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Use of CVD Diamond Sensors in Extreme Environments and Applications

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(On behalf of the Advanced Accelerator Diagnostic (AAD) Collaboration)

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SLAC

Outline:

- AAD introduction
- Motivation
- TCAD Simulation
- Real-Time radiation damage in Diamond
- High bandwidth diagnostic
- Summary

Advanced Accelerator Diagnostics (AAD) Collaboration

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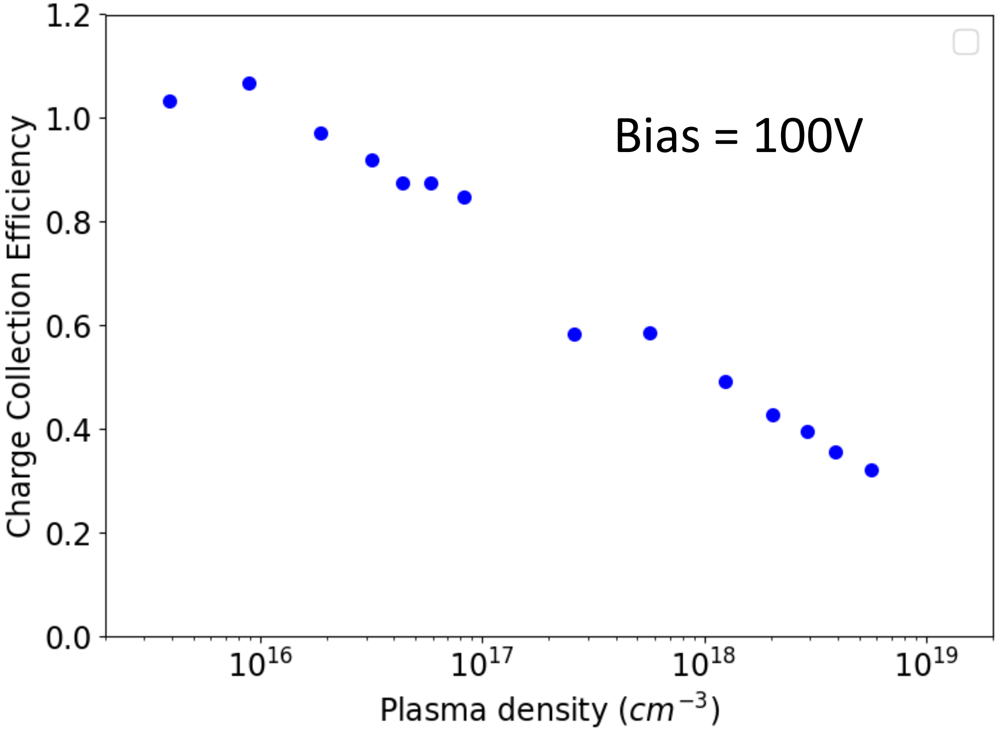
Why diamond?

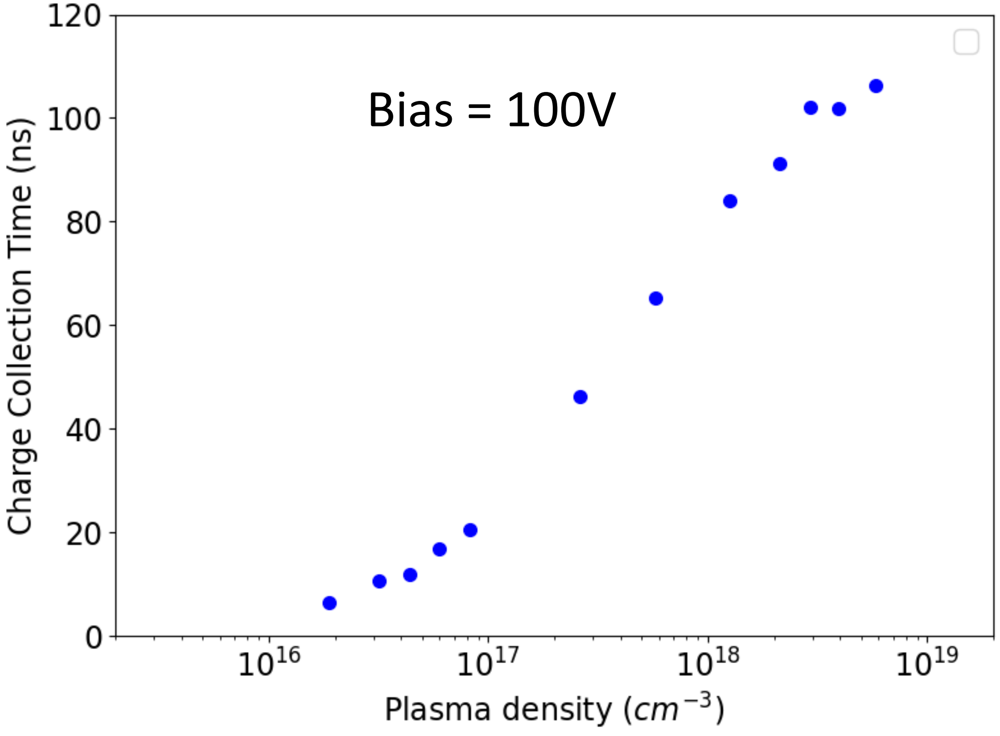
- Superior radiation tolerance
- Fast saturation drift velocity(~ 200 um/nm, 100 um/nm for Si) M. Pomorski et. Al
- Superior thermal conductivity (2200 W/m-K)
- Charge collection time for a 30 mm thick diamond sensor ~ 150 ps
- low X-ray absorption

Charge collection time and efficiency of diamond sensor:

A thin (37 ± 10 μm) diamond sensor was exposed to intense X-ray beams from the XPP beamline of LCLS to study charge collection time and efficiency of diamond sensor at increasing plasma densities and bias voltages.

J. Synchrotron Rad. (2022). **29**, 595-601





- We make use of 3D Silvaco tools to simulate diamond sensor response and benchmark with 100 V bias data.

Introduction to Silvaco TCAD

- Tool to simulate the electrical, optical and thermal behaviour of semiconductor devices.
- Individual sensor designs with arbitrary materials possible.
- Simulation can be done in 2D, quasi 3D and 3D.
- Electric field distribution is directly linked to the detector efficiency.
- Electrical Field properties depend on:

  -- Drift behaviour of charge carriers

  -- Properties of traps in Diamond

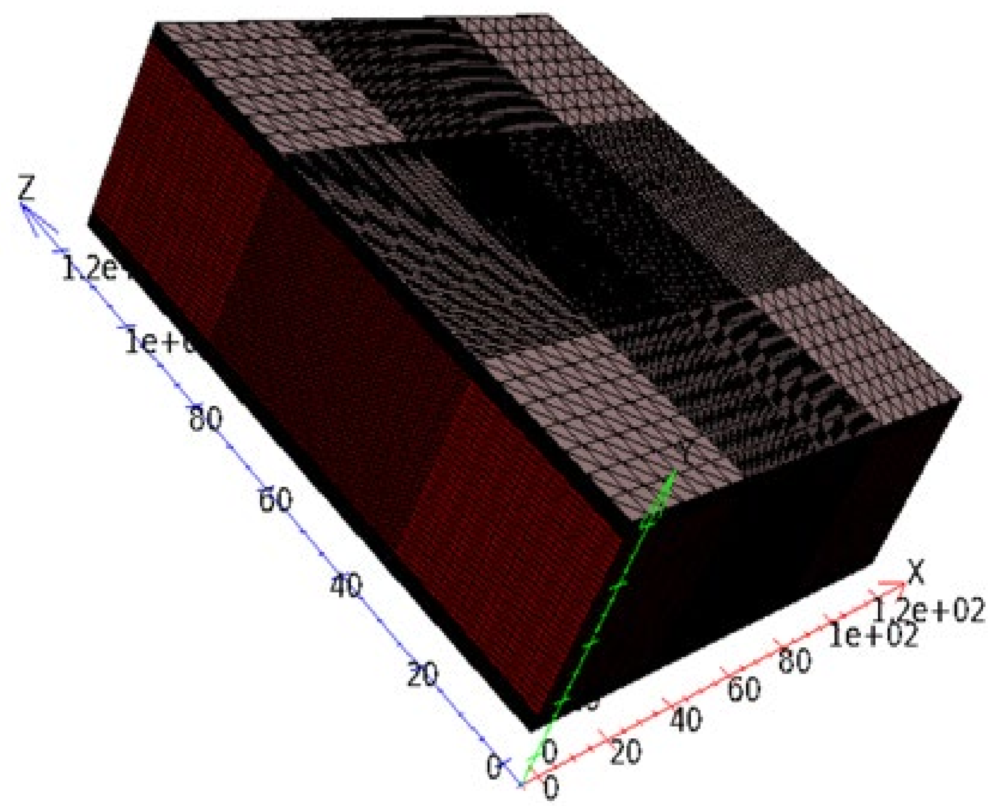
  -- Creation of space charge

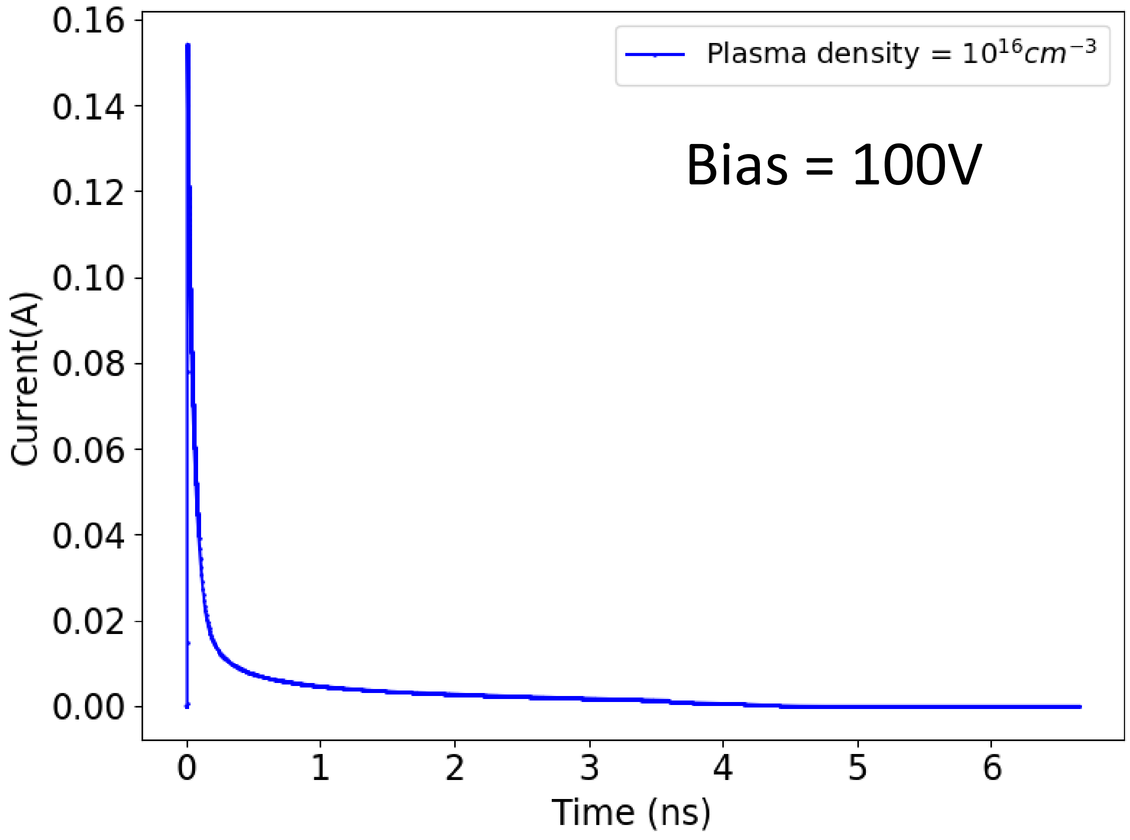
  -- etc, …

3D TCAD Simulation:

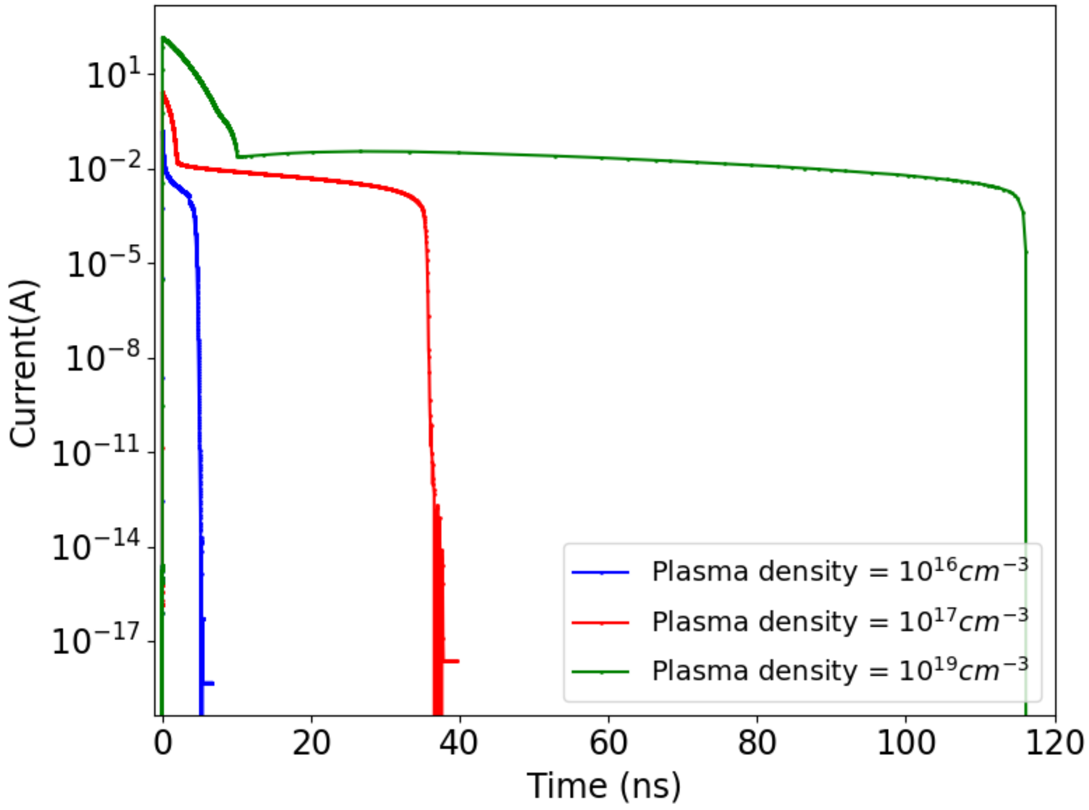
- Dimensions: 120umx120umx35um, Bias:100V
- Beam Diameter = 43 um
- Non-mixed mode: Only device simulation without any electronic circuit.
- Mobility parameters were tuned to achieve Saturation Electron drift velocity=220 um/ns, hole drift velocity=100 um/ns
- The currents are collected on the electrodes under the assumption that their potentials are fixed (i.e., perfect signal return path).

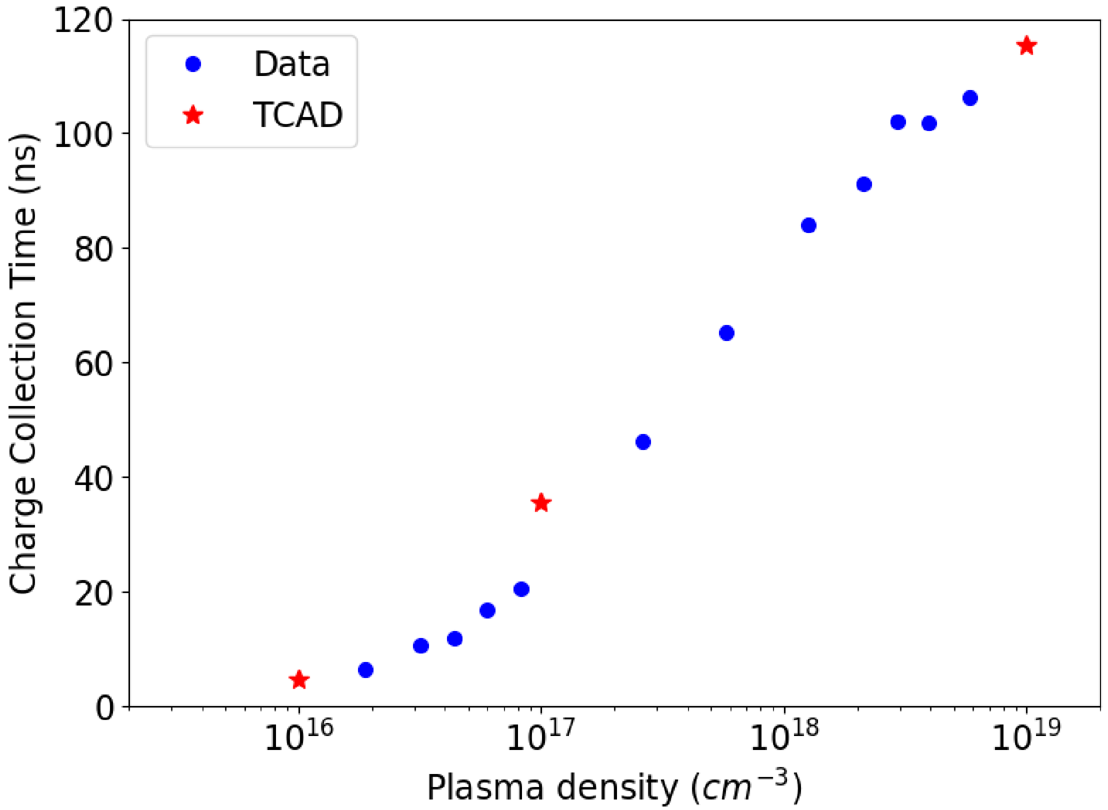
3D TCAD Simulation:





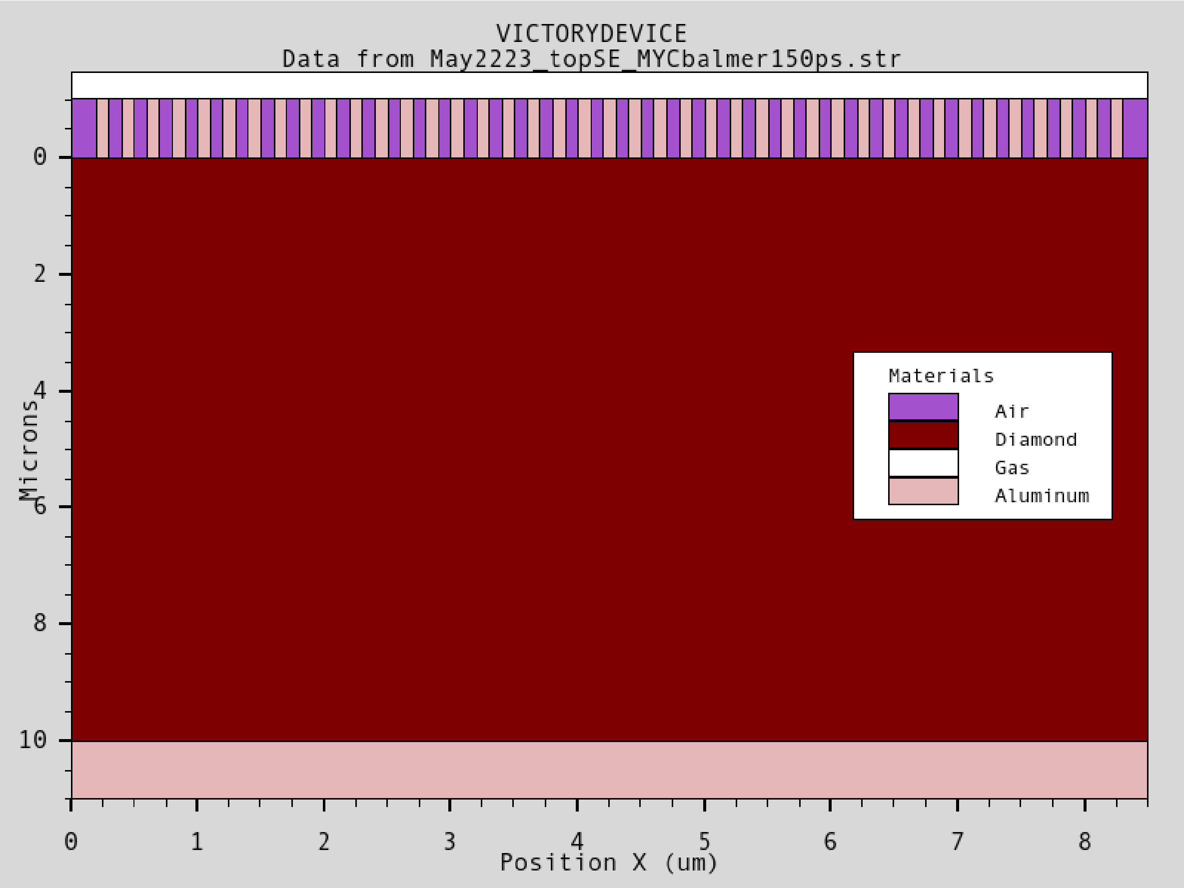
3D TCAD Simulation:





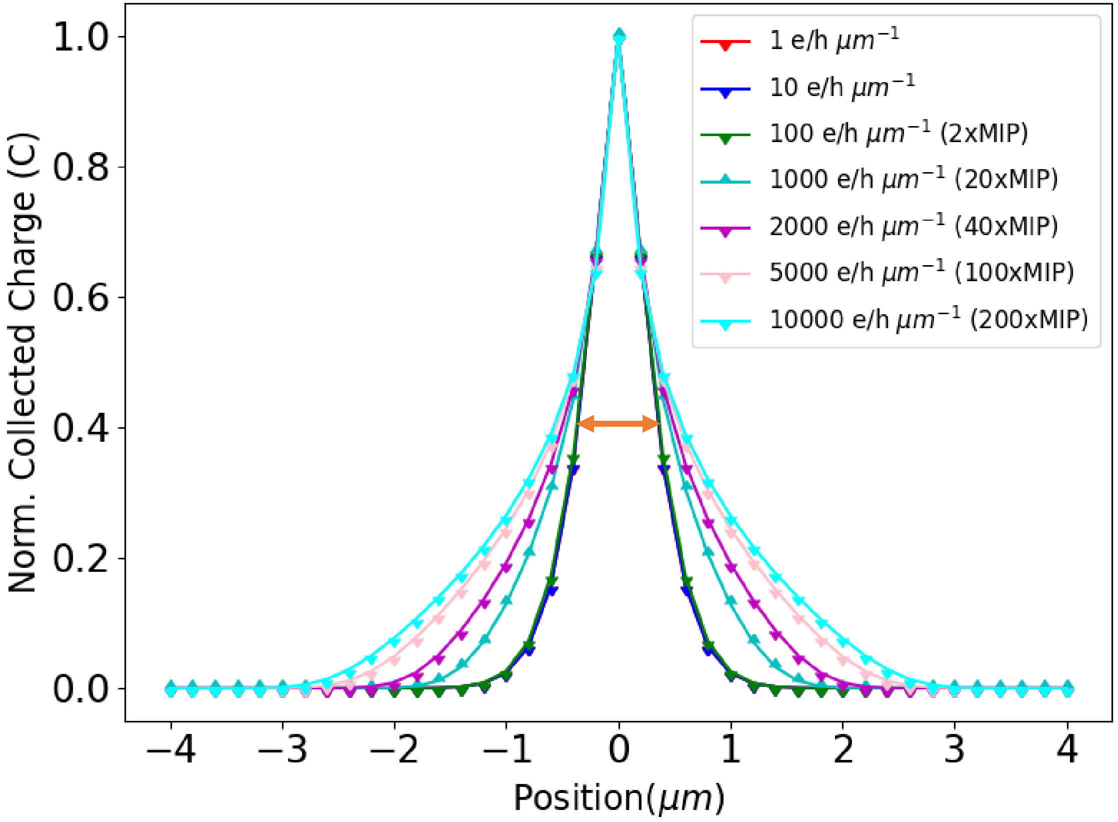
- ➢ Charge Collection Efficiency simulation is underway.

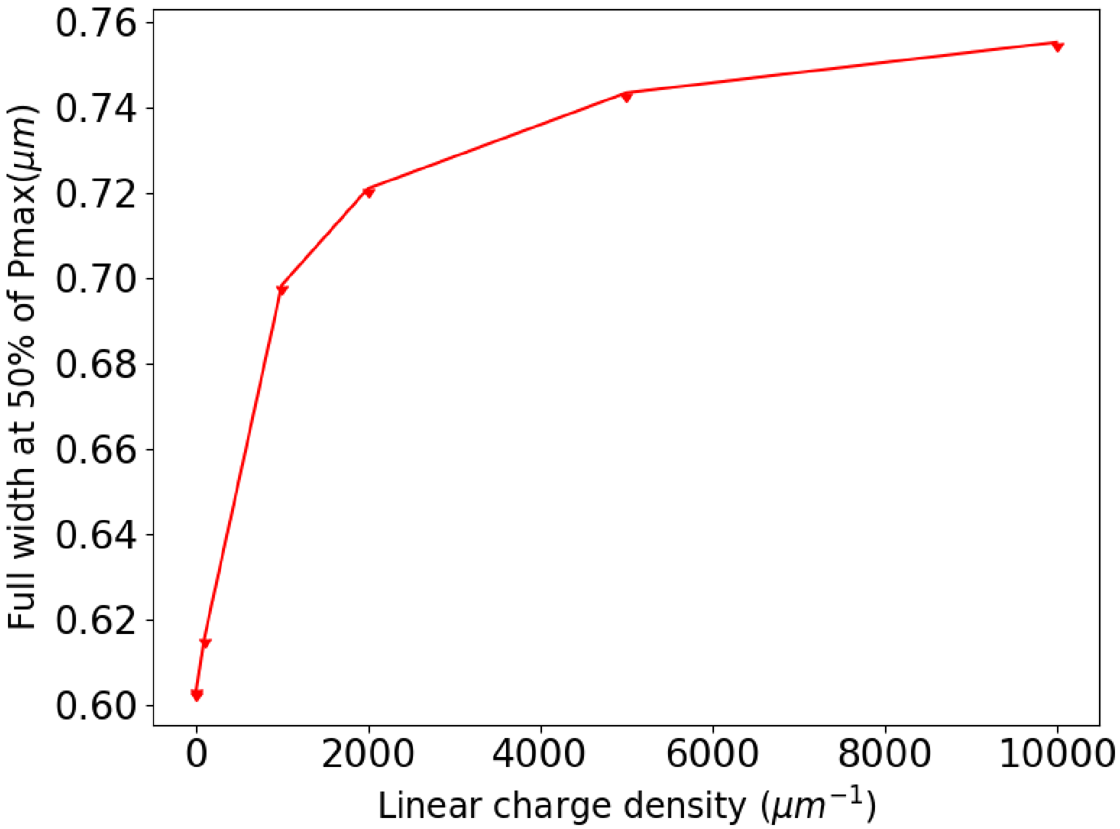
2D TCAD Simulation (Charge diffusion):



- We simulate a highly segmented thin device to explore resolution limit of diamond sensors.
- A 10um thick diamond under 1 - 50V bias.
- There are 41 channels in the segmented geometry with 200nm pitch and 100nm electrode width.
- A linear charge is deposited along the central axis of the device.

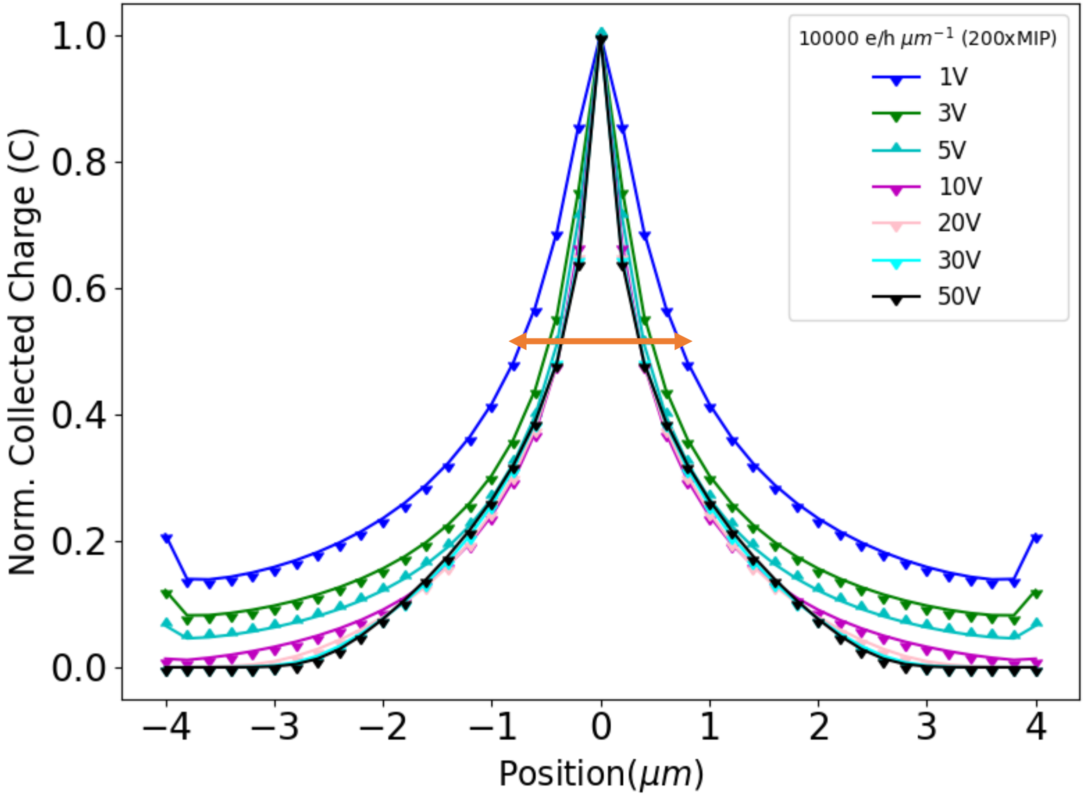
2D TCAD Simulation (Charge diffusion):

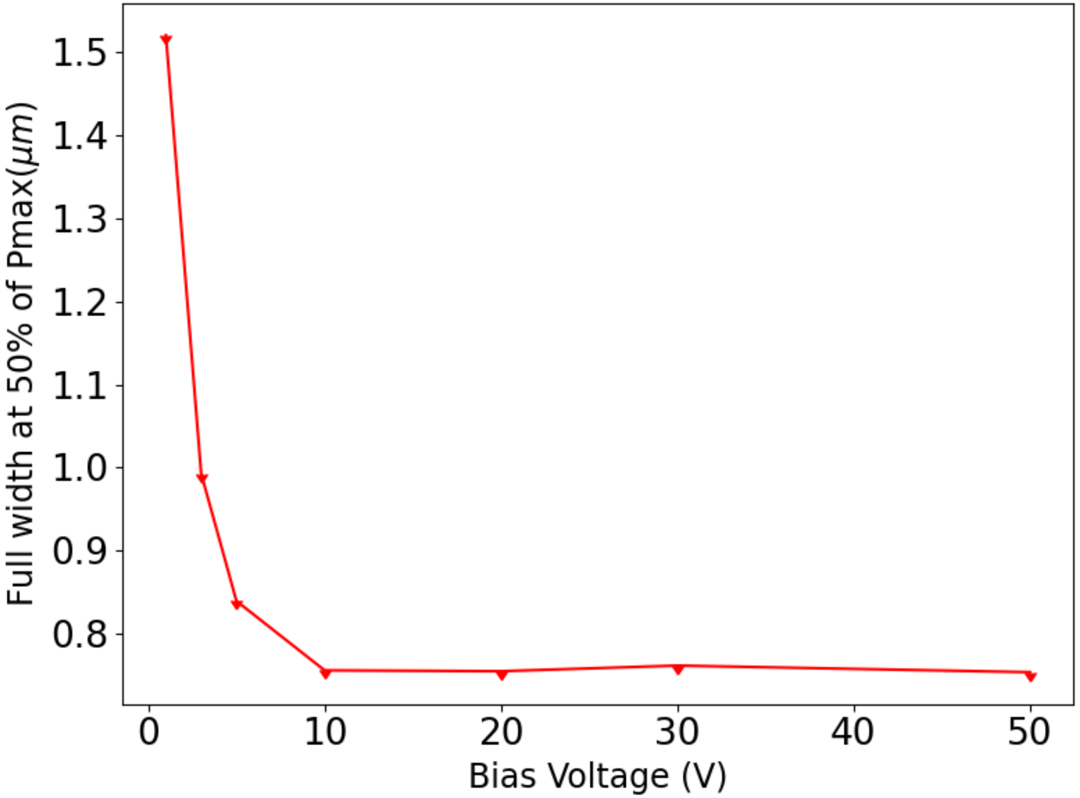




- ➢ Sub-micron feature size resolution looks possible, but results need to be confirmed in heavy ion beam

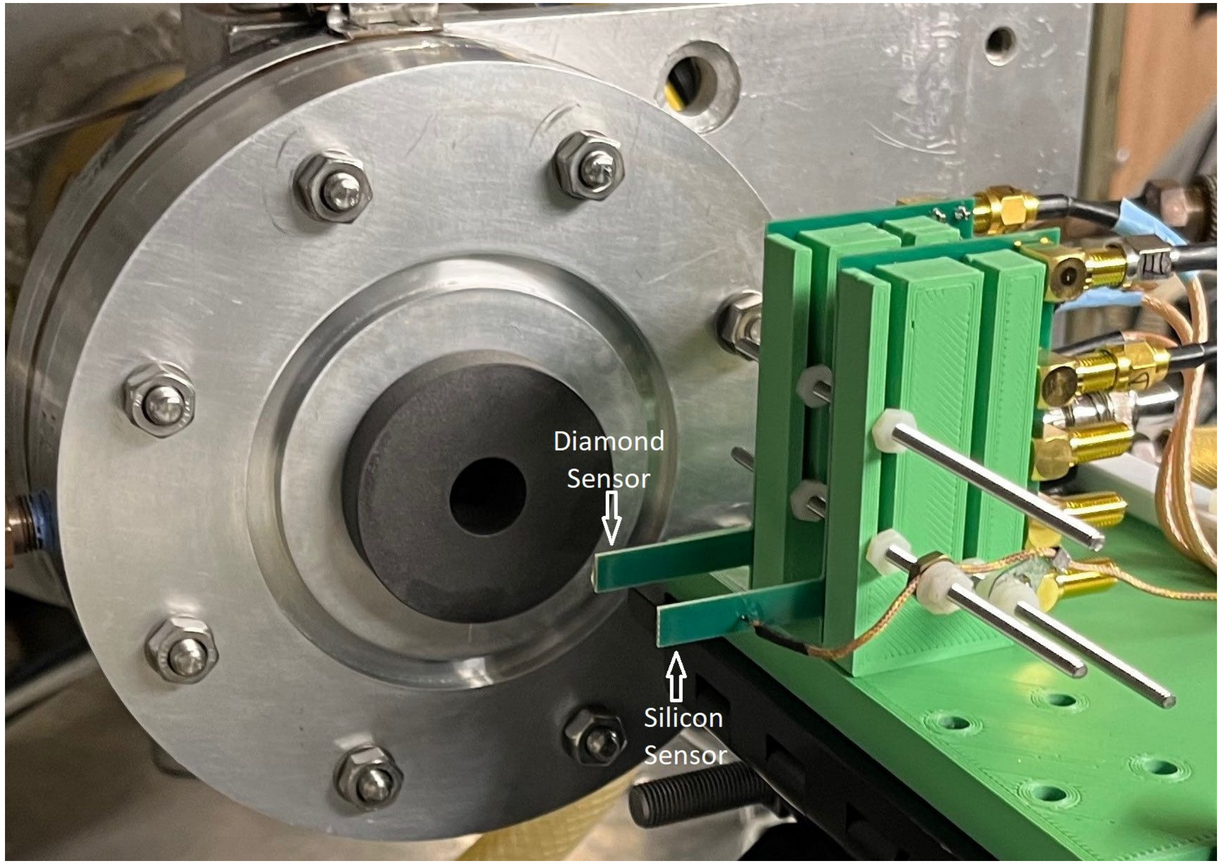
2D TCAD Simulation (Charge diffusion):





Radiation damage study @ Proton Synchrotron (Crocker Nuclear Lab on the UC Davis Campus) :

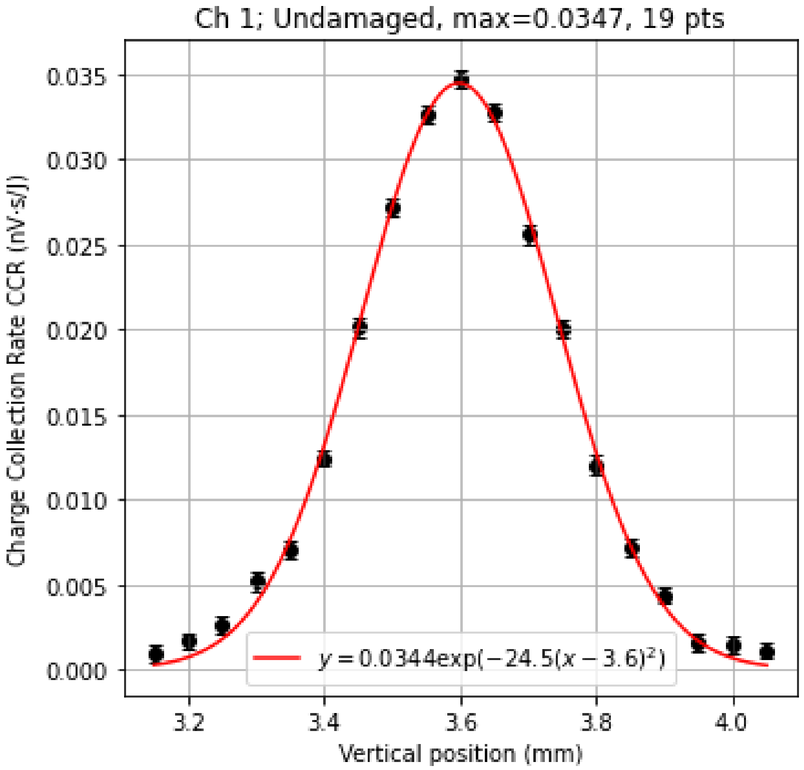
A 4mm x 4mm x 0.030 mm diamond and a Silicon sensor with similar dimensions were mounted in parallel on two four-channel readouts board designed at SCIPP. The proton beam energy was 67.5 MeV and the total fluence was ~ 4×10^{16} .

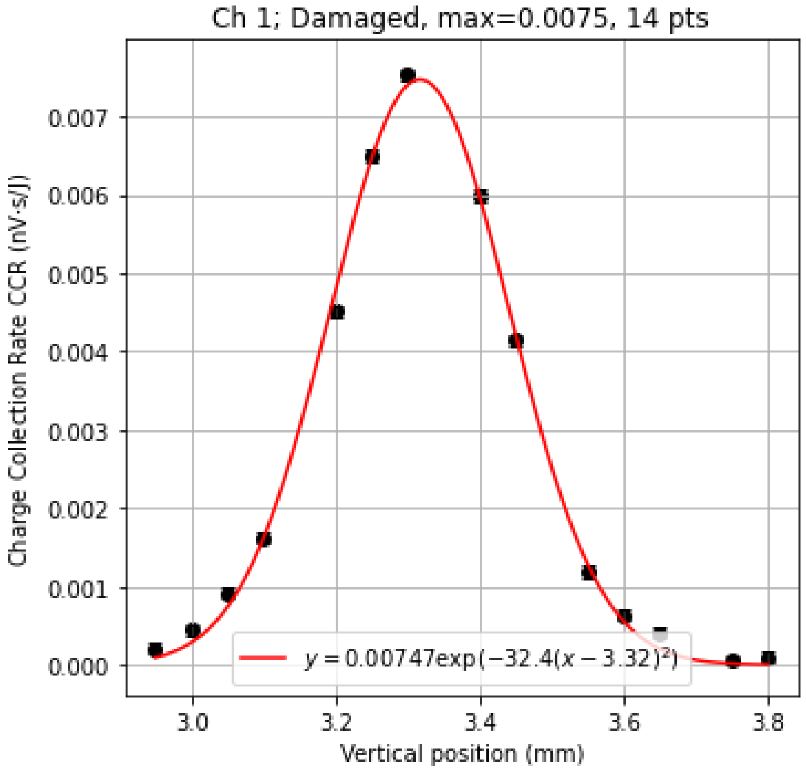


Damaged v/s Undamaged sensor:

- Since, the sensor was already damaged a bit during the setup of the experiment, we do not have the absolute charge collection efficiency (CCE).

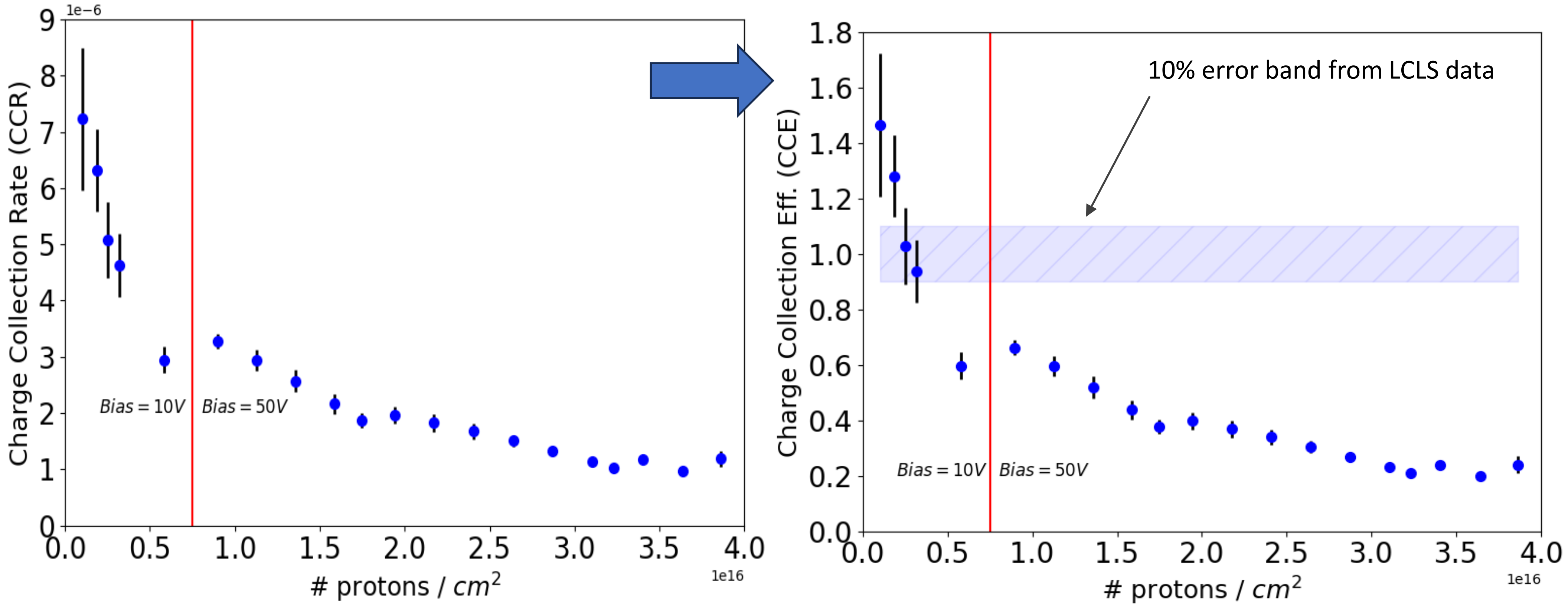
- We took a fresh and fully damaged sensor to the LCLS to measure the absolute CCE.





Charge collection efficiency:

- ➢ The charge collection efficiency of the fully damaged sensor was found to be ~ 24% of that of the undamaged sensor.
- ➢ We use that final point to set the absolute scale of the relative CCE by scaling the results so that the CCE measured for the highest fluence has a value of 0.240.



High Bandwidth Diagnostic system:

- Upgraded and next generation XFELs envisioned mJ scale pulses delivered at repetition rates up to 10 GHz.

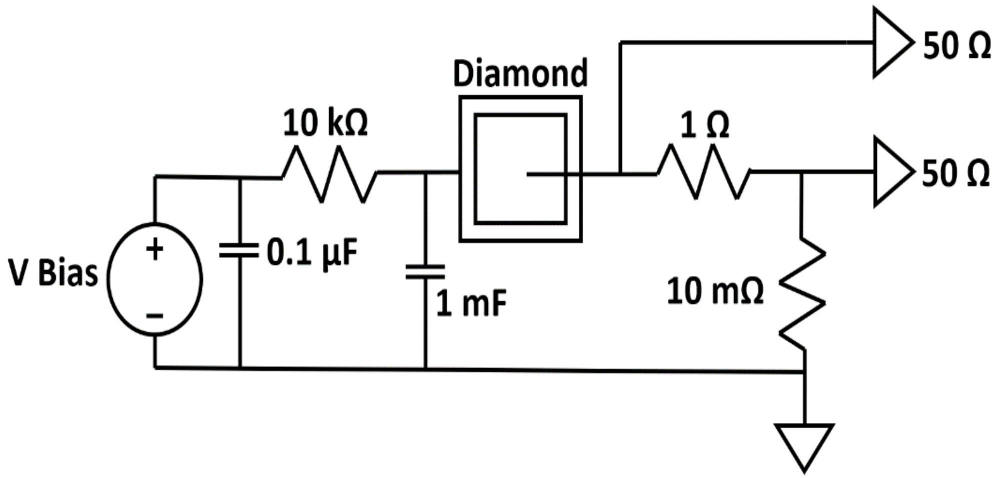
  -- Need to understand intrinsic charge collection limitations of diamond.
  -- Need to develop high bandwidth (10 GHz) readout of ionising particle sensor.

- Monitoring of the evolution of the plasma on time scales in the 100-ps regime during laser ignition of plasma events.

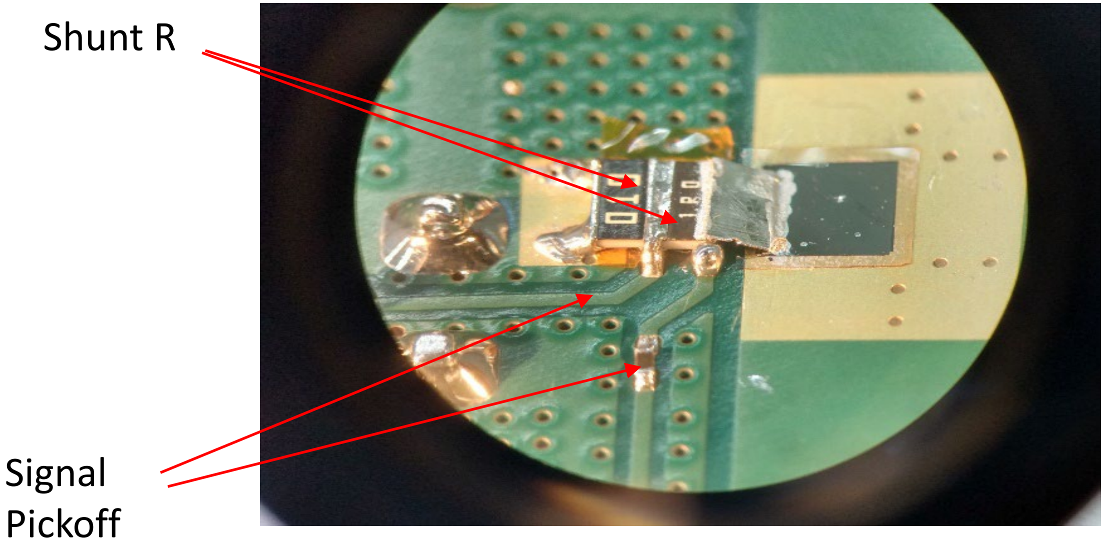
- AAD Collaboration has been awarded a DOE grant for the Basic Energy Science and Accelerator Stewardship to pursue the development of Mult-GHz diagnostic capable to address these challenges.

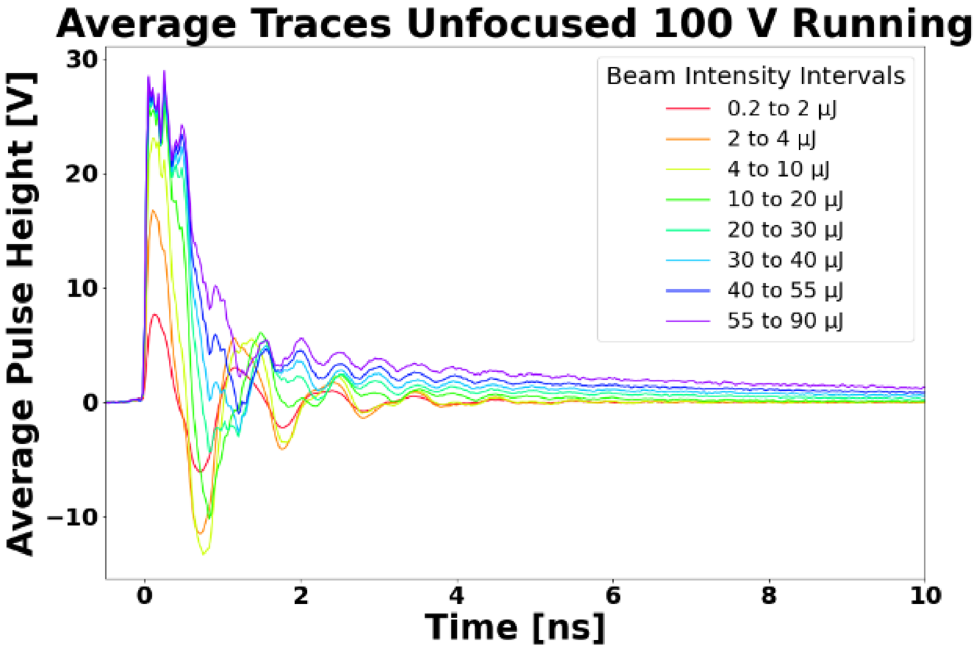
High Bandwidth Diagnostic system:

- Initial Attempt at Low-Impedance Signal Path
- Sensor connected to the readout path through an Indium band.
- A series array of 1 Ω and 10 mΩ shunt the signal current directly to ground.
- 50 Ω pick-off traces connected to the sensor side of both the 1 Ω and 10 mΩ resistors.



High Bandwidth Diagnostic system:

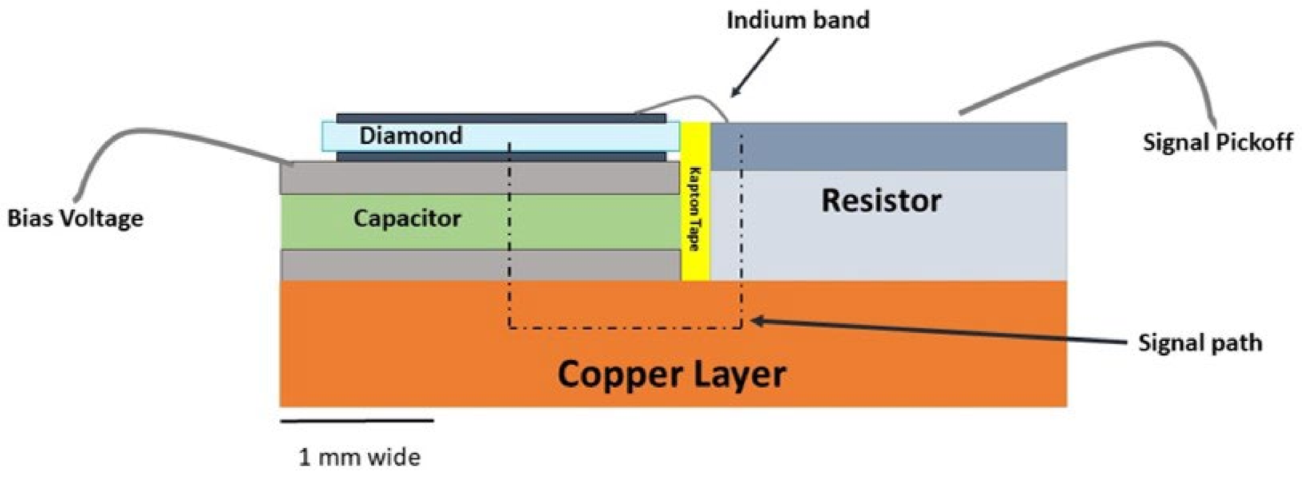




- Signal pulse extends for 1-2 nsec, limiting the system for repetition rates above 0.5-1 GHz.

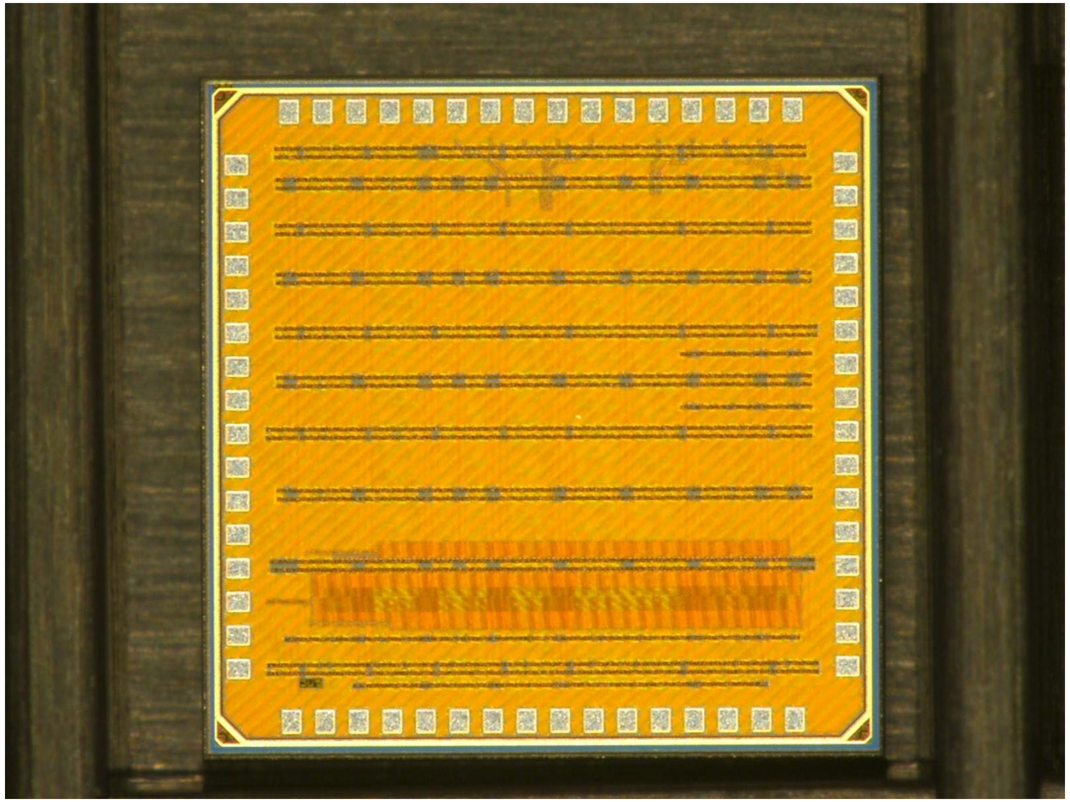
- The ”ringing” suggests that inductive impedances are limiting the performance of the system.

High Bandwidth Diagnostic system (Multi-GHz):



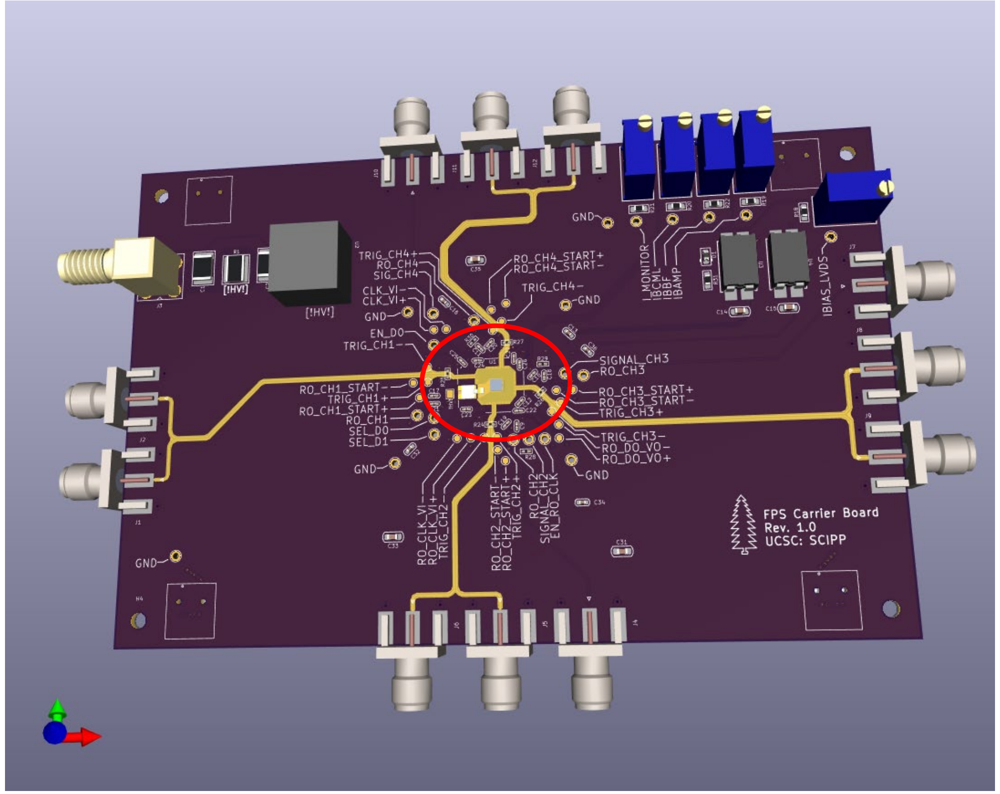
- Significantly more compact geometry
- limiting the enclosed area of the signal circuit loop
- Use of miniaturized components developed for RF communications applications.
- Frequencies of internal resonances within individual components above 10 GHz.

High bandwidth amplifier/buffer ASIC

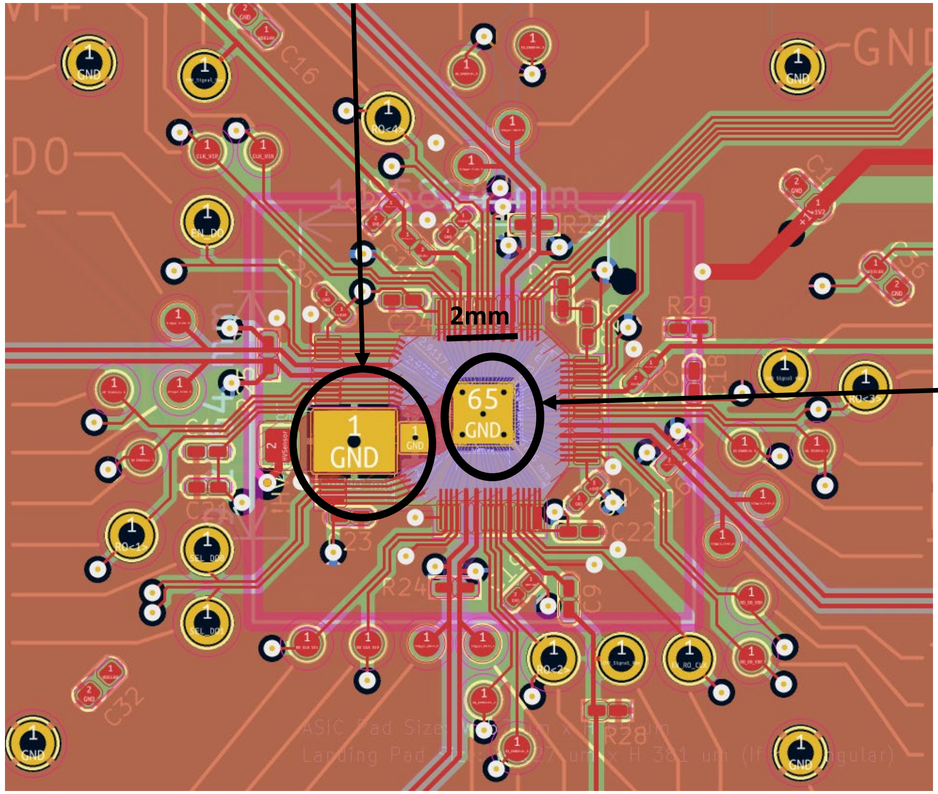


High Bandwidth Diagnostic system (Multi-GHz):

Integration of the signal stackup and the ASIC



Signal path



Chip

➢ An RF-simulator (HFSS) model is under development for the signal and readout path

Summary and Future:

- 3D TCAD simulations are in good agreement with the actual data in terms of charge collection time. We plan to use TCAD tools to understand radiation damage in diamond by introducing lattice defects.

- 2D Simulation of charge diffusion in diamond sensors agree with the sub-micron resolution possibility. We need to experimentally verify by irradiating such a sensor with a heavy ion beam.

- Radiation damage study done using the proton beam at the Crocker Lab confirms that these sensors can be safely used in the proton beam monitor at the Isotope Production Facility (IPF), LANL.

- The Multi-GHz detection system is expected to greatly improve the next generation XFEL diagnostics and monitoring of high plasma ignition.

Backup

Charge collection rate:

- Beam current = 1 uA
- Beam Diameter = 1.5 cm
- Fluence = 3.54e12 p/s/cm^2
- Maximum Frequency = 22 MHz
- Both Silicon and Diamond sensors mounted
- Total number of events collected = 11367
- Trigger rate = 1Hz
- Bias voltage for diamond = 10 V – 50 V

Diamond sensor signal: