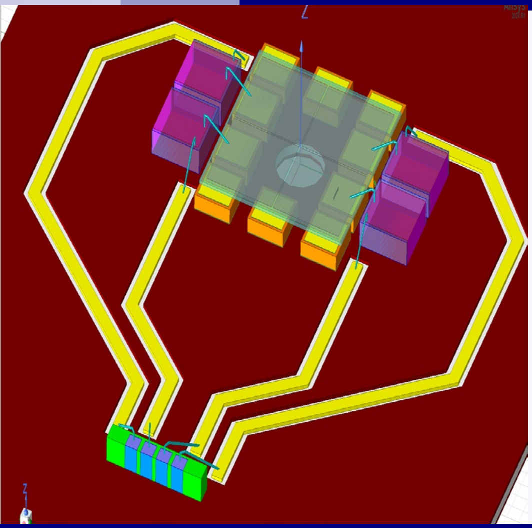
IBIC 2024

Beijing, China

September 9-13, 2024

Development of ultra-fast diamond-sensor based systems for advanced accelerator diagnostics



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Santa Cruz Institute for Particle Physics
and the
University of California, Santa Cruz

Sponsor: US Dept of Energy

Talk Outline

The elements of this presentation include:

- The Advanced Accelerator Diagnostics (AAD) Collaboration
- Diamond as a sensor material
- Warm-up: 50 MHz position-sensitive pass-through diagnostic
- Towards high bandwidth
- Integrated multi-GHz detection system idea
- Readout studies (electronics only)
- Signal path studies (sensor and signal path only)
- Speculation about applications
- Summary and Prospects

The Advanced Accelerator Diagnostics Collaboration

- Consists of six University of California Campuses and National Labs
  - UC Santa Cruz (Santa Cruz Institute for Particle Physics), UC Davis, UC Santa Barbara
  - Lawrence Berkeley NL, Los Alamos NL, SLAC NL
- Funded by the University of California Office of the President and the US Department of Energy
- Developing diagnostic systems for XFEL, synchrotron and proton beams
- Also performing basic diamond sensor R&D (transport properties, radiation tolerance)
- Work in this talk driven by XFEL developments but applications likely broader

Diamonds Sensor Characteristics

Some aspects of diamond as a sensor material

- Large electron/hole pair creation energy (13.3 eV vs. 3.6 ev for Si)
- **Fast transport (200 μm/nsec vs. 100 μm/nsec for Si)**
- Highest thermal conductivity of any natural material
- Superior radiation tolerance
  - No appreciable leakage current to fluence > 5×10^{16} n_{eq}/cm^2
  - Significant charge collection efficiency remains

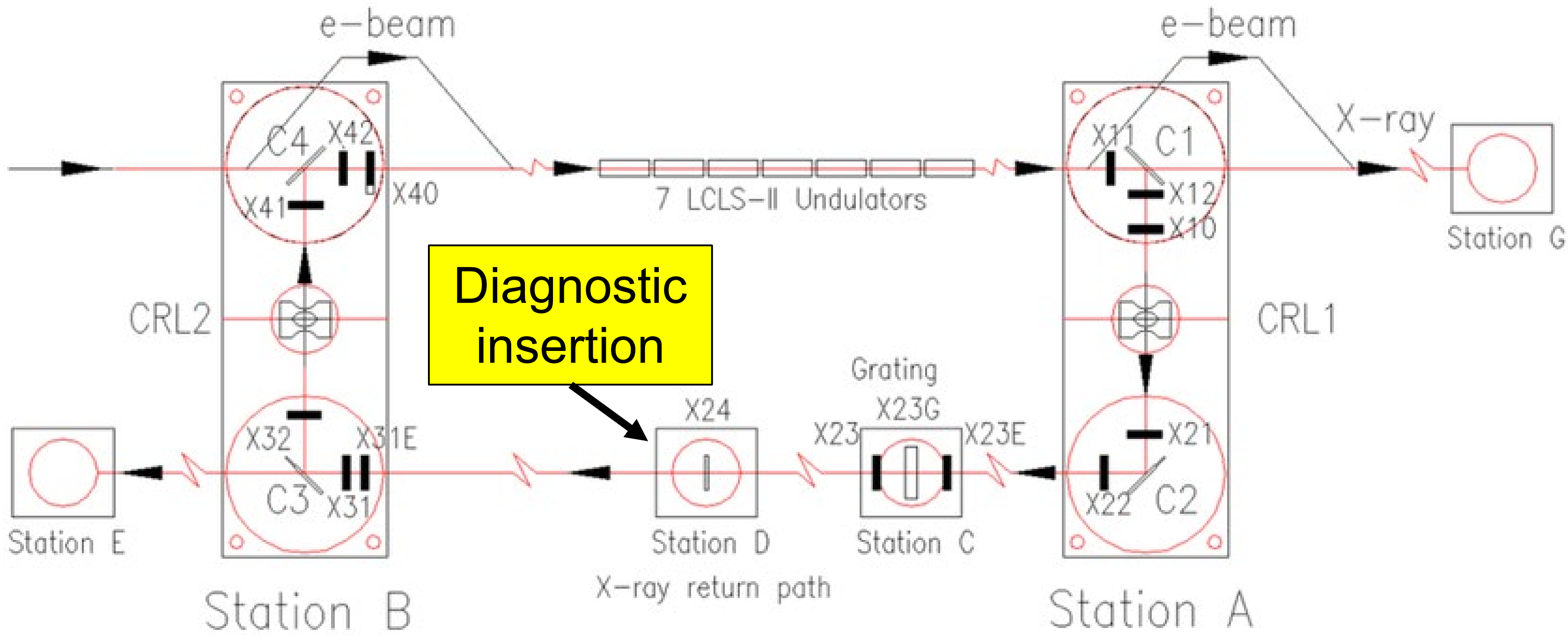
- Low X-ray absorption (K-shell energy <300 eV)
- Commercially available “electronic grade” CVD diamond has essentially infinite carrier lifetime

Second (bolded) characteristic is most important for this talk.

Warmup: 50 MHz Quad Pass-Through Diagnostic

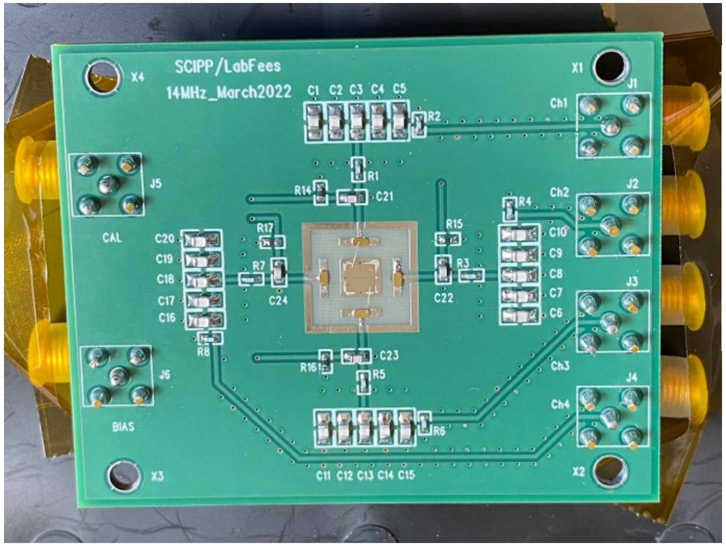
Cavity-Based XFEL (CBXFEL) Development (SLAC/ANL)

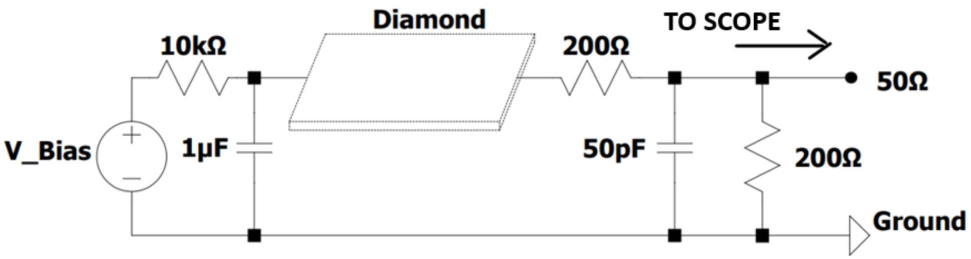
- Requires position/intensity measurement of recirculating beam
- > 20 MHz recirculation rate



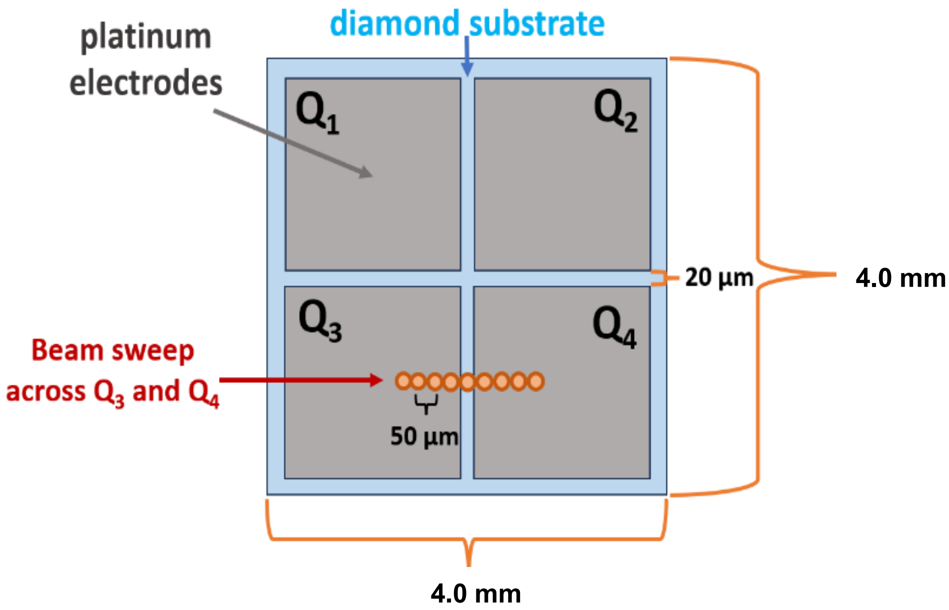
➔ Design multi-MHz quadrant diagnostic

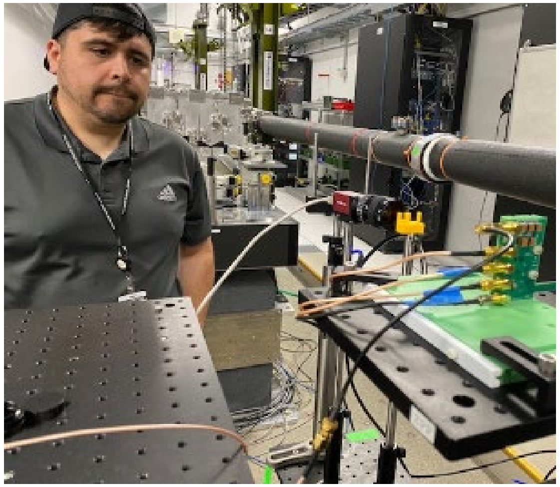
AAD 50 MHz Quadrant Diagnostic





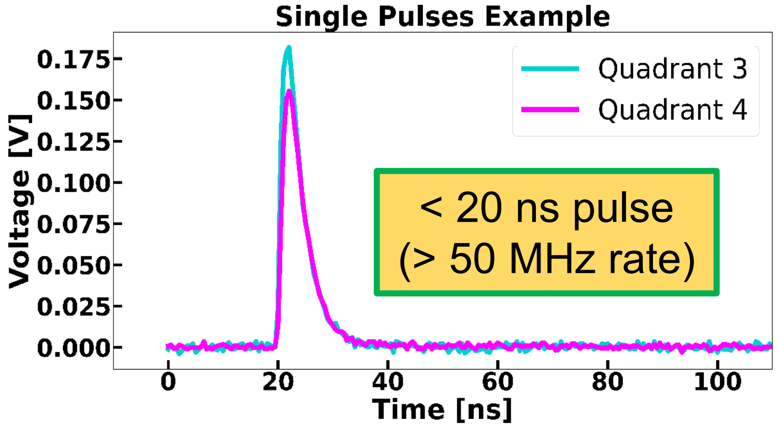
Passive shaping network (x4)

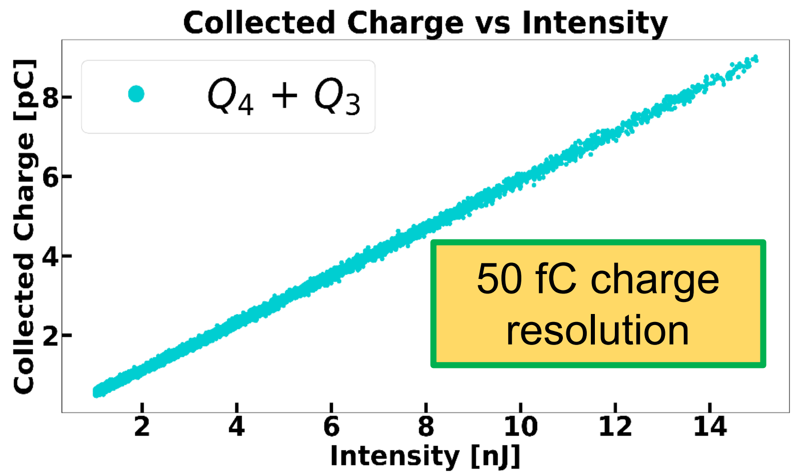


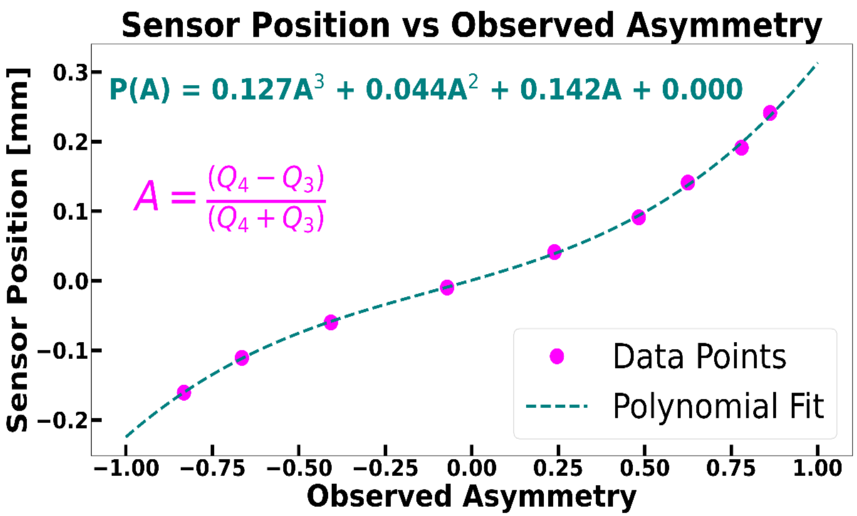


Test at SLAC LCLS, April 2022 (1D beam sweep)

50 MHz Quad Diagnostic Performance







$$\sigma_P = \frac{dP}{dA}\sigma_A \approx \frac{dP}{dA}\frac{\sigma_Q}{Q}$$

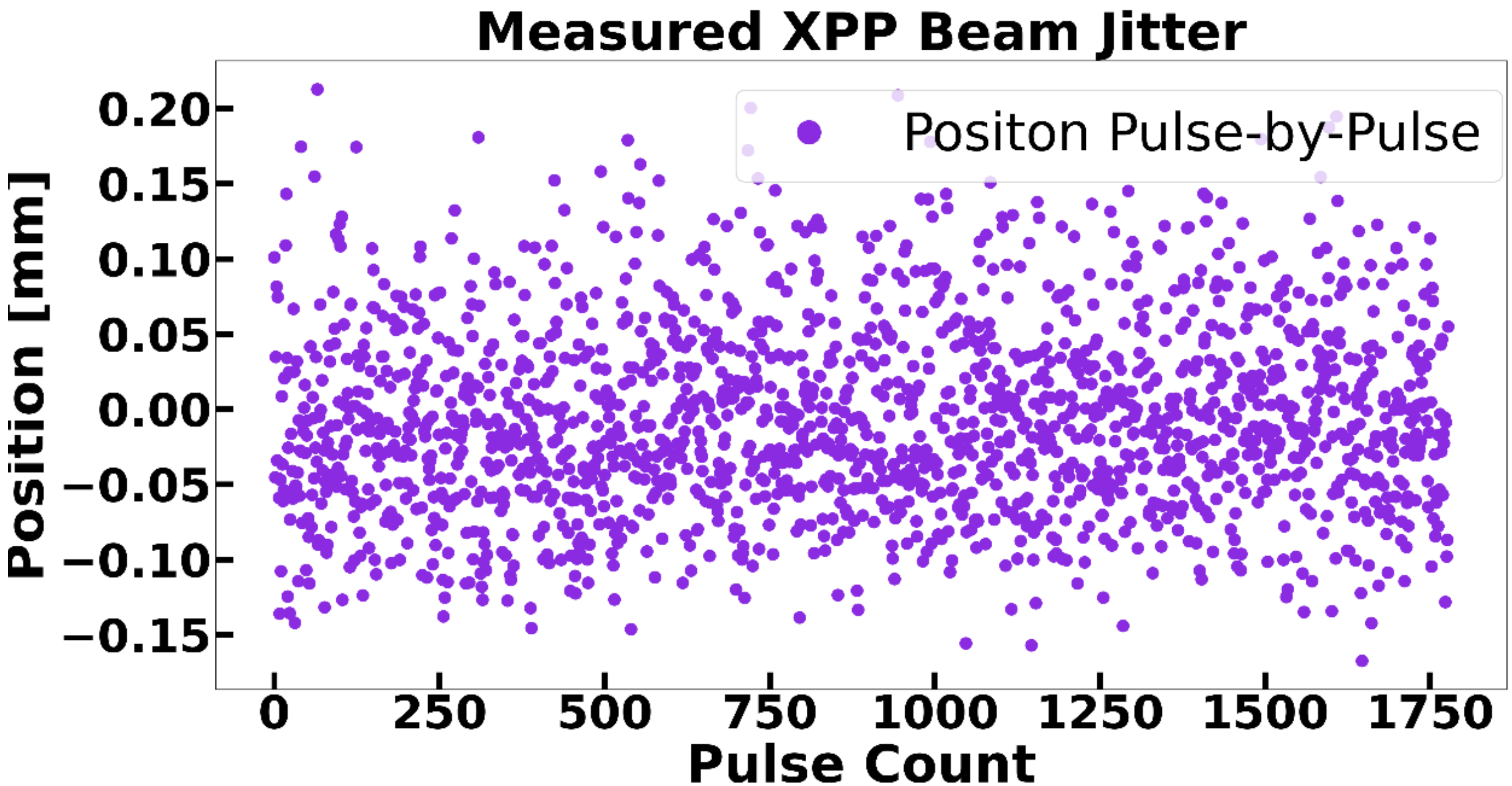
For a low-ish CBXFEL intensity of 4 nJ, this yields

$$\sigma_P \cong (0.01)\sigma_{beam} \cong \mathbf{3\mu m}$$

for a beam FWHM of 300 μm

R. Padilla et al., "A 50 MHz position sensitive pass-through diagnostic for XFEL applications", to be submitted to J. Synchrotron Radiation

Example 50 MHz Quadrant Diagnostics Result



3 μm resolution small fraction of observed pulse-by-pulse jitter

Question: How to do this at 5+ GHz?

Original motivation: intended high repetition-rate XFEL facilities; multi-GHz operation via pulse splitting and delay

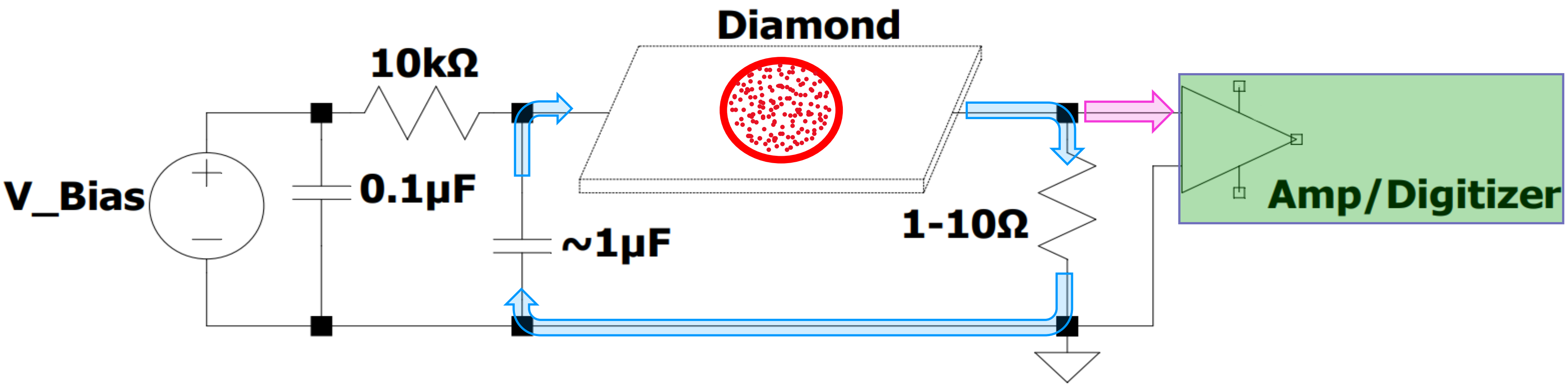
- LCLS to 3 GHz [F.J. Decker et al., Proceedings of FEL2010]
- LANL to 10 GHz [R.W. Garnett, Proceedings of LINAC2016]
- Other applications conceivable (see end of talk for some)

Above 1-2 GHz, enter “RF regime” where inductance and electrodynamics starts to take hold

➔ Compact, integrated approach

Entering second year of three-year US Dept of Energy-funded project to explore this question

Components of the High Bandwidth Problem



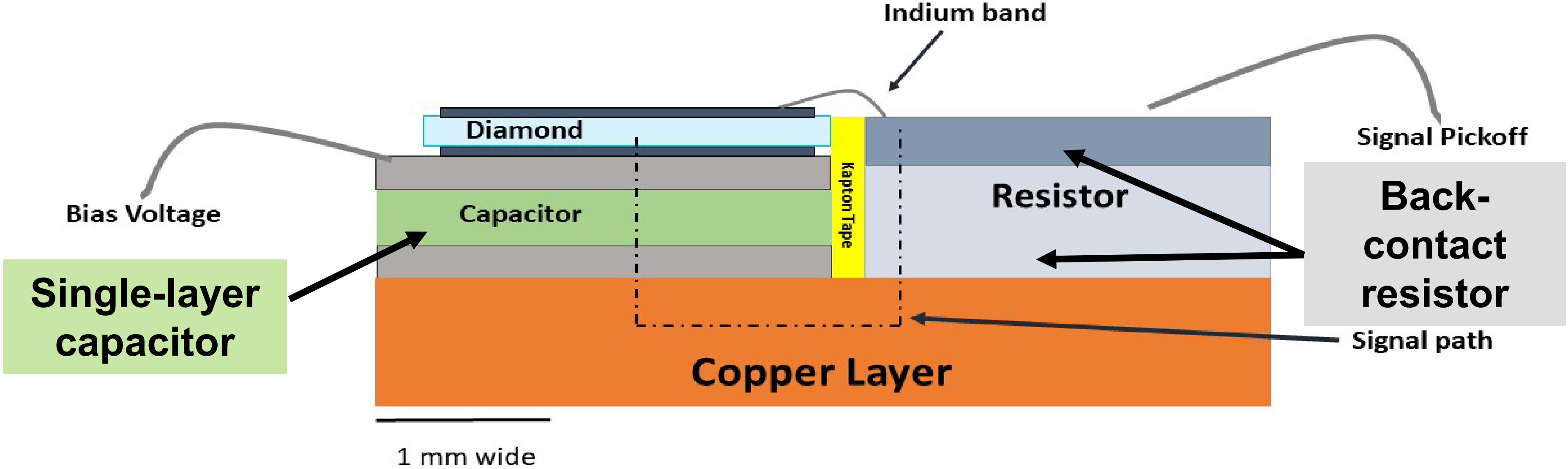
Problem factorized into 4 challenges, all significant in RF regime (>1-2 GHz)

- **Charge Collection**
  - Seems fast and efficient to an instantaneous generation of 10^{16} charges/cm^3 [J Bohon et al., J Synch Rad **29** 292 (2022)]
- **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 radiation and dielectric absorption during transport a concern

Focus of this work

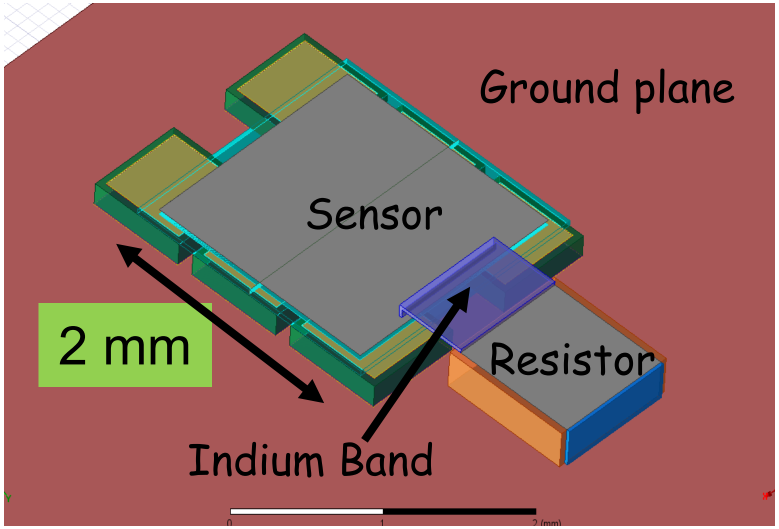
Compact Signal Path

- Make use of RF industry components to develop mm-scale signal path
- Limit inductance, capacitance to push LC resonance above 10 GHz



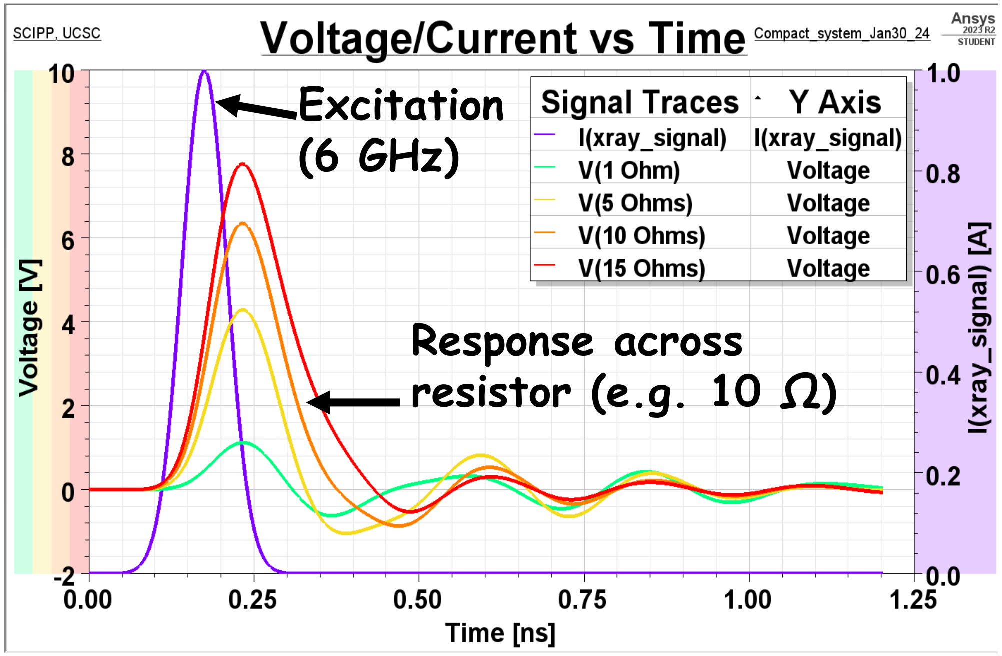
Integrate with localized readout to eliminate signal transport degradation

Simulation of Compact Signal Path (ANSYS HFSS)



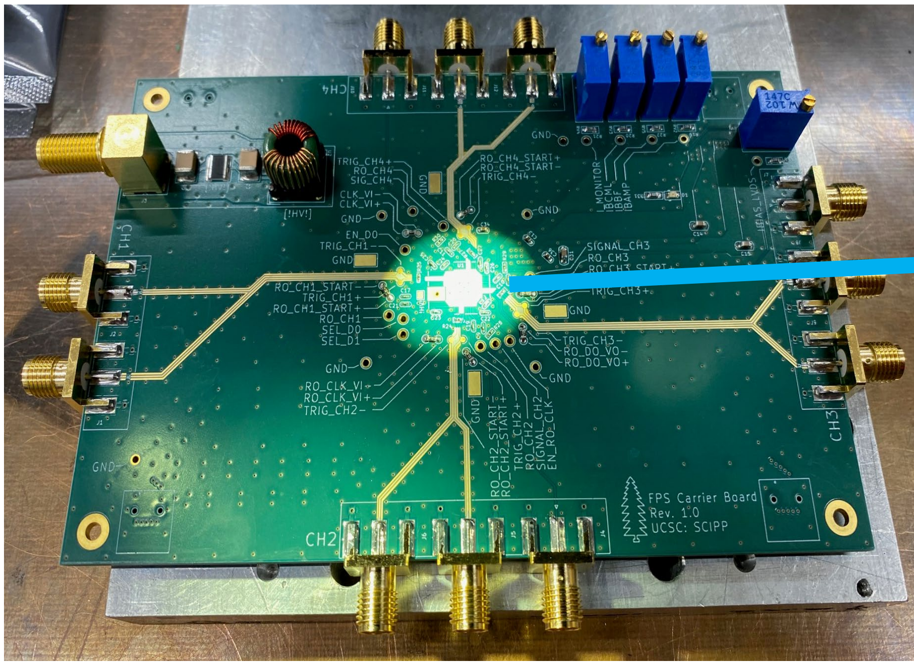
- Simulation suggests 10Ω optimal for signal shaping
- 10Ω resistor doubles as sensing element
- Signal FWHM of ~120 ps in response to 6 GHz excitation suggestion > 5 GHz signal path response

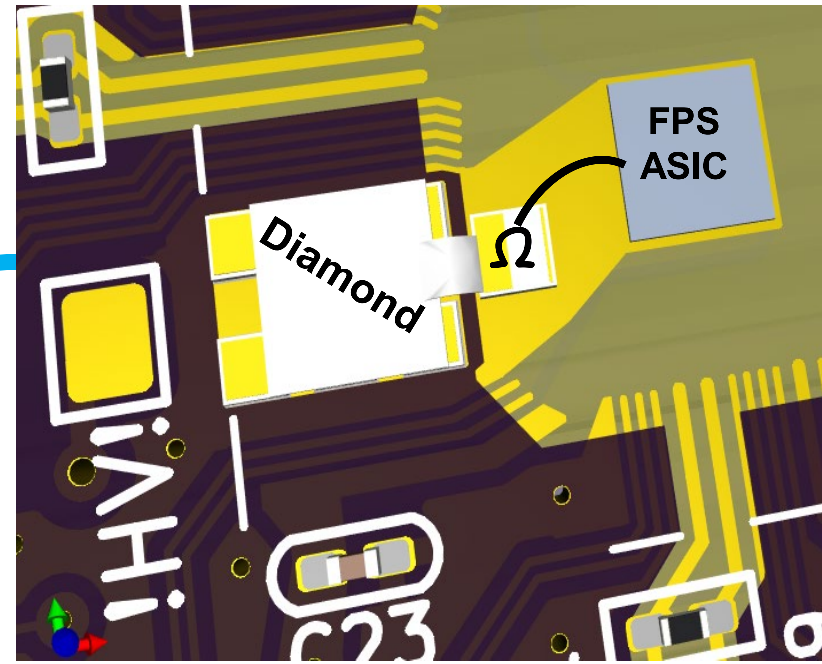
- Simulate with models of industrial components as realistic as possible
- Fabrication techniques established and verified in the SCIPP laboratory



Integrated Multi-GHz Detection System

The compact signal path is integrated with the high-bandwidth **FastPulse Precision Sample** (FPS) ASIC

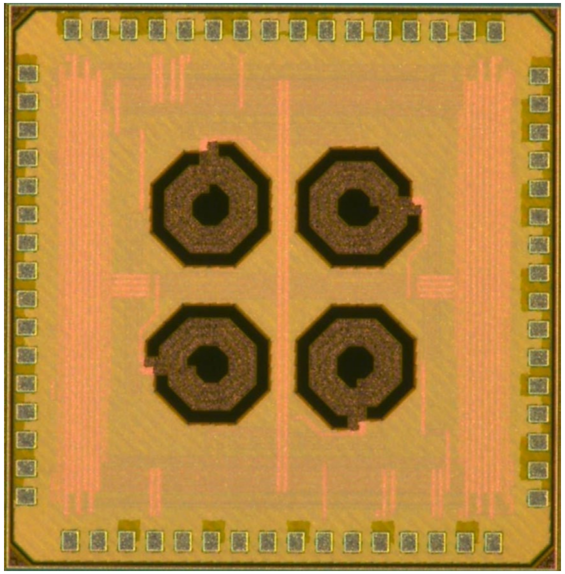




- ASIC design: LBNL Integrated Circuit Group
- Integration & Characterization: SCIPP Laboratory

The FPS ASIC: Design Specifications

- High-bandwidth (~10 GHz) amplifier/buffer system
- Feeds an internal 45-element switched capacitor array
- Variable sampling rate, up to 40 Gs/s
- Four channels (quadrant sensor system)

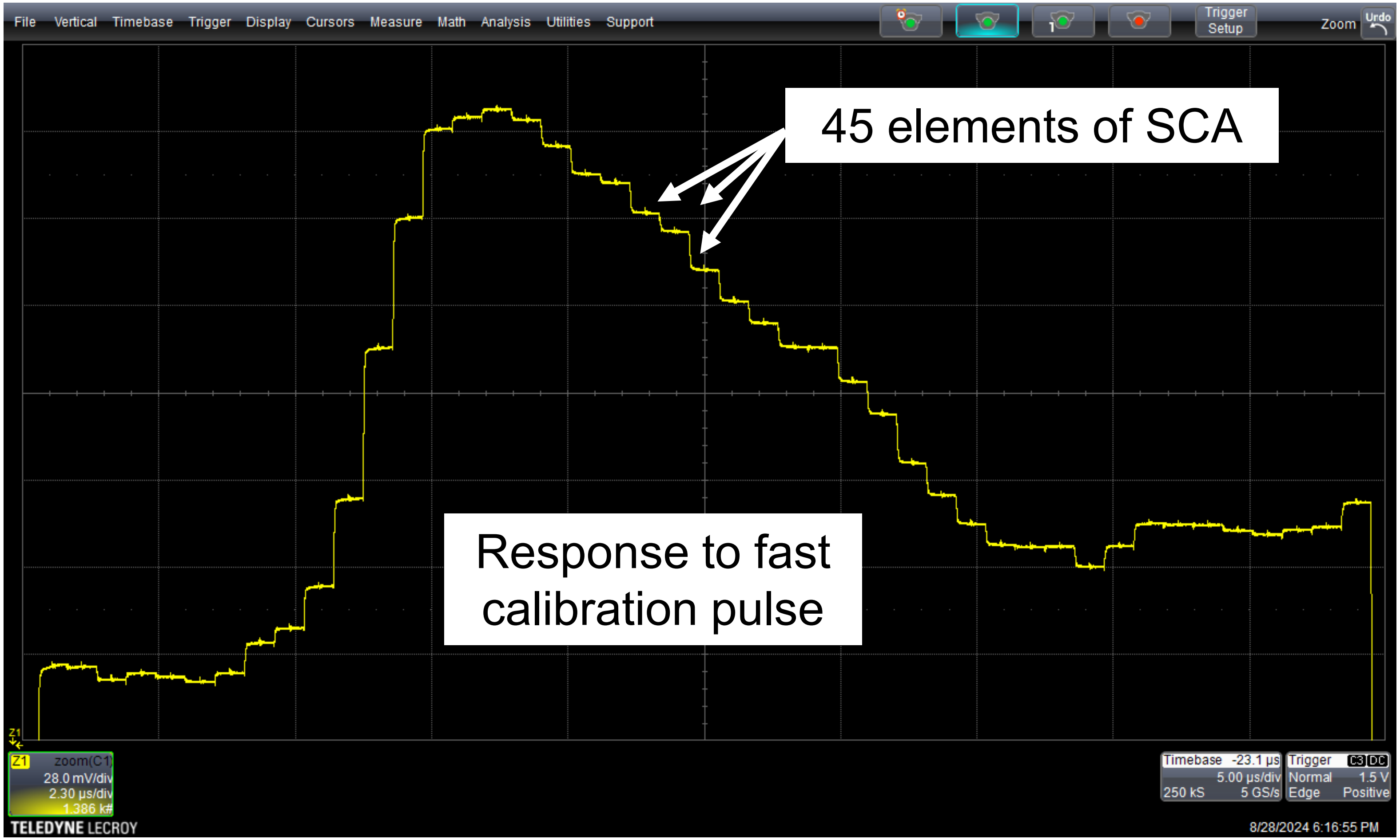


Spec	Value	Unit
Bandwidth	11	GHz
Sample Rate	40	Gs/s
Capture Window	1-2	ns
Readout Rate	500	MHz
Resolution	10	Bits

How does this device perform?

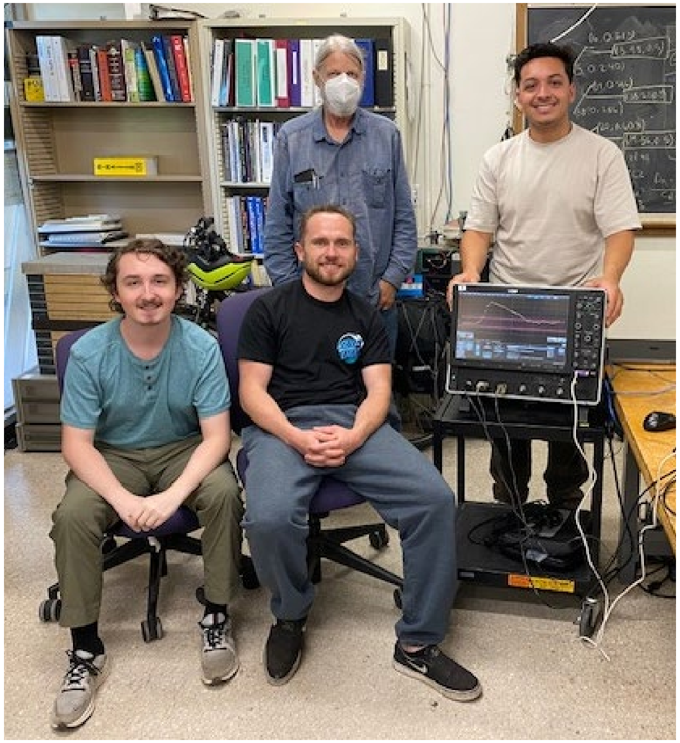
Readout of FPS Switched Capacitor Array

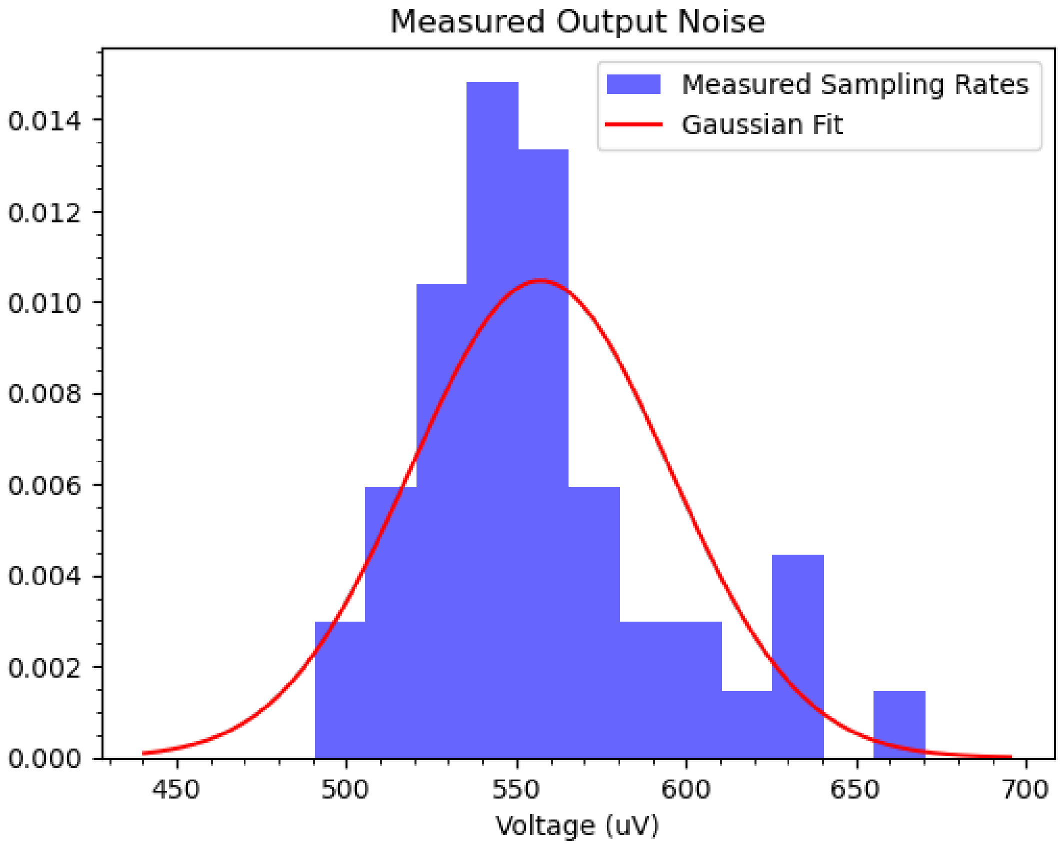
- Stored voltage levels clocked out at 2 MHz
- By sweeping pulser delay across full ns capture window, **digitization period** measure to be **28 ps**



FPS Electronic Noise

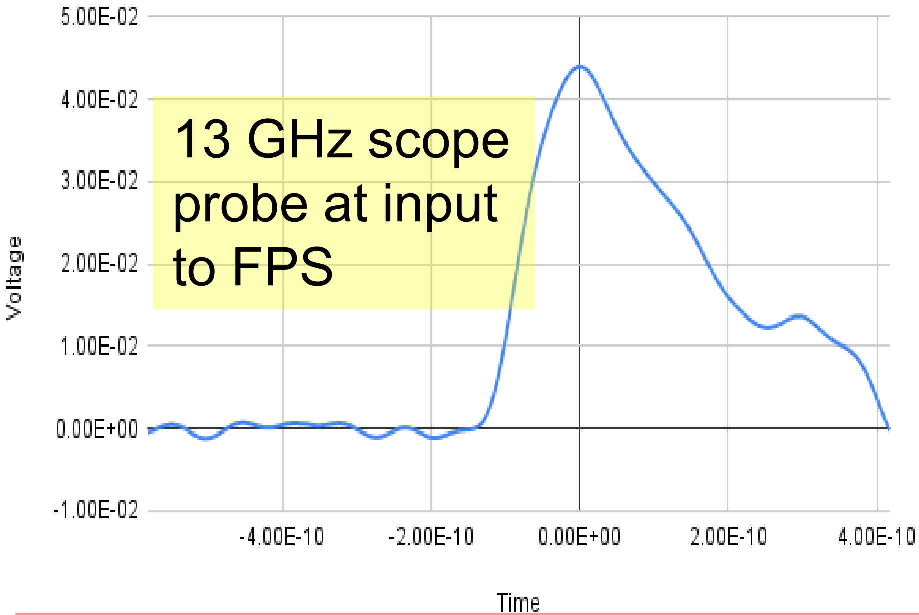
- Observed electronic noise for each of the 45 SCA elements
- Variance of 1000 measurements of pedestal level
- Mean σ_V = 550 μV

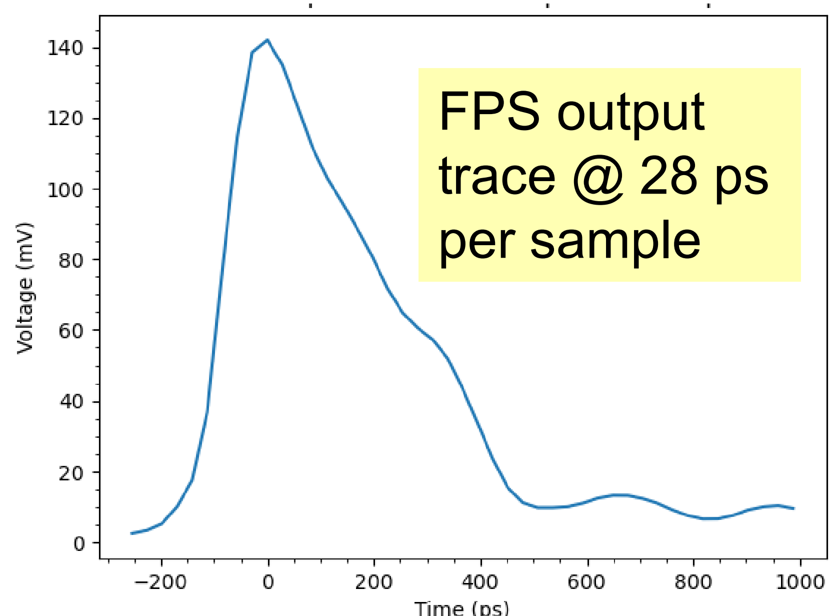




FPS Response / Bandwidth

- Compare input trace (fast pulser) to output trace
- For output trace, use measured 28 ps sampling increment
- Evaluate bandwidth using 20%-80% rise time $\tau_{20\text{-}80}$

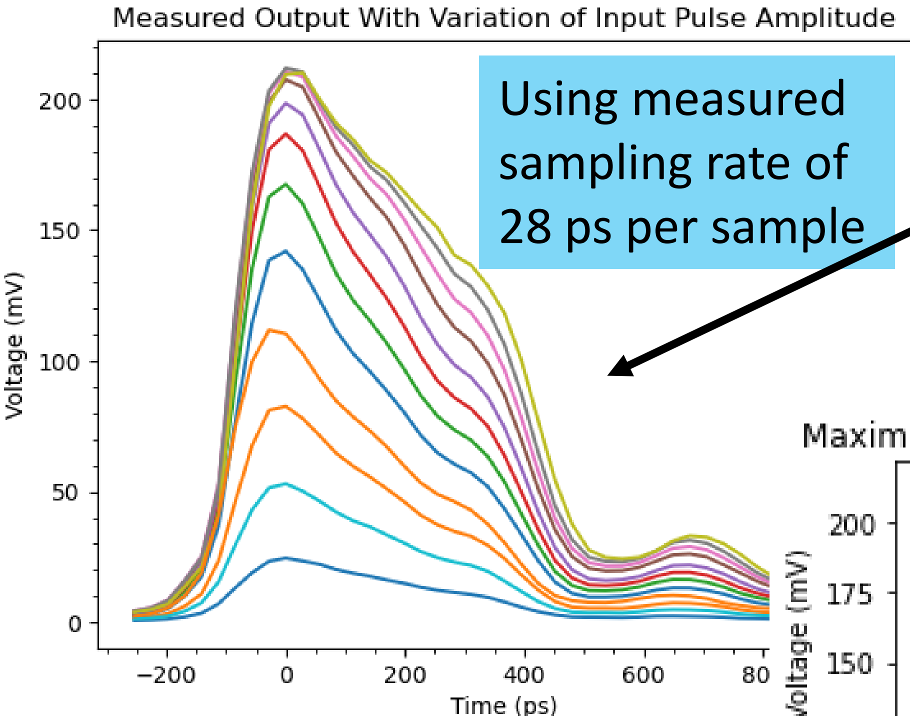




Bandwidth ≈ $0.23/\tau_{20\text{-}80}$

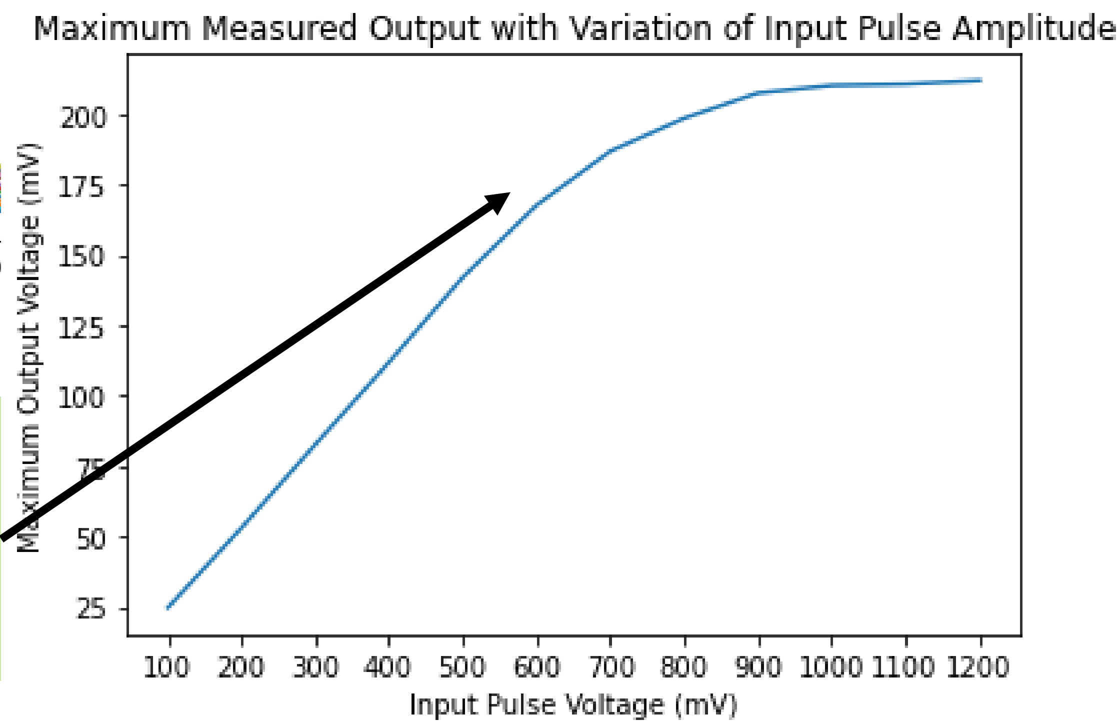
- Input rise time: $\tau_{20\text{-}80}$ = 47 ps
- Output rise time: $\tau_{20\text{-}80}$ = 67 ps
- FPS contribution: $\tau_{20\text{-}80} = \sqrt{(67^2 - 47^2)}$ = 48 ps ➔ **5 GHz**

FPS Linearity and Dynamic Range



Using measured sampling rate of 28 ps per sample

Excite ASIC with increasing input signals, uniform step size in input voltage



Gain linear until ~ 160 mV

Dynamic range 160/0.55 = 290 (great than 8 bits)

Digression: FPS Timing Prospects

- There are many ways to degrade the timing resolution of a system
- One of the most fundamental is electronic noise
- Let's look at this one and ignore all others (i.e. take the following with a huge "grain of salt")

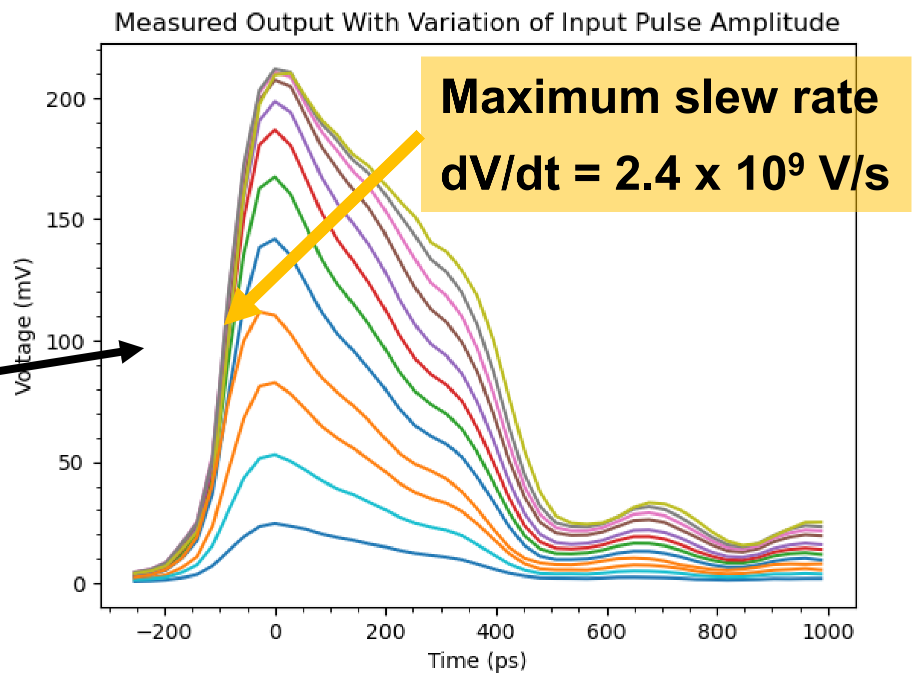
For constant-fraction discrimination,

$$\sigma_t = \frac{\sigma_V}{\left|\frac{dV}{dt}\right|}$$

- Measured noise σ_V = 550 μV
- $|dV/dt|_{max}$ = 2.4 x 10^9 V/s

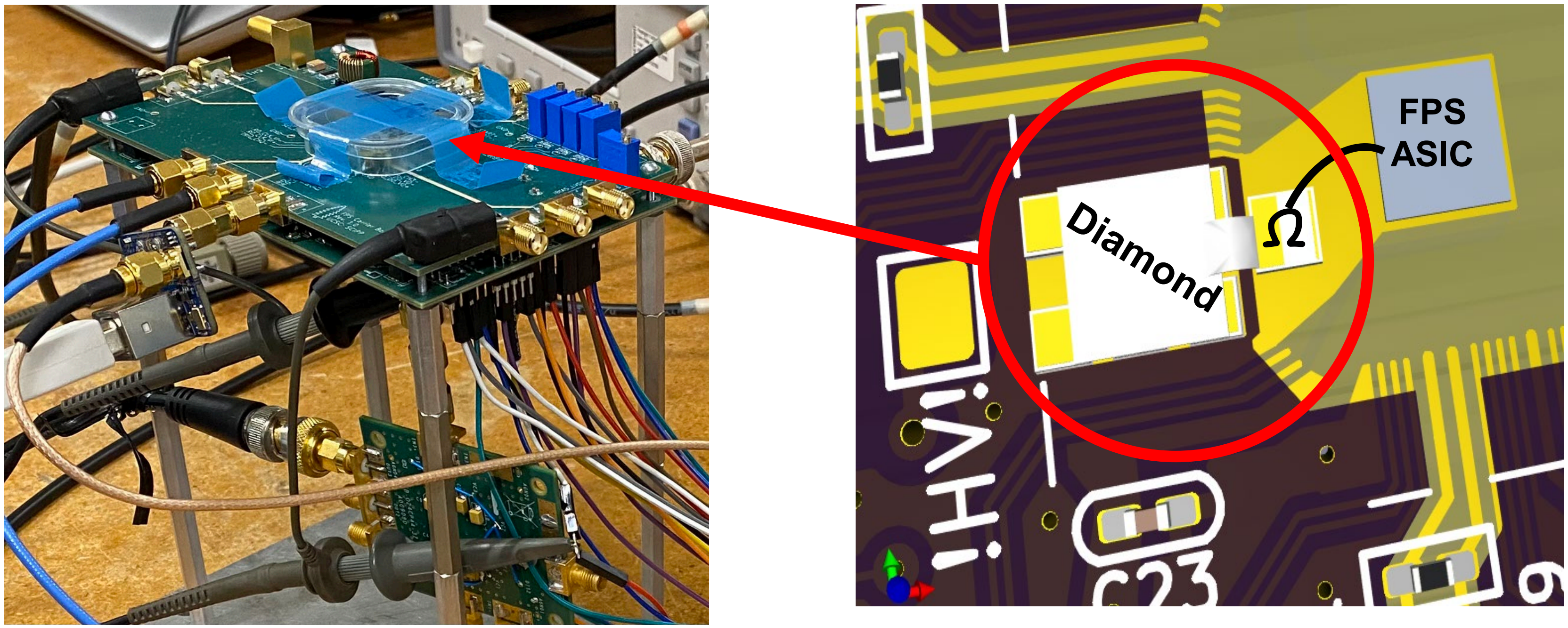
$$\sigma_t \cong 2.3 \times 10^{-13} s = 230\ fs$$

From electronic jitter only!!!



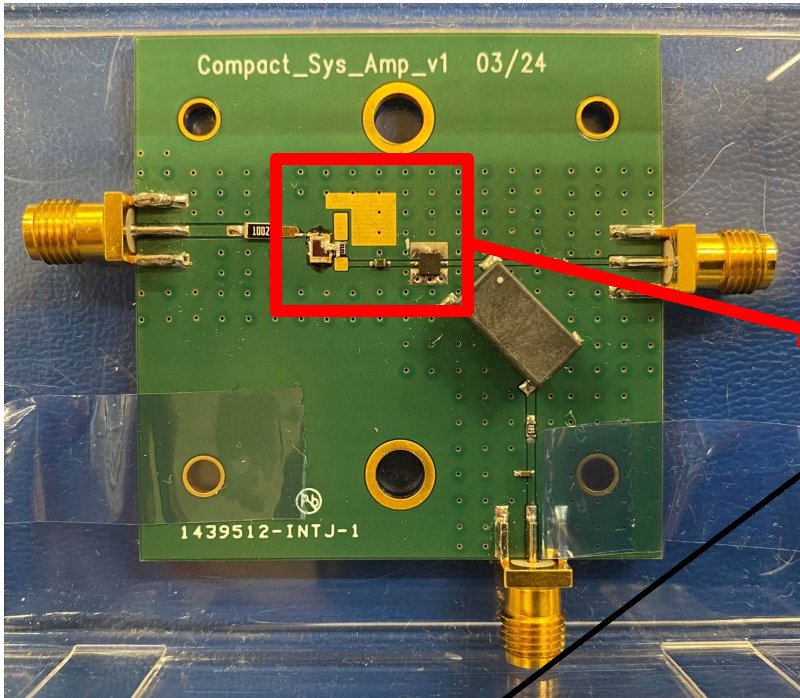
Next Steps: Signal Path

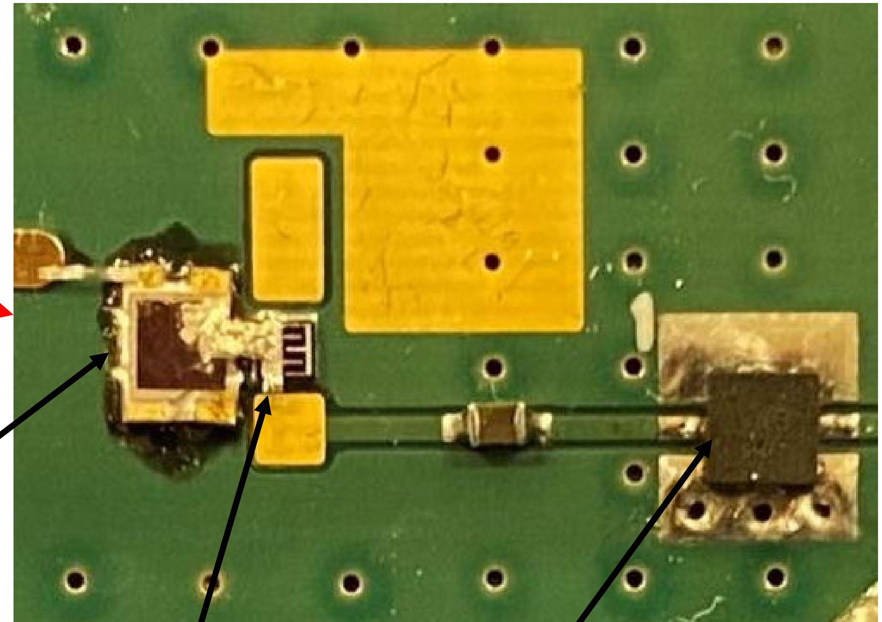
Next step is to add sensor/signal path and take to test beam



- Working on it (end of calendar year)
- But for now test signal path with independent system based on discrete 13 GHz amplifier

Direct study of compact signal path





Diamond: 2x2x0.033 mm^3

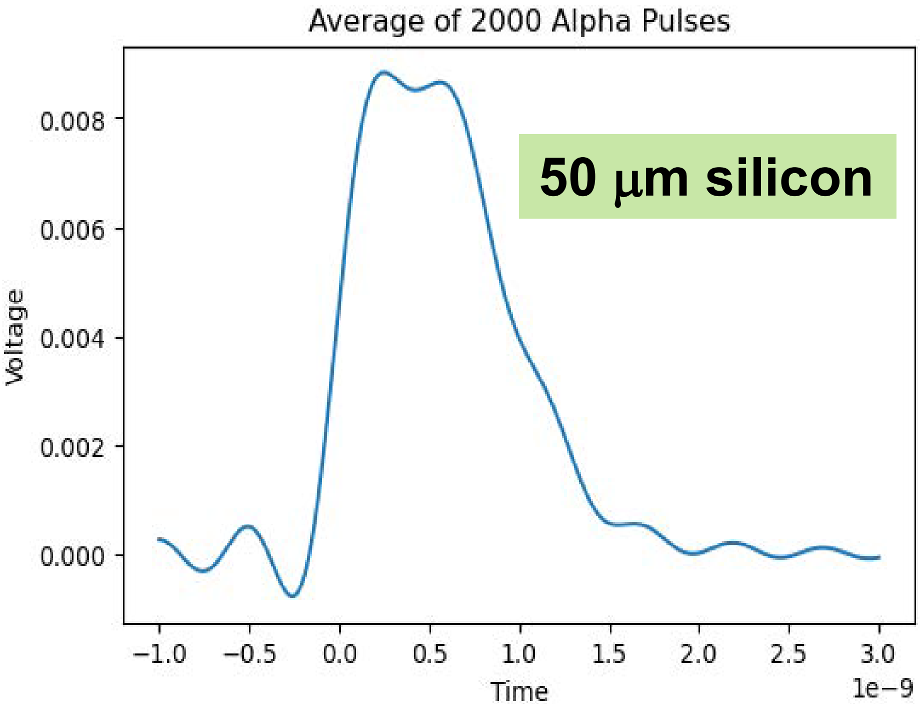
Minicircuits EHA-163L+ RF amplifier

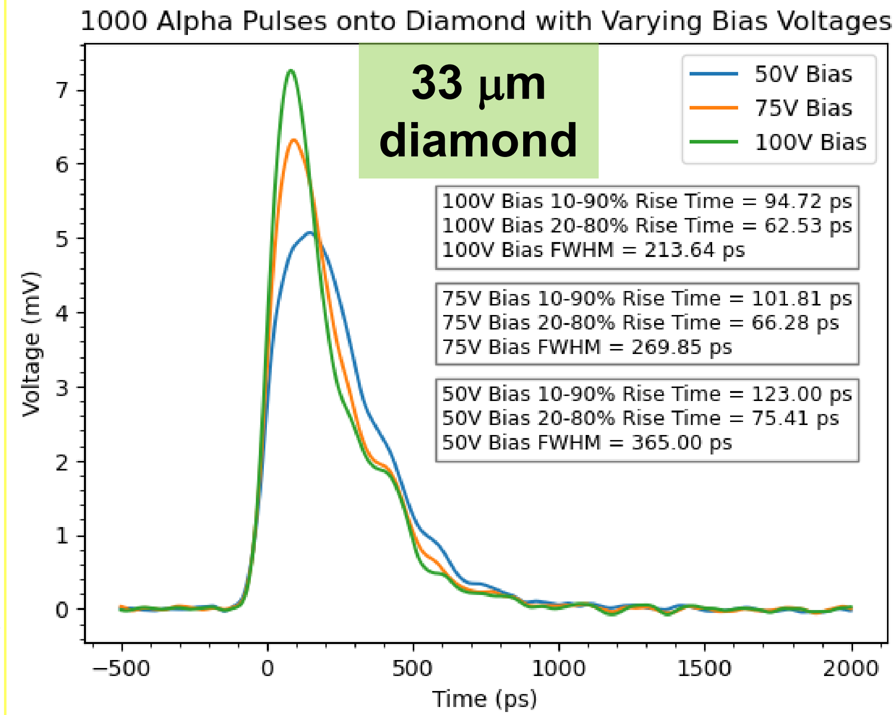
10 Ohm back contact resistor

Caveat: this preliminary implementation is on standard FR4 PC board dieletric, which is known to degrade GHz signals

Compact Signal Path Result

Excite with alpha particles (Americium source)

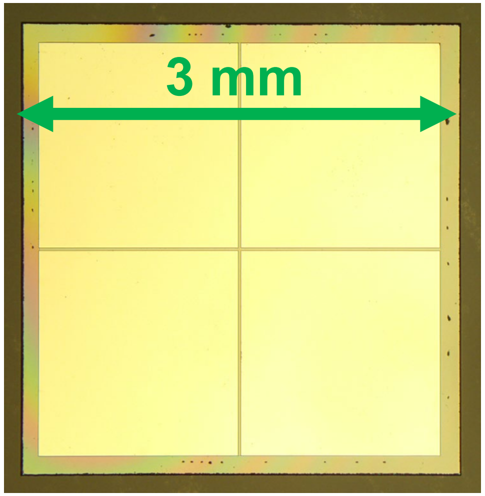




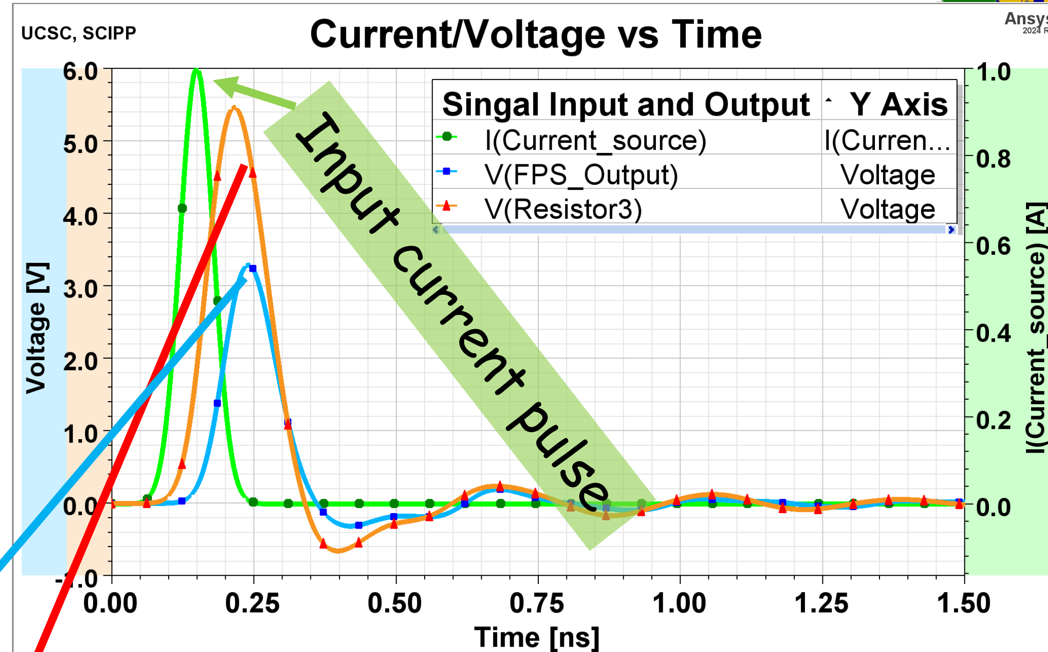
For diamond, 95 ps 10-90% rise time consistent with **3.8 GHz signal**

We expect that switching PCB dielectric from FR4 to Rogers4350b will provide further improvement. New board in fabrication now.

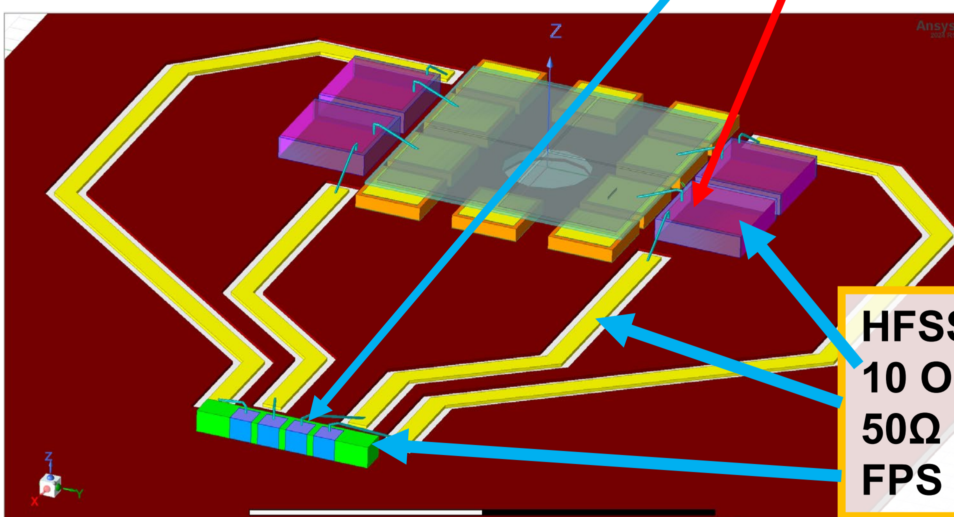
Towards a Multi-GHz Position Sensing System



Quadrant sensor (LANL) is in SCIPP lab



- 5 GHz signal integrity maintained
- Actual design will be integrated with FPS-II front end development



HFSS Simulation
10 Ohm back-contact sense resistor
50Ω traces on Rogers Material
FPS is 50Ω resistive load

Summary and Outlook

- Operating 50 MHz position-sensitive system being pushed into multi-GHz regime
- Approach is design of compact, integrated detection system
- First prototype of "FPS" ASIC performing at or above 5 GHz
- Compact signal path approach looks promising to achieve 5 GHz
- Awaiting full system test (for planar sensor) and independent high-bandwidth signal path results
- Design of quadrant (position sensitive) system underway
- Detection system hints at prospect for femtosecond timing
    - But far from proven
- Applications outside of Accelerator Physics may be offered
    - e.g. inertial confinement (ICF) burn width ~100 ps, commensurate with FWHM of 5 GHz signal

Acknowledgements

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University of California Office of the President

- Laboratory Fees Research Program