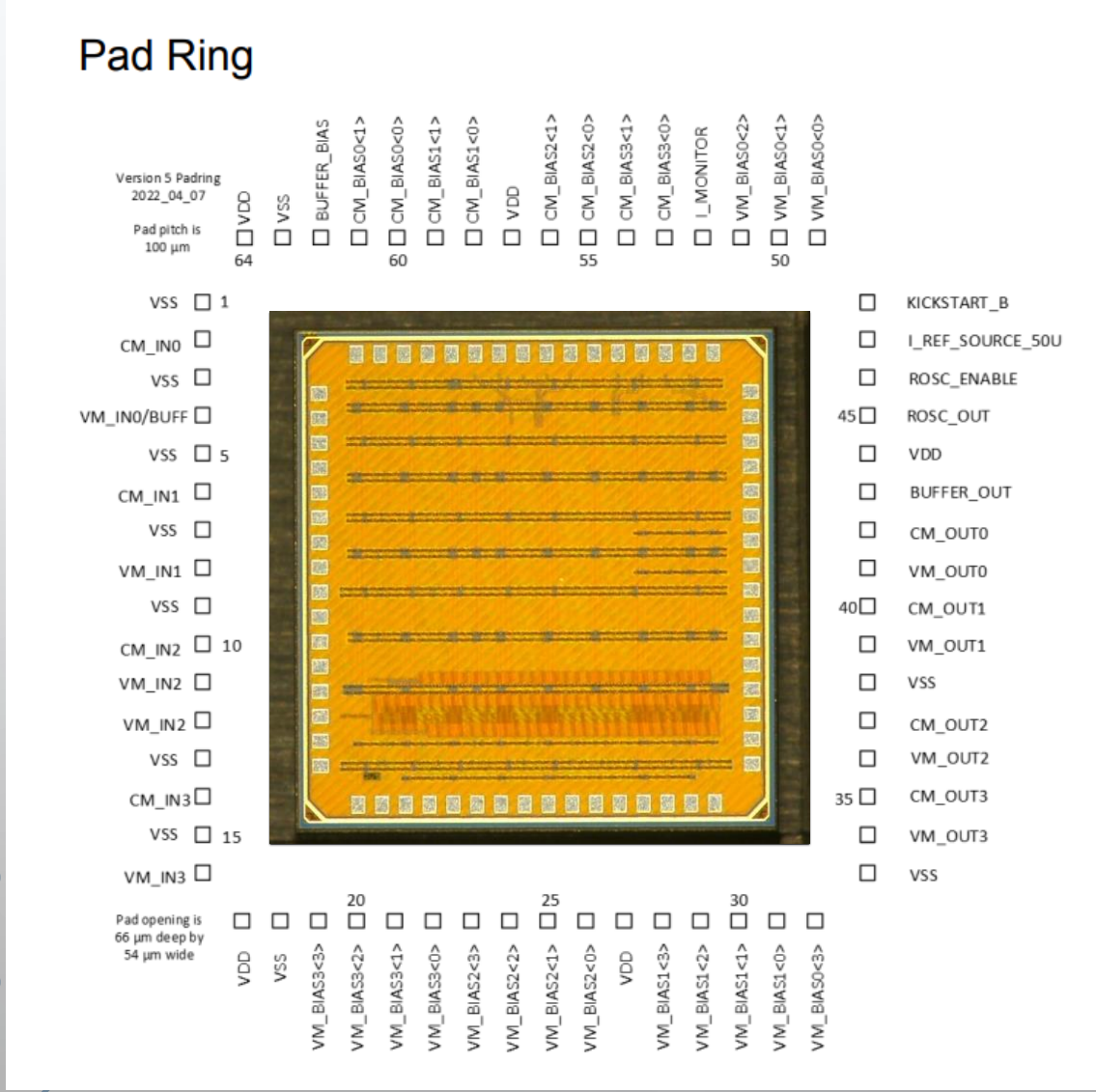




- Fabrication underway at SCIPP laboratory
- Hope to test it at LCLS this year

SIGNAL PROCESSING

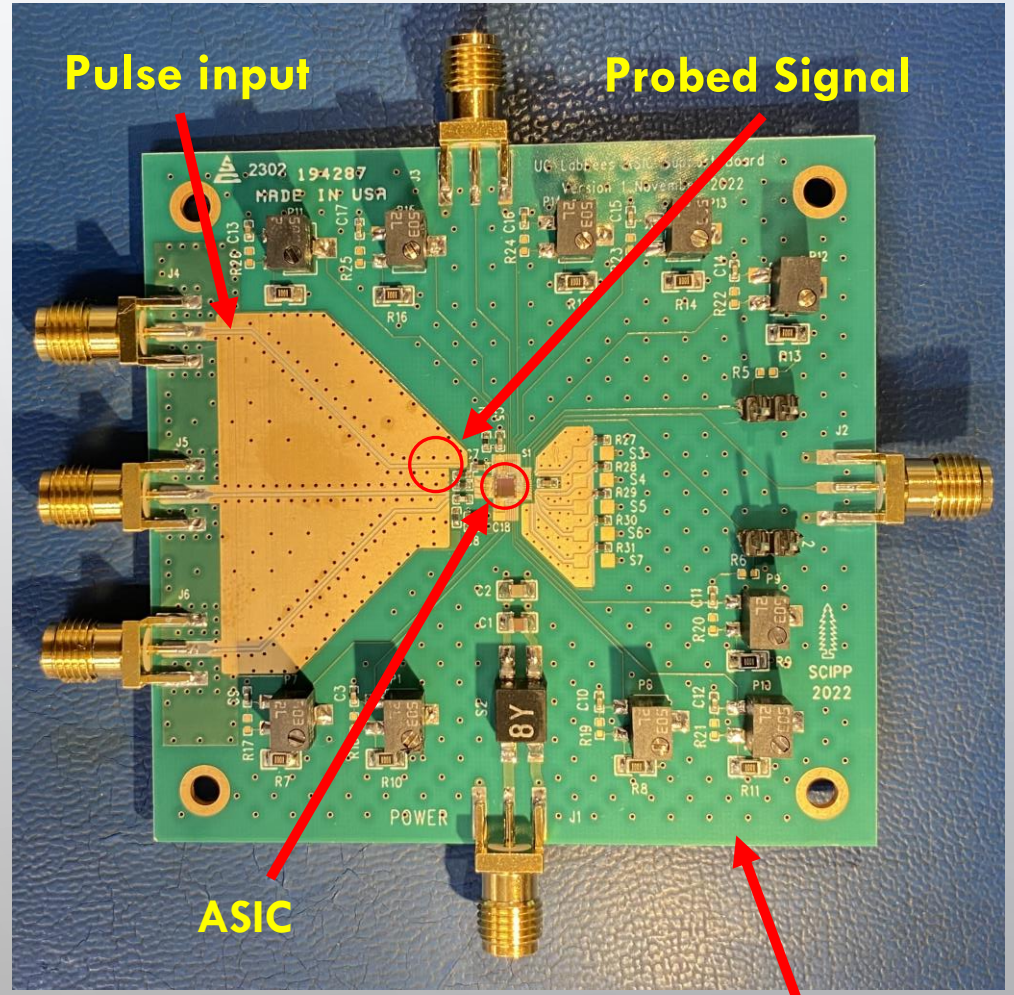
High-Bandwidth Amplifier-Buffer ASIC (LBNL, Davis)

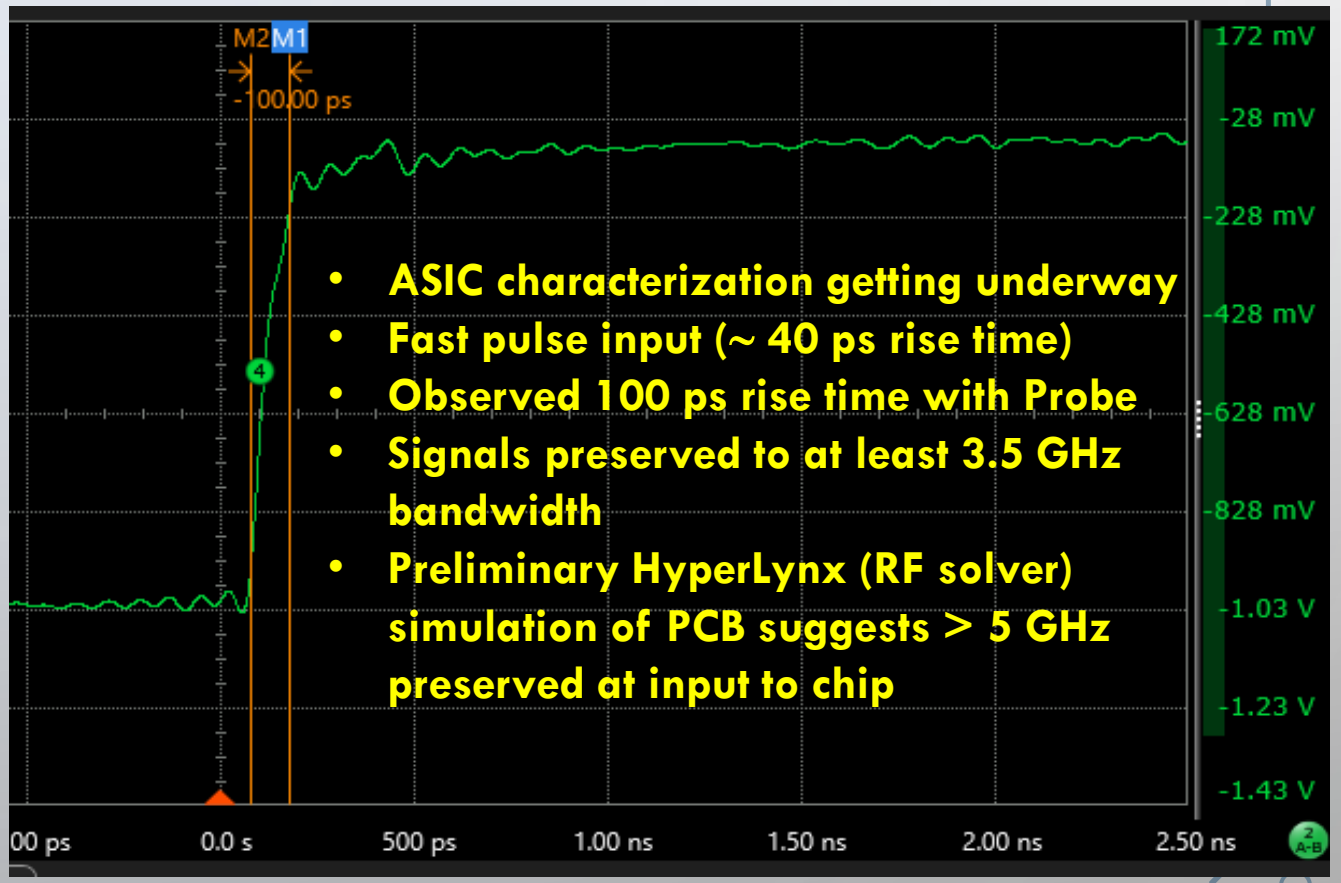


- **11 GHz bandwidth**
- **Charge-sensitive inputs**
- **Voltage-sensitive inputs**
- **40 Gs/s on-board digitization (under development)**

ASIC chip capable of amplifying, digitizing, and storing multiple pulses

SIGNAL TRANSPORT AND PROCESSING CHARACTERIZATION





- ASIC characterization getting underway
- Fast pulse input (~ 40 ps rise time)
- Observed 100 ps rise time with Probe
- Signals preserved to at least 3.5 GHz bandwidth
- Preliminary HyperLynx (RF solver) simulation of PCB suggests > 5 GHz preserved at input to chip

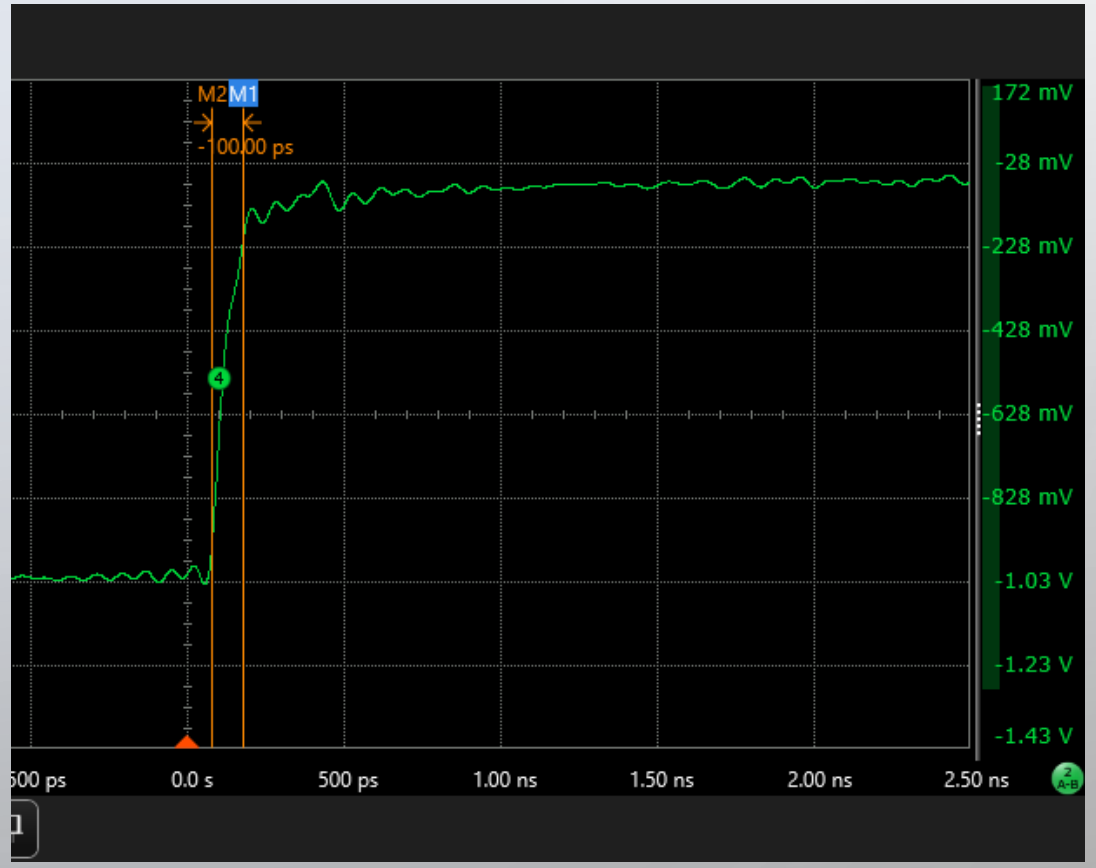
"Rogers Material" used by RF community for signals above ~ 2 GHz

CONCLUSION

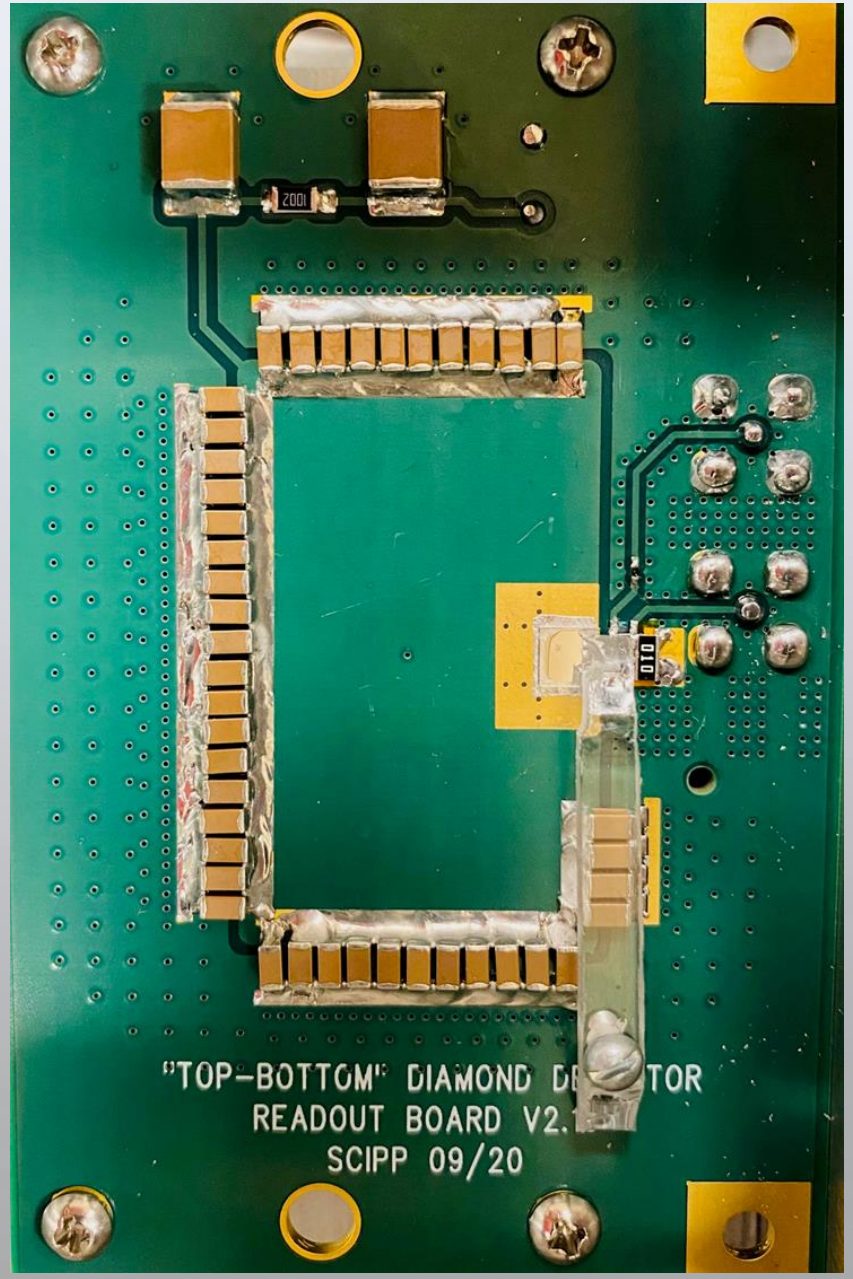
- Quadrant pass-through diagnostic achieves 0.025 pC charge resolution and 2 µm position resolution at 50 MHz repetition rate
- 1 GHz pass-through diagnostic developed and used to characterize charge collection in diamond
  - At high intensity → internal space charge field impacts charge collection
  - Charge collection efficiency and speed degrades for plasma densities above 10^{16} charge/cm^3
- Multi-GHz pass-through system under development
  - So far, signal integrity preserved to at least 3.5 GHz (probably greater than 5 GHz) over 5 cm trace
  - 11 GHz amplifier ASIC being characterized
  - Ultra-compact signal readout path to be fabricated soon

BACK-UP SLIDES

PROBE TRACE AT SIGNAL INPUT



1 GHZ COMPLETE BOARD



PLASMA DENSITY DEFINITION

#eh-pairs/volume generated by the beam

$$\rho_P = \frac{1}{2}\frac{Q_{dep}}{V_{dep}}$$

$$V_{dep} = \pi T \left(\frac{d}{2}\right)^2$$

Overall scale uncertainty of approximately ± 30%