

Ultra-fast Diamond Detectors for HENP and PP

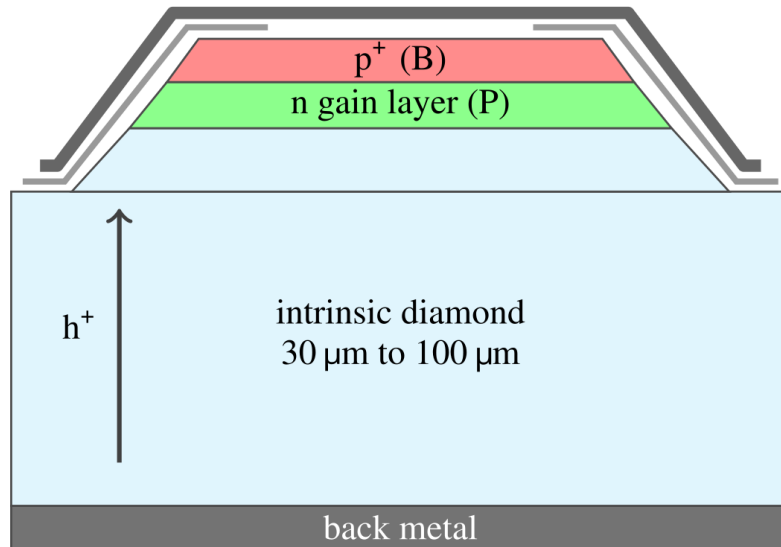
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T. Shin, H.F.-W. Sadrozinski, A. Seiden, B. Schumm

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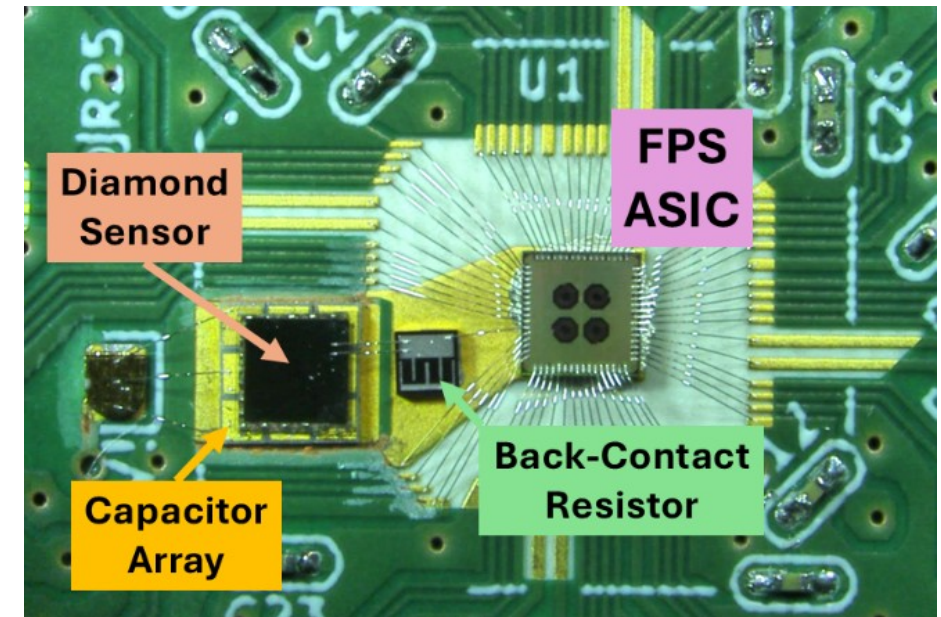
[CPAD 2026](#)



Diamond timing detectors with gain



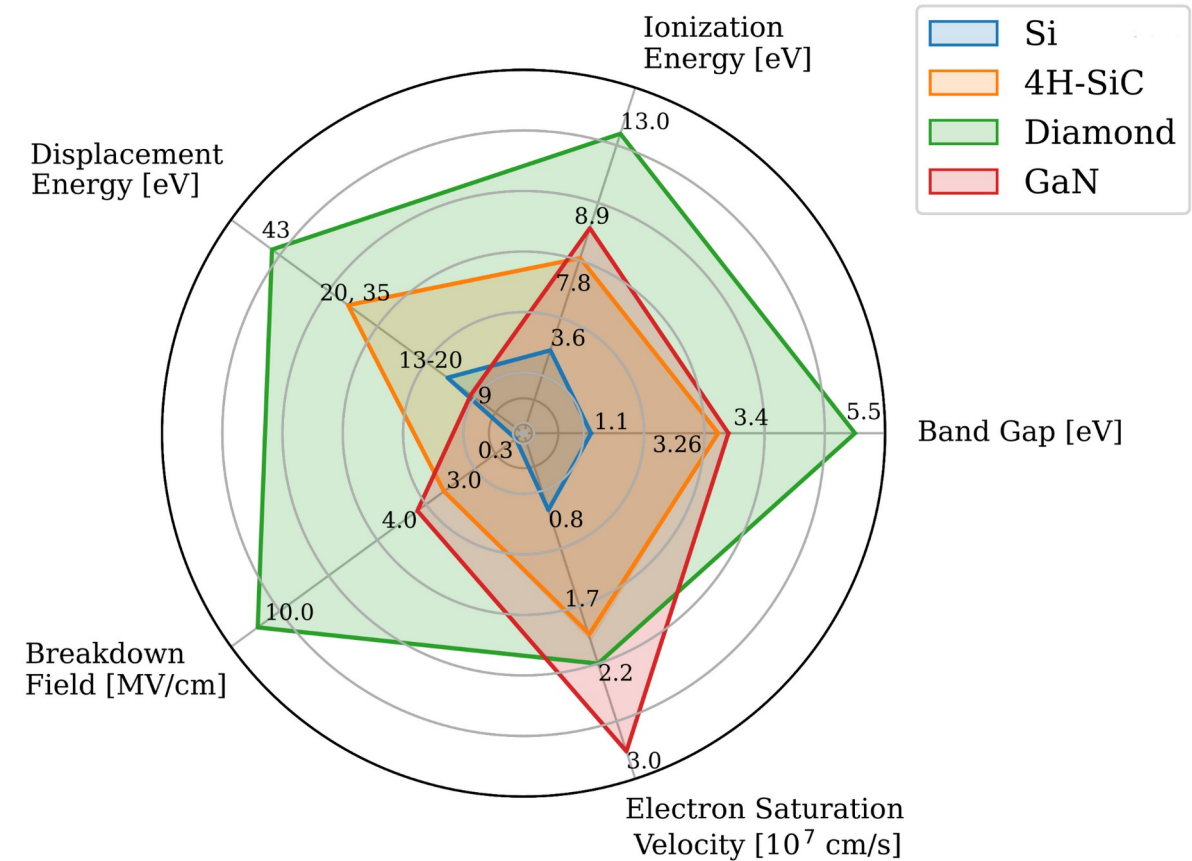
GHz diamond detector applications



Diamond Detectors

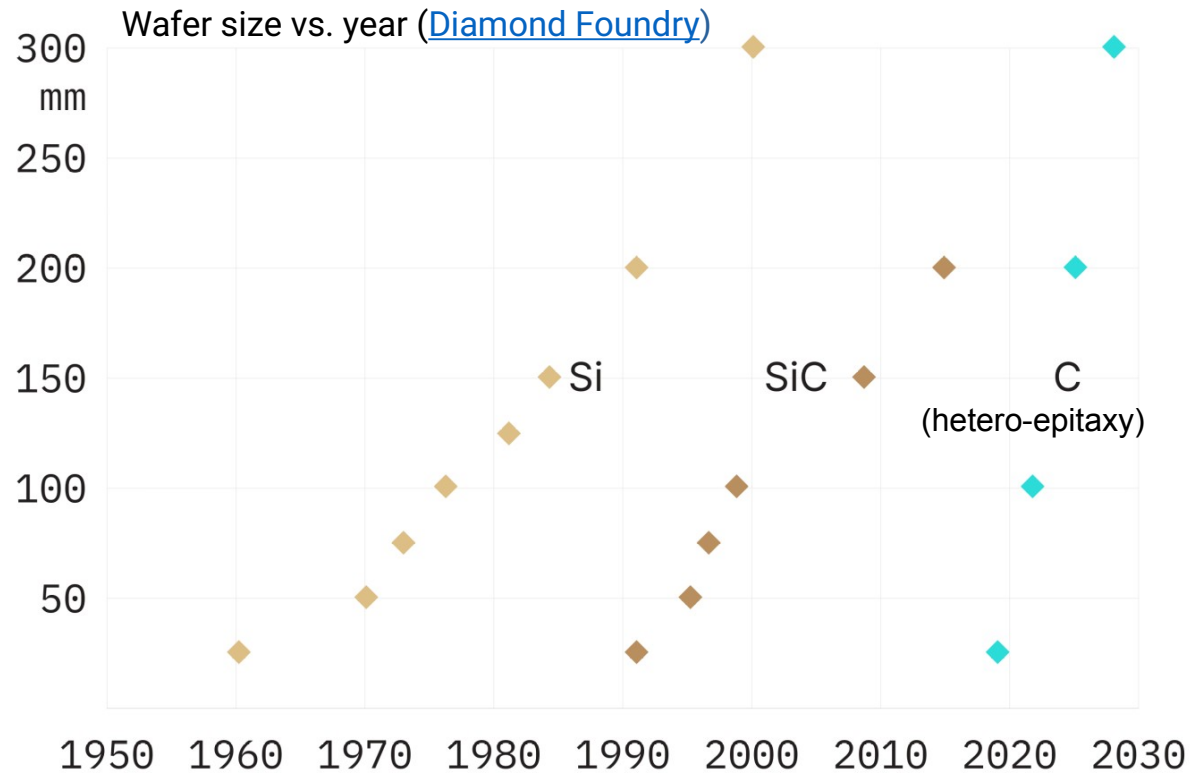
- + Large v_e/v_h , $\mu_e/\mu_h \rightarrow$ fast
- + Wide band gap, exceptional thermal conductivity $\rightarrow$ high temp operation
- + Low $\epsilon \rightarrow$ low C_{det}
- + Radiation hard, annealing during operation

- Low charge yield
 $\rightarrow$ 3D detectors / gain
- Doping challenging
- Large areas expensive



Diamond Commercialization

- Electronic grade sCVD is mature (e6, etc.), but expensive
- Industry interest driven by heat spreaders (AI/GPU chips) and RF / power electronics
DARPA LADDIS, DARPA UWBGs
- Heteroepitaxy-grown seeds promise large areas, material quality already better than pCVD



**Large Area Device-Quality
Diamond Substrates (LADDIS)**



DARPA wide bandgap programs

Progress in detector properties of heteroepitaxial diamond grown by chemical vapor deposition on Ir/YSZ/Si(001) wafers

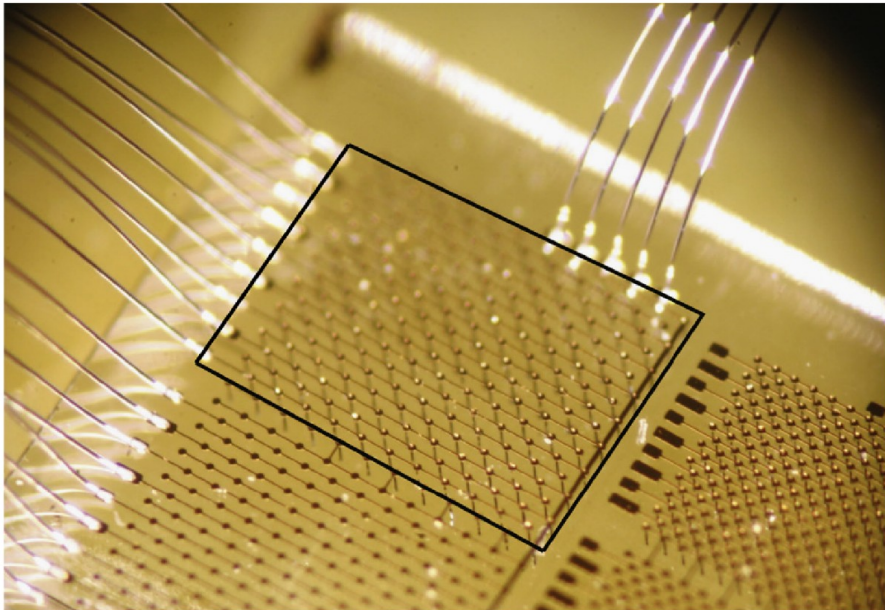
E. Berdermann^{a,*}, K. Afanaciev^b, M. Ciobanu^{a,c}, M. Fischer^d, S. Gsell^d, M. Kiš^a, S. Lagomarsino^e, W. Lohmann^{f,g}, M. Mayr^d, M. Pomorski^h, M.S. Rahman^{a,i}, C.J. Schmidt^a, S. Sciortino^e, M. Schreck^d, C. Stehl^d, M. Träger^a, for The NoRHDia,, CARAT, and, ADAMAS Collaborations

[Hetero-epitaxy diamond detectors](#)

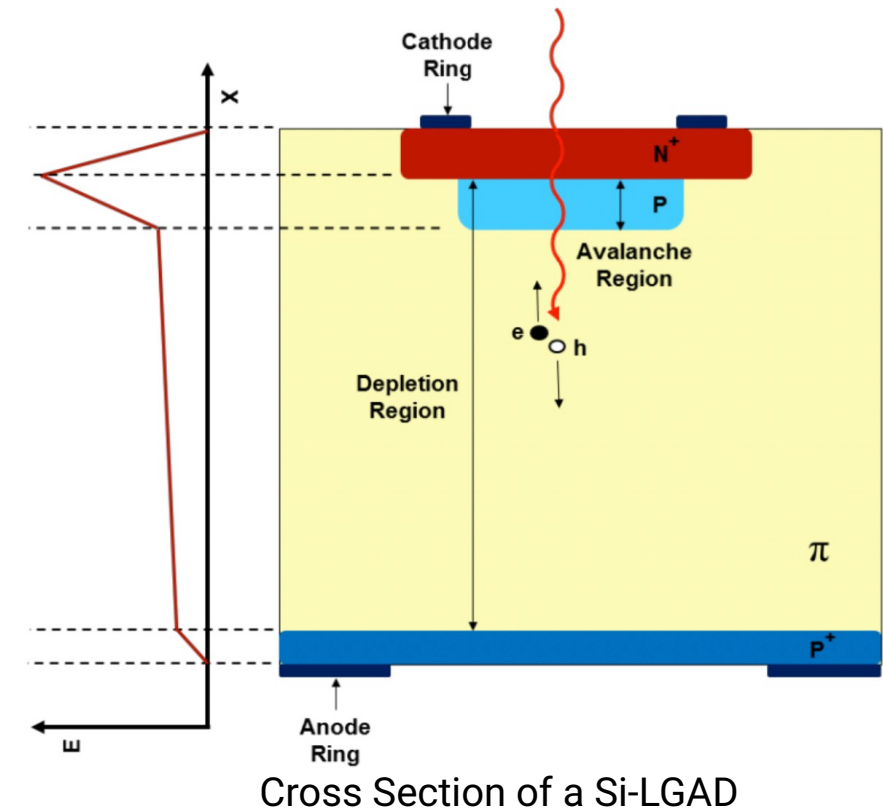
Hole collection OK, electron collection still needs work

Diamond Timing Detectors

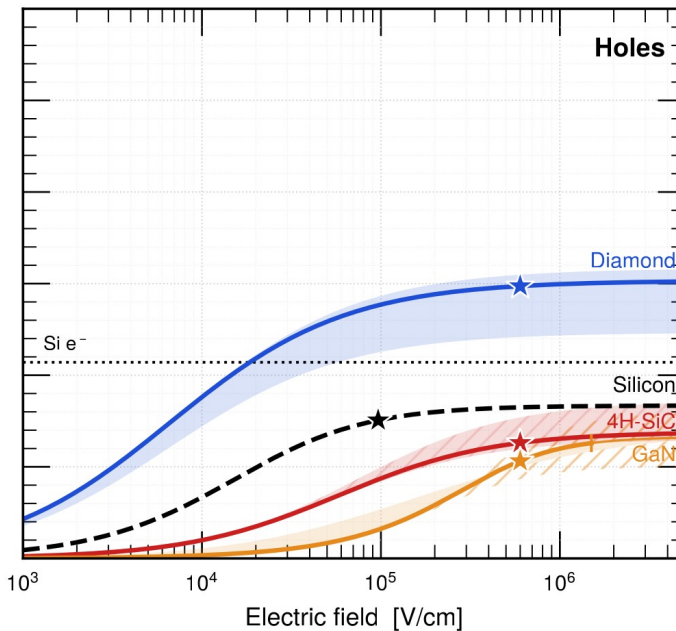
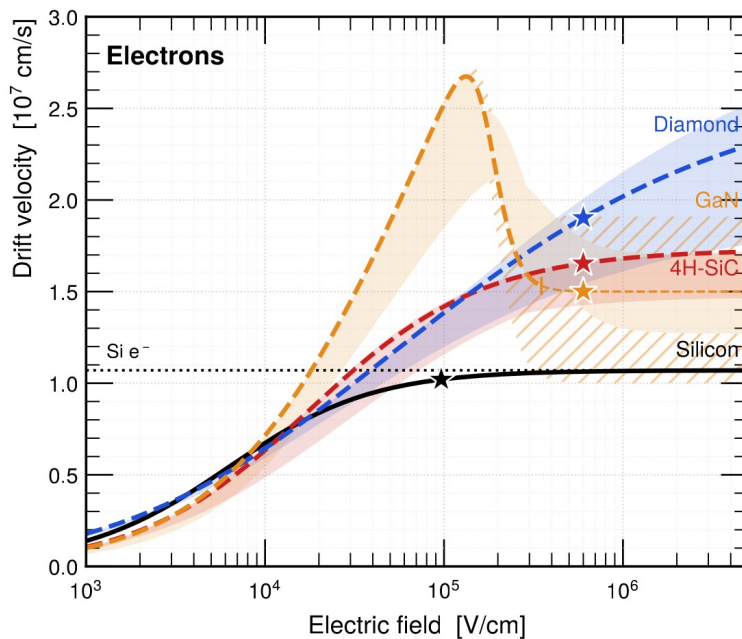
- Low charge yield $\rightarrow$ thick detectors or gain
- 3D detectors are a solution, however, large material budget, high resistivity columns $\rightarrow$ diamond detectors with gain layer (LGADs)



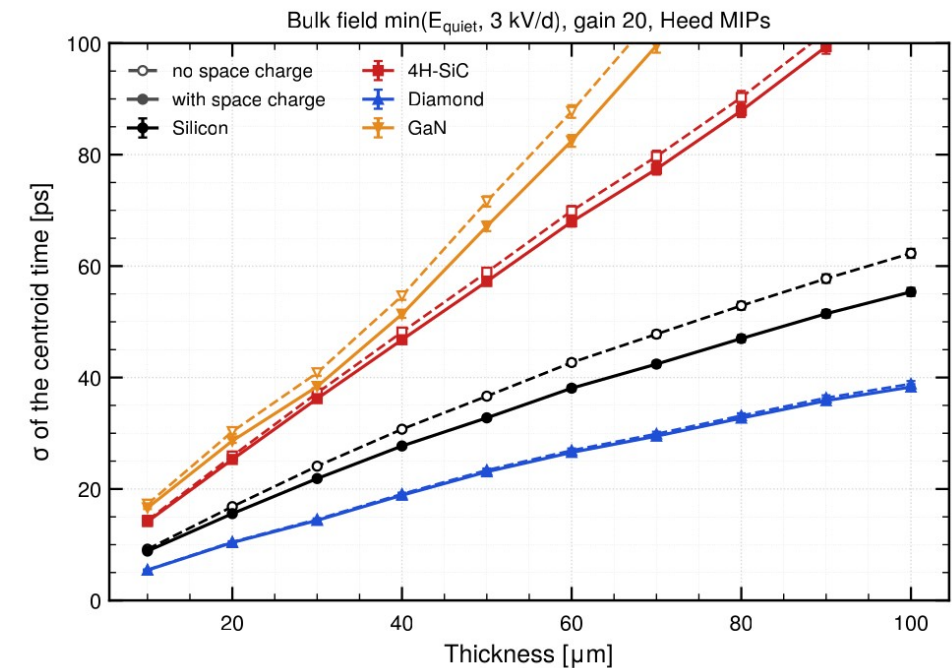
[3D diamond detector](#)



- Is the time resolution of a diamond detector better than Si, other WBG materials?
- Landau fluctuations limited by arrival time at gain layer (see for ex. [Riegler 2017](#))
 e^- for Si, h^+ for WBG $\rightarrow$ diamond fastest
- However, fair comparison depends on X/X_0 , max. gain, I_{shot} , shaping time, CFD, max. E-field, ...
stay tuned for a paper!



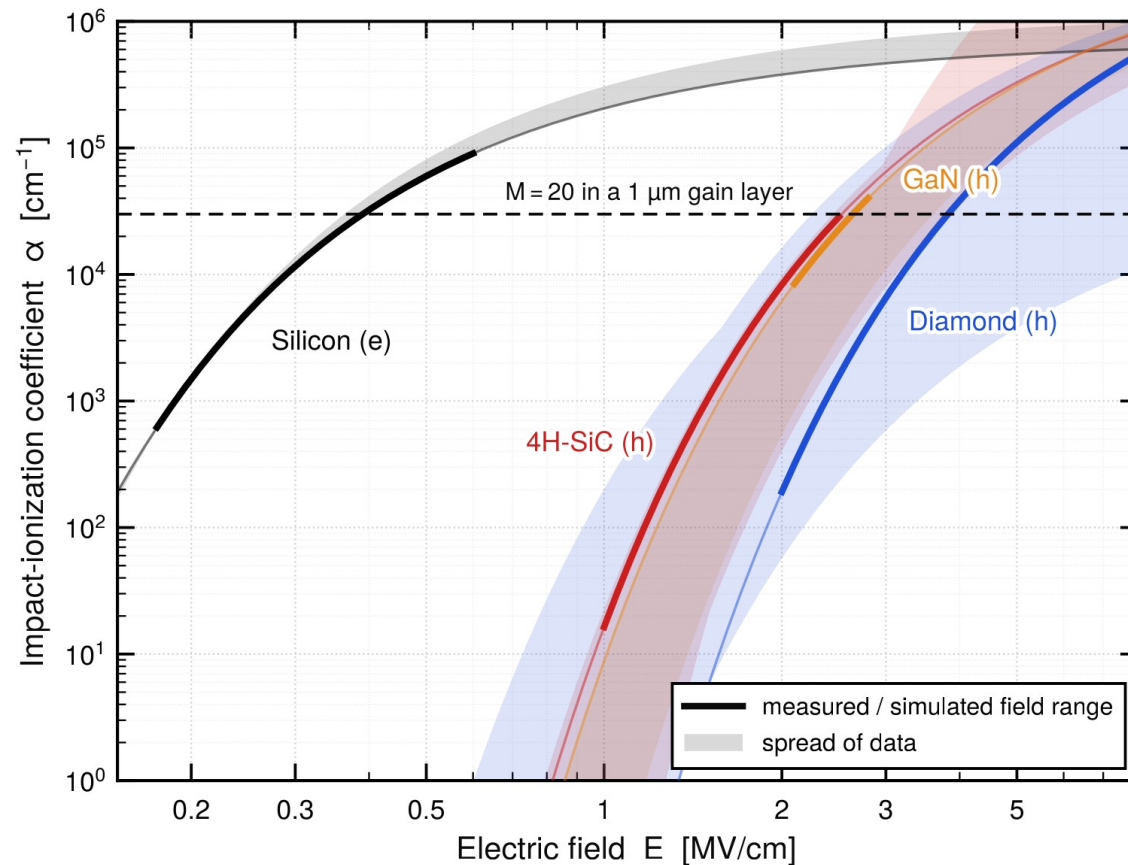
Charge carrier velocities for electrons and holes in silicon and WBG materials. The stars indicate the electric field obtained using 3kV at a thickness of 50 μm , or for silicon, the field where multiplication in the bulk 50 μm of a detector starts to be significant.



MC simulated Landau fluctuations (Allpix² fork), gain suppression modeled after Janssens et al. 2026 ([arxiv:2609.08666](#))

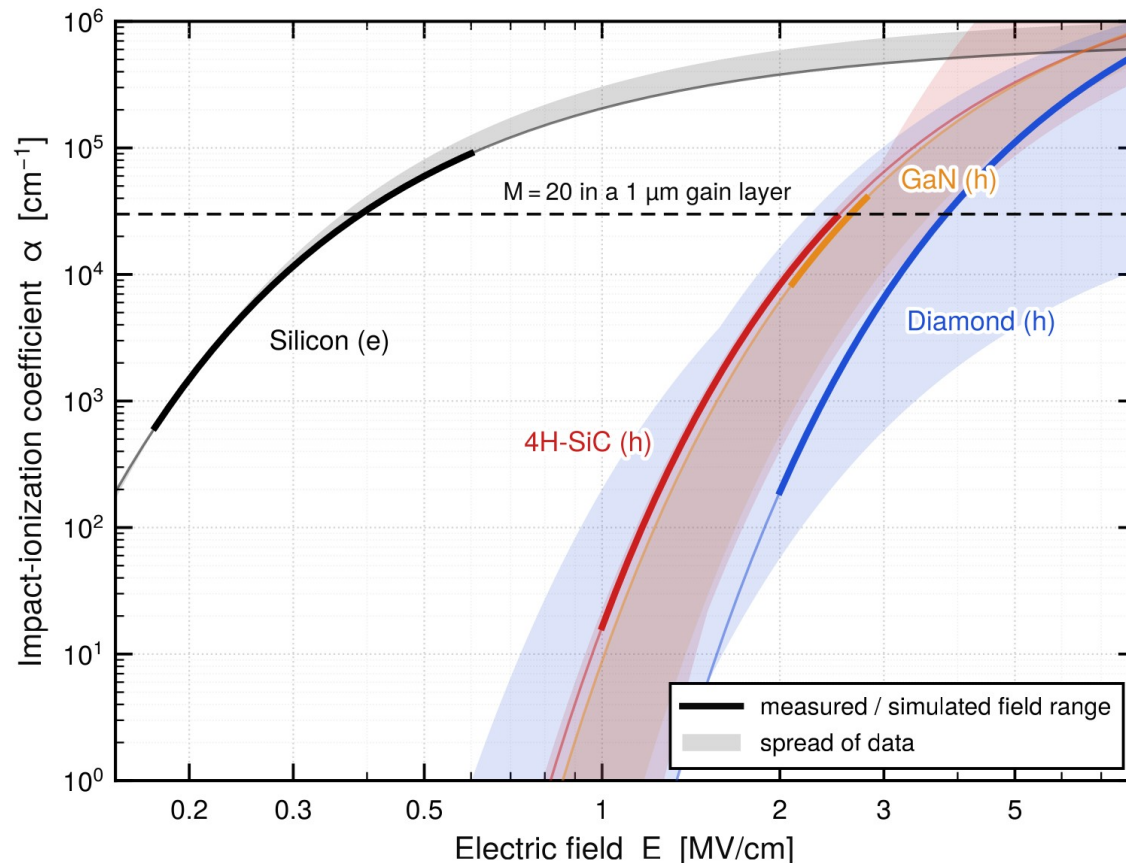
Impact Ionization in Diamond

- Similar to GaN and 4H-SiC, diamond is thought to be driven by hole multiplication
- Very little experimental measurements, mostly just MC simulations
- Wide range of breakdown field, from 3-10 MV/cm



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- Very little experimental measurements, mostly just MC simulations
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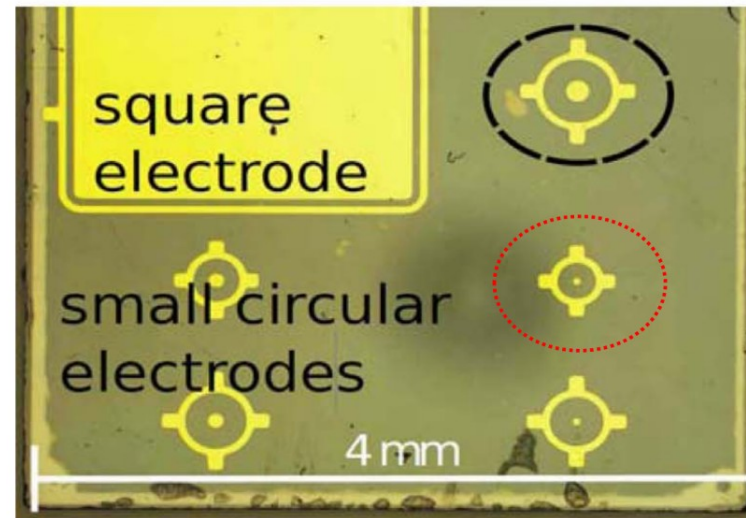
- Very little **measurements** exist!
- e/h asymmetry and max. gain uncertain
- How do we achieve these high fields?
field enhancement and gain layers!

- Thin films ($< 10 \mu\text{m}$) at up to $\sim 1 \text{ kV}$ have been used to probe fields up to (2 MV/cm) ([Skukan et al. 2016](#); [Skukan et al. 2019](#), [Jakšić et al. 2026](#), [Guckes et al. 2020](#)) with limited results
- Achieve higher fields using *field crowding* (using circular electrodes)
- Previous work probed up to $E_{\text{eqv.}} \sim 1 \text{ MV/cm}$ ([Muškinja et al. 2017](#))

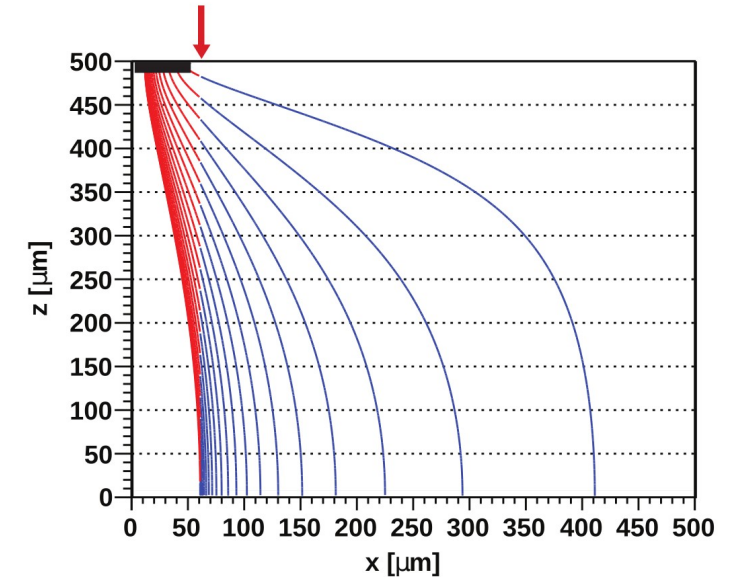
$$E_{\text{max}} \approx \frac{2V}{r \ln(4d/r)}$$

$$\beta = \frac{E_{\text{max}}}{E_{\text{avg}}} = \frac{2d}{r \ln\left(\frac{4d}{r}\right)}$$

Geometrical field enhancement

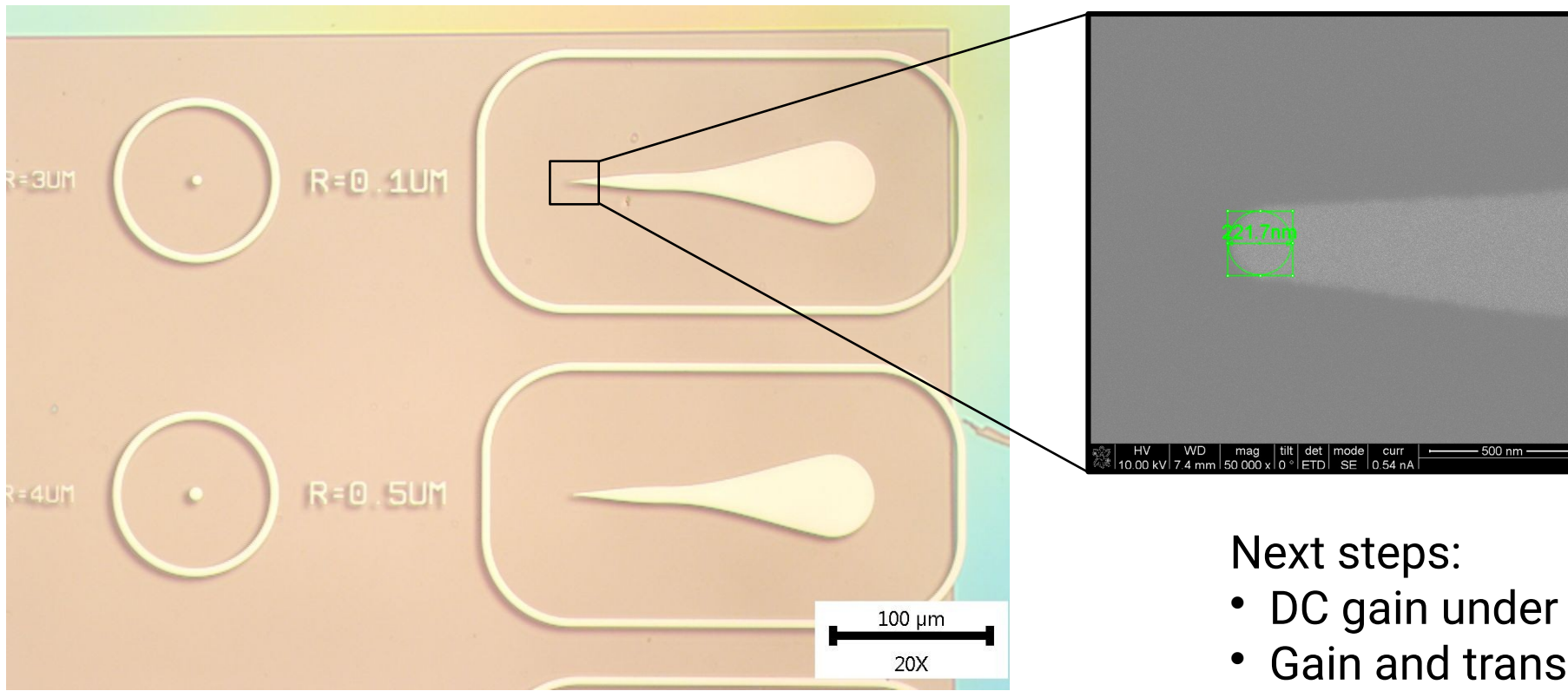


Field enhancement and circular electrodes, taken from [Muškinja et al., 2016](#)
 $d = 500 \mu\text{m}$, $r = 500 \mu\text{m} \rightarrow \beta = 25$



Field Enhancement Structures

- Thin substrate (30 μm) and sub μm electrode radius $\rightarrow$ enhancement (β) up to 100
 $\rightarrow$ reach up to 6 MV/cm for $< 1\text{ kV}$ bias voltage
- Small radii not wirebondable $\rightarrow$ tear drop structure



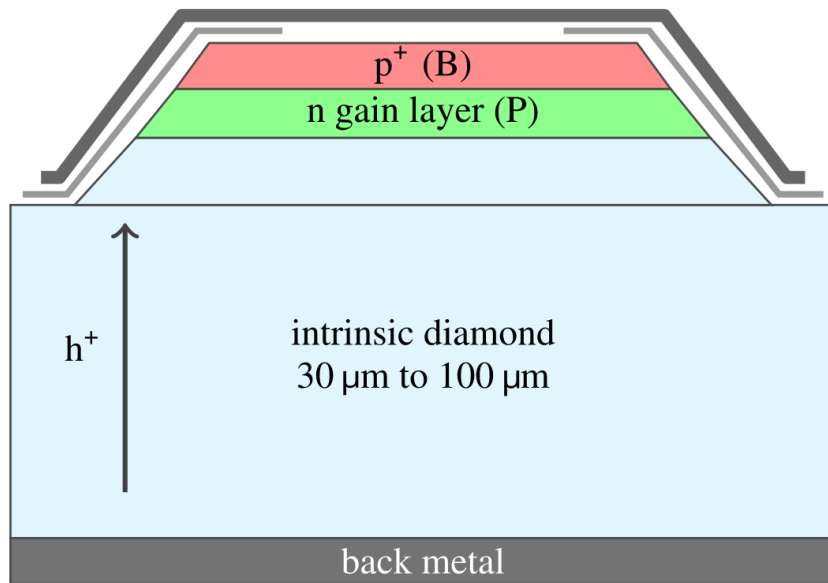
SCVD diamond samples manufactured by Dongsung Kim, LANL-CINT.

Next steps:

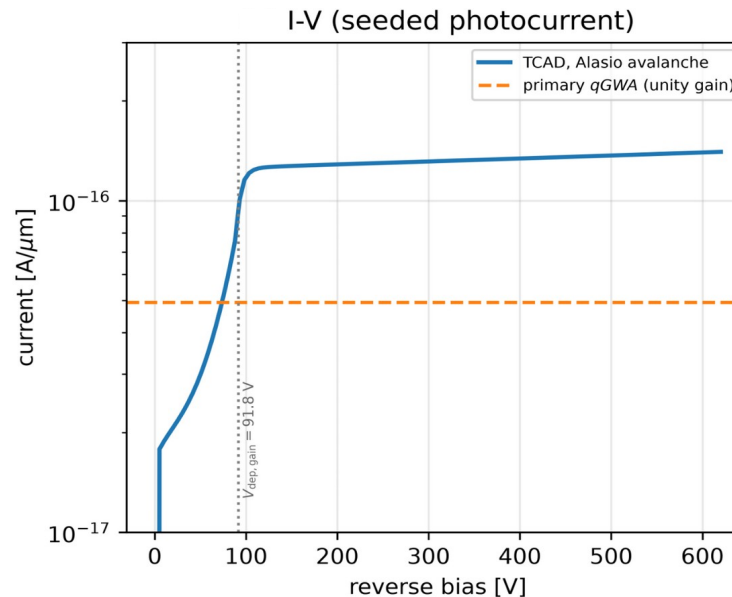
- DC gain under x-ray irradiation
- Gain and transients
w/ alphas, IBIC or TPA-TCT

Diamond LGADs

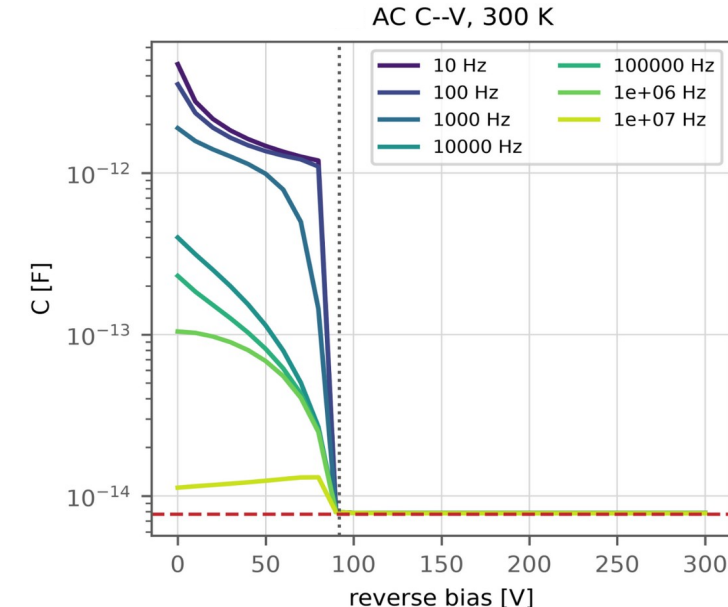
- Doping diamond is non-trivial (deep energy levels, epi-growth required), but not impossible
- SCIPP is developing TCAD simulations of diamond LGADs
→ how to address uncertainties in models and manufacturing?
- Radiation hardness of dopants?
P (n^{++}) and B (p^{++}) doped samples (Advent Diamond) to be irradiated



Proposed diamond geometry

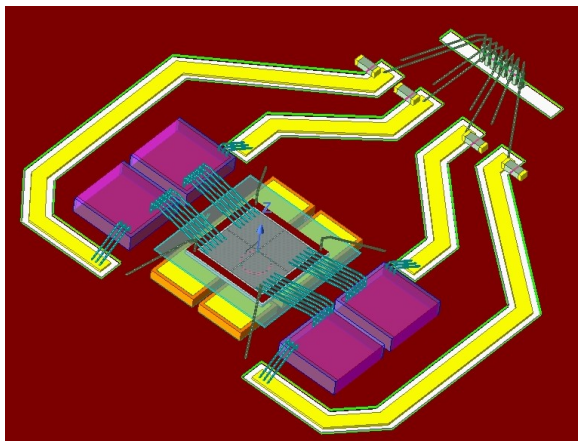


First TCAD simulations of diamond DC gain (I-V) and C-V



- Many detector applications do not require sensitivity to MIPs, but very fast speeds (> 1 GHz)
- SCIPP is developing detectors in a wide variety of applications

Beam Monitoring speed / rep. rates

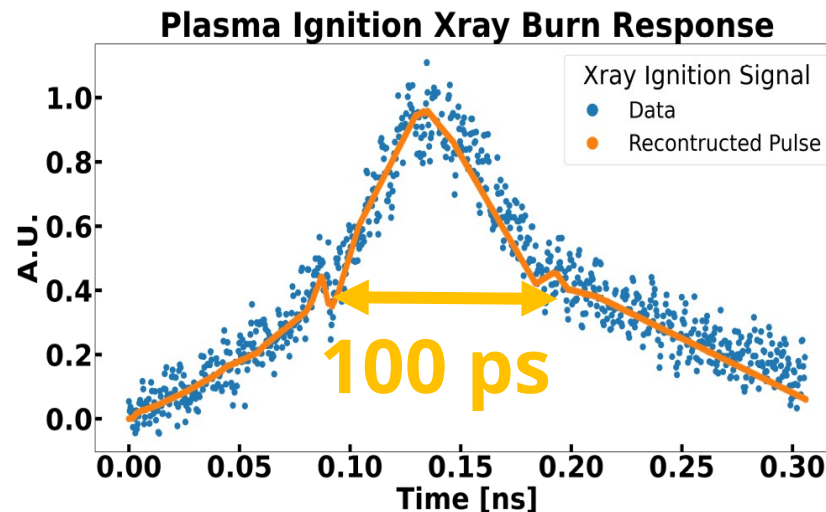


Diamond beam position monitor
w/ASIC (FPS-I/II) monitor for future
XFELs with GHz repetition rates

[10.1103/m79w-ft8t](https://arxiv.org/abs/10.1103/m79w-ft8t)

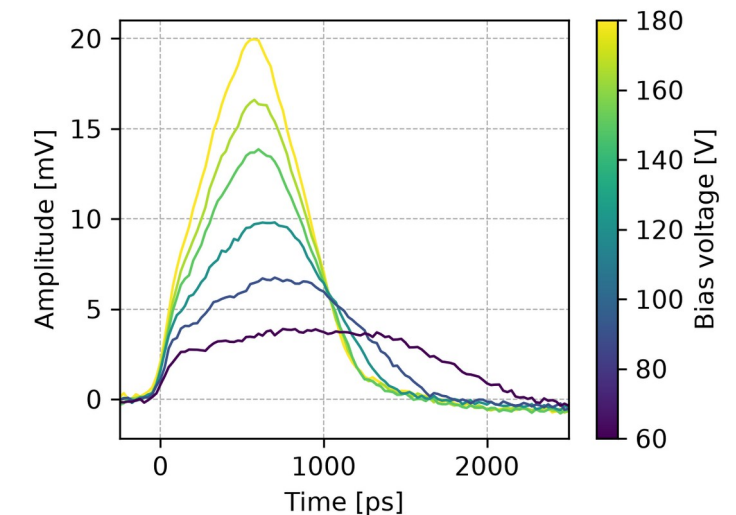
[10.1063/5.0213921](https://arxiv.org/abs/10.1063/5.0213921)

Fusion Diagnostics speed + rad. hardness



NIF burn measured by a [X-ray streak camera](#)

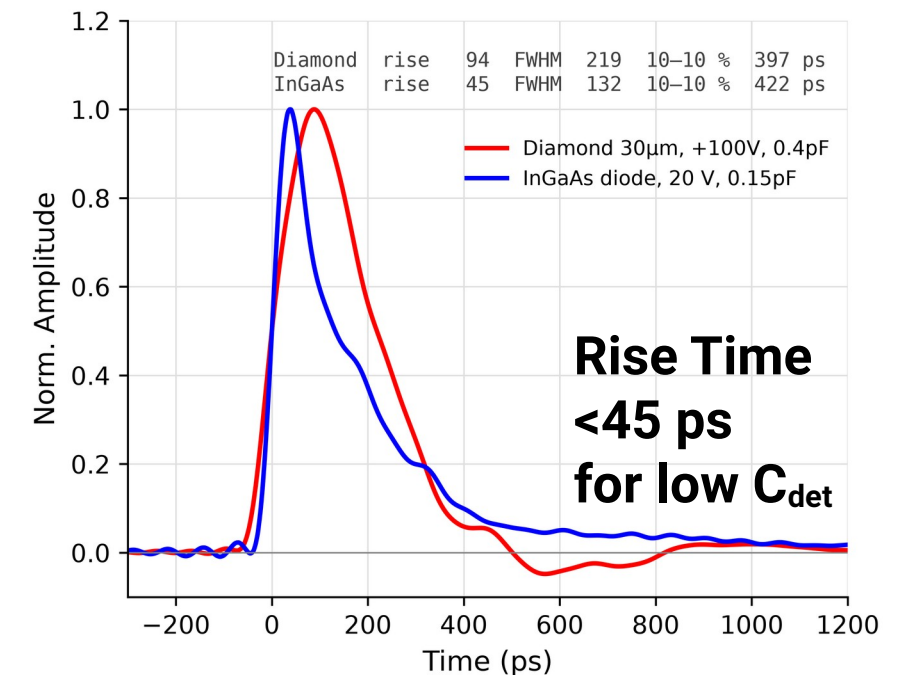
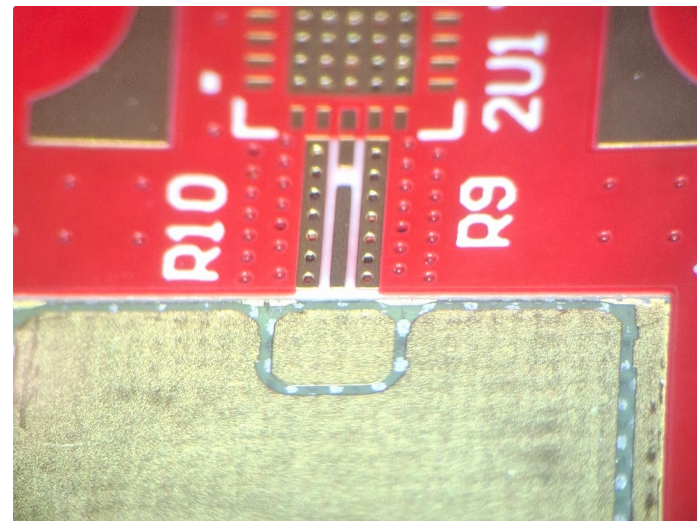
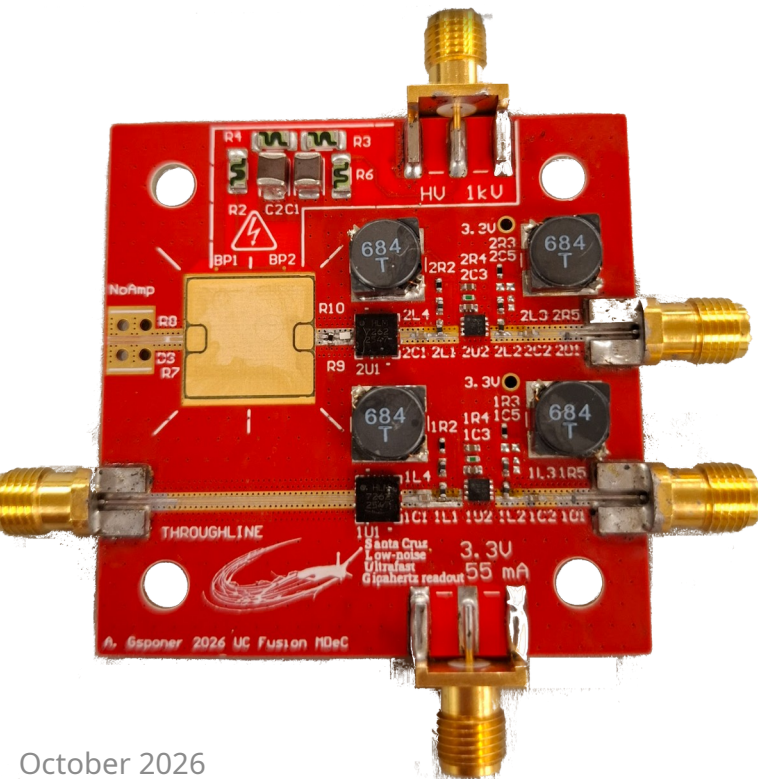
TCT Electronics <1 MHz to >1 GHz



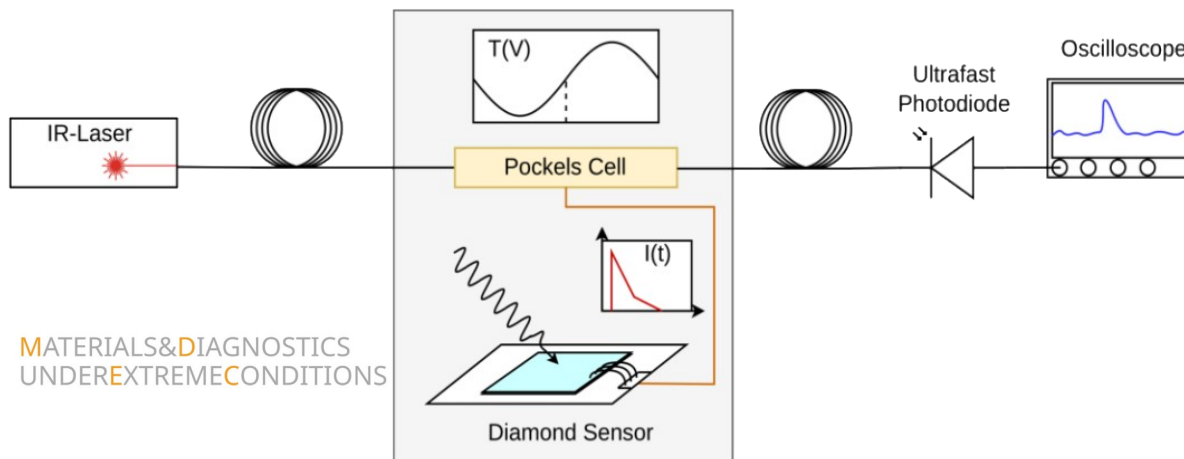
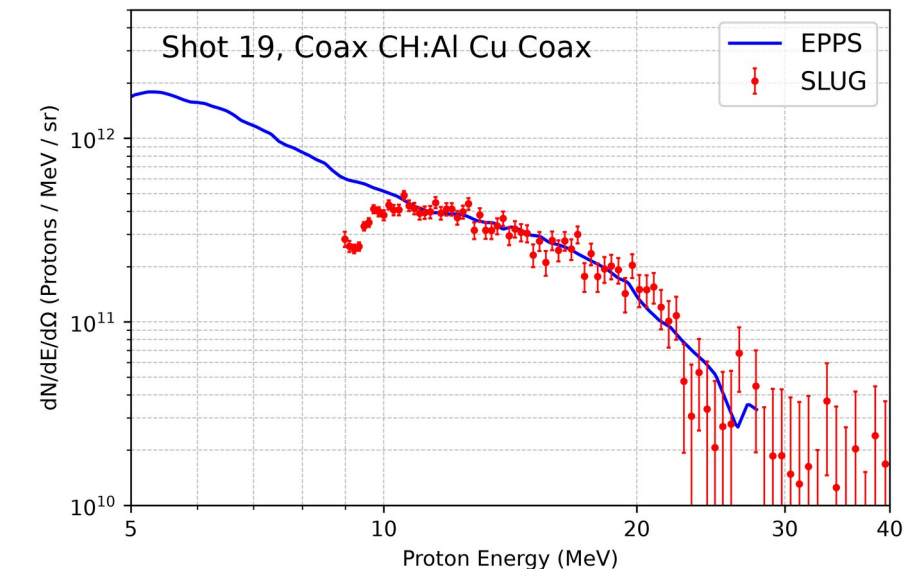
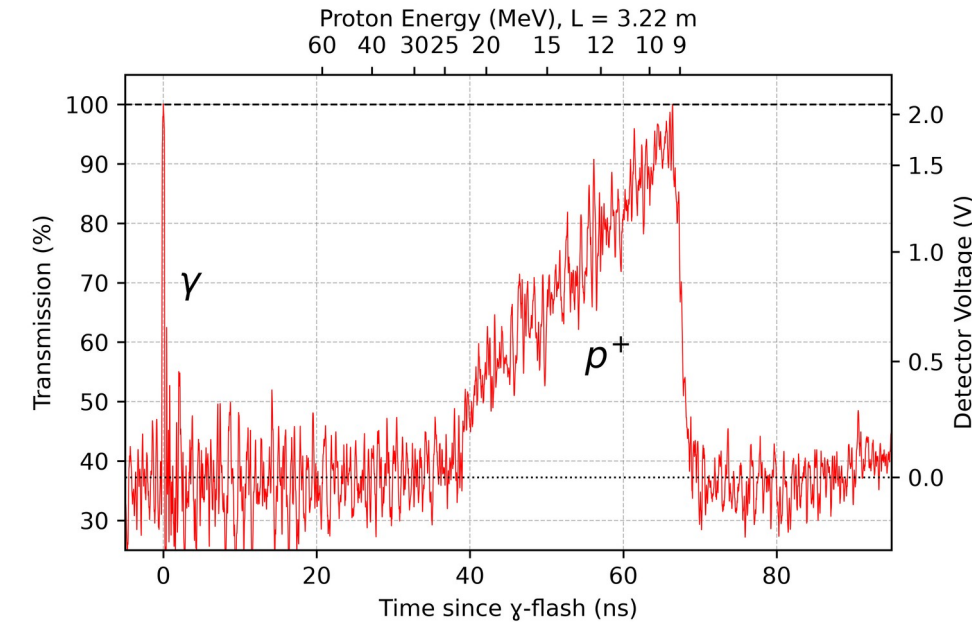
Transient current for a 50 μm Si-LGAD

The SLUG Board

- Optimized for TCT measurements with thin detectors
- Bandwidth of 75 kHz – >12 GHz, based on ADL8120 LNA
- Cavity to minimize bondwire height, accommodate single layer caps
- RF limiter and ESD protection, Rogers 4350B substrate



- Measure particle / neutron ToF / X-ray burnwidth (< 100 ps) using thin ($30\text{ }\mu\text{m}$) diamond on SLUG board, $\sim 3\text{m}$ L_{drift}
- Beamtime at Titan Laser of the Jupiter Laser Facility (LLNL)
 - $150\text{ J} / 0.5\text{ ps} \rightarrow 1\text{E}20\text{ W/cm}^2 \rightarrow$ laser acceleration
 - More than $\sim 10^{12}$ p^+ per shot up to 50 MeV
- EMP pickup $\rightarrow$ electro-optic readout + Faraday cage
- $O(100\text{ ps})$ for γ -flash, dozens of ns for proton ToF



Summary & Acknowledgments

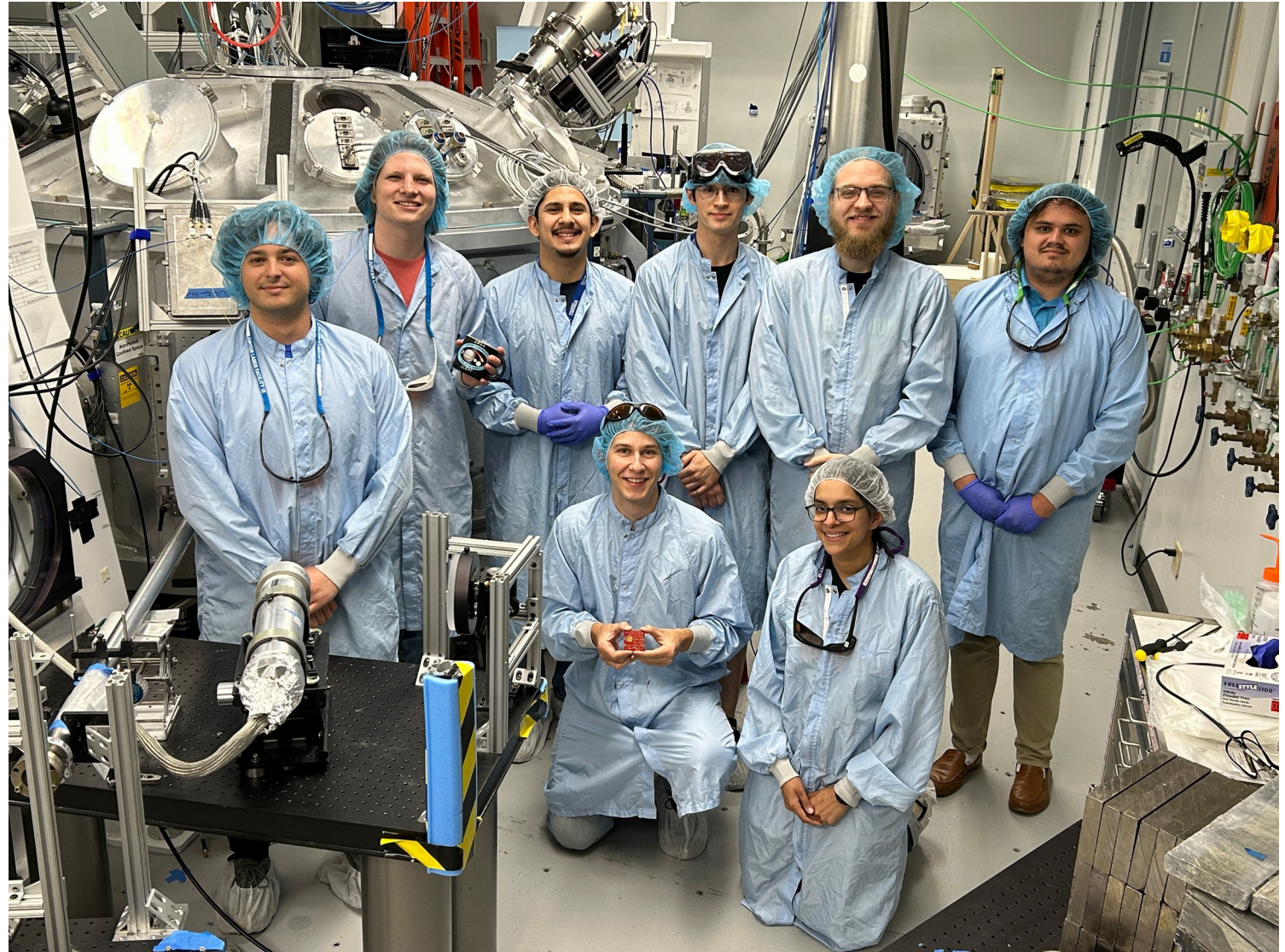
- Large area diamond wafers
- Diamond LGADs
- Diverse GHz detector applications

Special thanks to Eric Prebys (UC Davis) for his contributions to the electro-optical readout system.

This work was supported by the United States Department of Energy grants DE-SC0010107.

This project is supported by University of California Office of the President Lab Fee program award number L26CR10183.

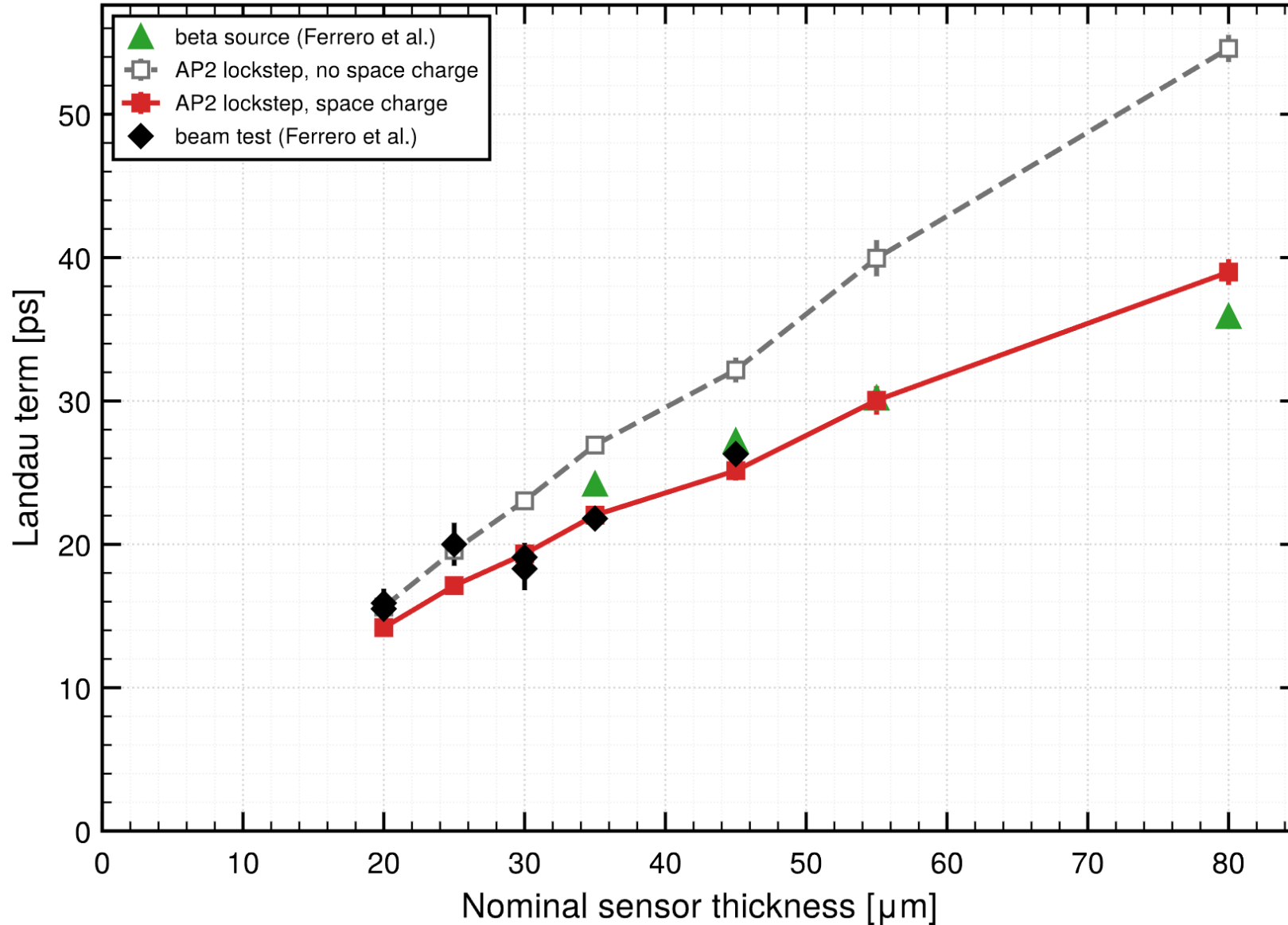
This work was supported in part by U.S. Department of Energy Office of Basic Energy Sciences Grants No. DE-SC0024205 (UC Santa Cruz), No. DE-AC02 05CH1152, by the Office of High Energy Physics Grant No. DE-SC0010107, and by the UC-National Laboratory Fees Research Program grant ID No. LFR-20-653232. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department, of Energy (DOE) Office of Science by LANL and Sandia National Laboratories (Contract No. DE-NA-0003525).



2026 Titan Beamtime (MDEC collaboration)

Backup

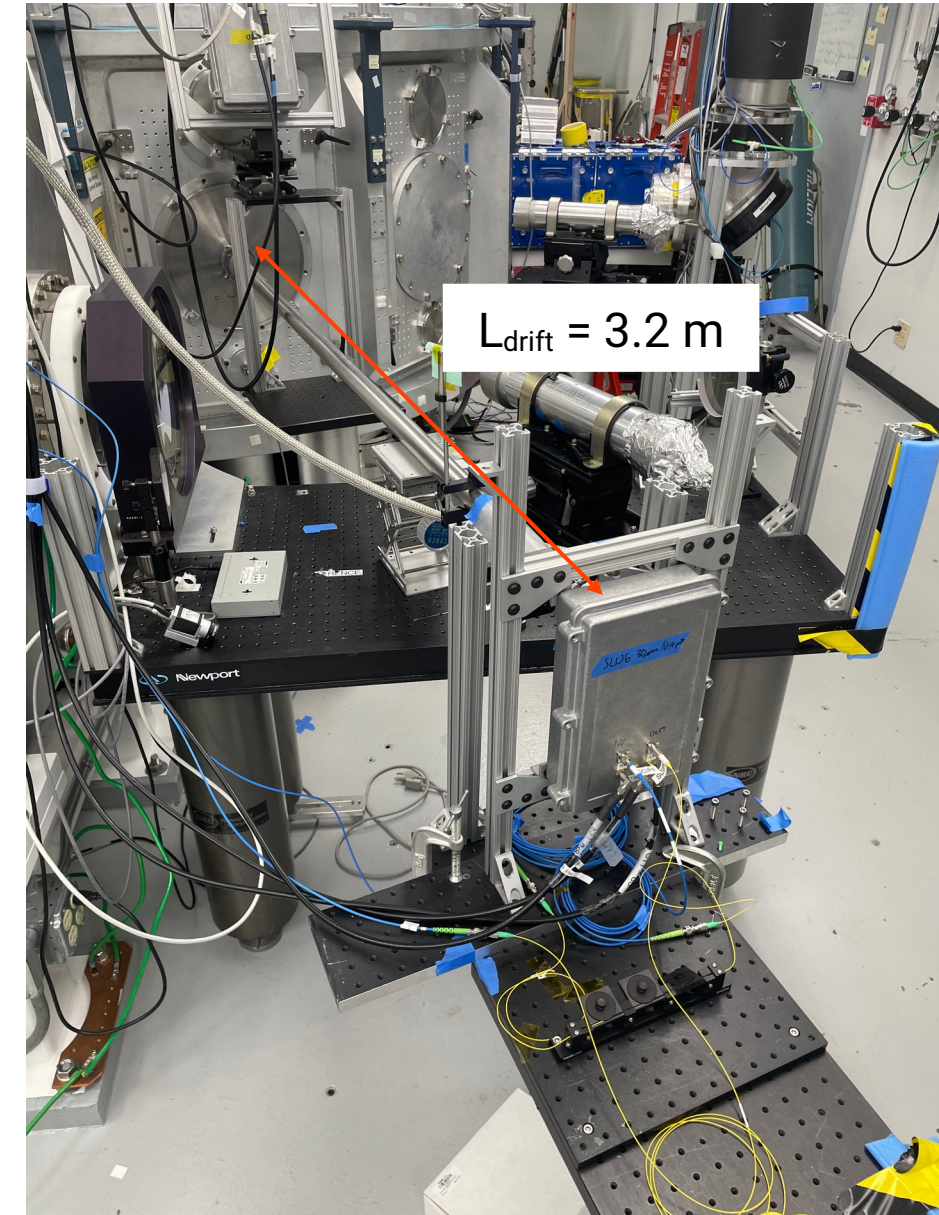
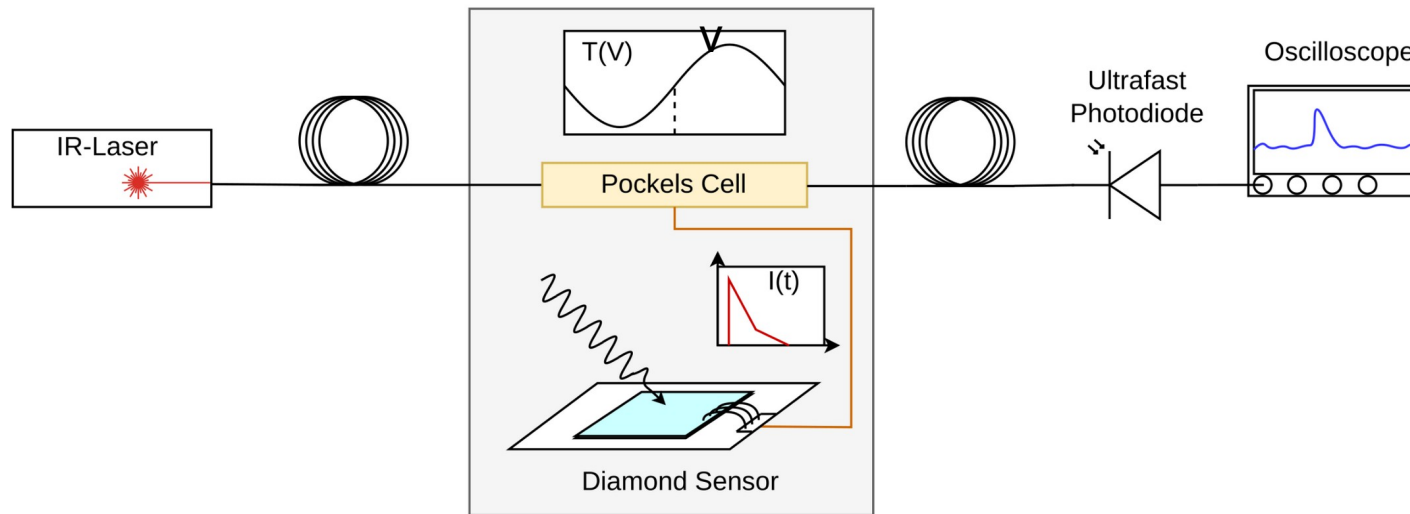
Effect of Gain Suppression on LGADs



MC simulated Landau fluctuations (Allpix² fork), gain suppression modeled after Janssens et al. 2026 ([arxiv:2609.08666](https://arxiv.org/abs/2609.08666)), exploiting radial symmetry to solve electric field screening in 2D

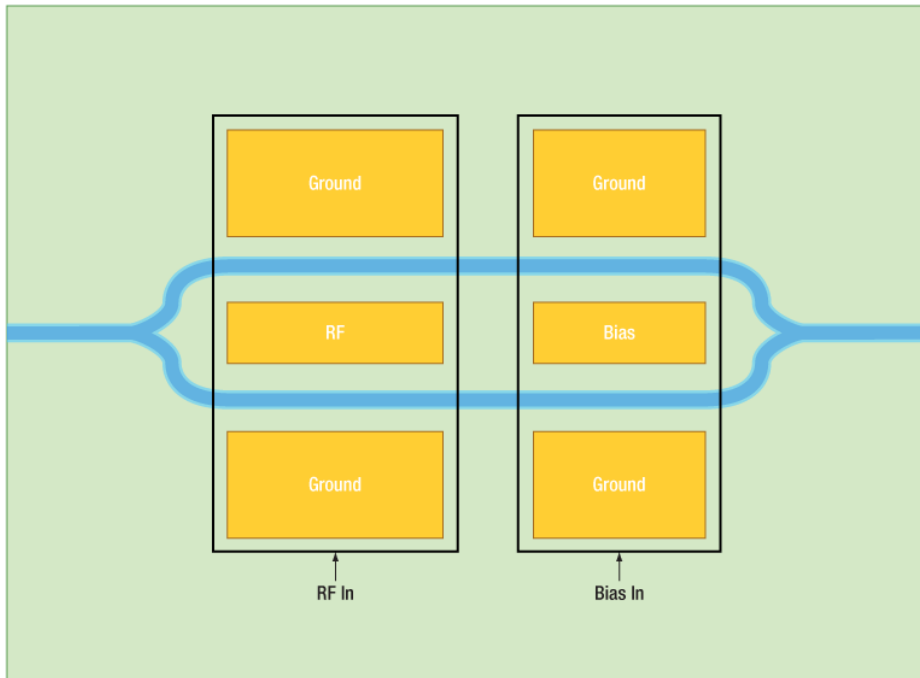
Electro-Optic Readout

- SNR depends on shot noise of photodetector and relative intensity noise (RIN) of noise
- Increasing laser power up to ~ 10 mW (photodetector limit) helps reducing shot noise, RIN is intrinsic to laser $\rightarrow$ needs a low noise laser



Electro-Optic Readout

- Change of refractive index (n) as a function of electric field, “Pockels”-effect
- Using LiNbO_3 modulators, can work at very high frequencies (>40 GHz)
- Pockels cell can also be used to modulate / “chop” laser beam and produce arbitrary, <100 ps laser pulse forms (using an sufficiently fast pulse generator / AWG)



From [Thorlabs](#)

- Each arm picks up a phase shift of $\Delta\phi$, 1x for RF and DC bias
- Light for both waveguides interferes positively or destructively

Phase Shift

$$\Delta\phi = \frac{2\pi}{\lambda} \Delta n(E) L$$

Transmission

$$T(V) = \sin^2 \left(\frac{\pi V}{2V_\pi} \right)$$

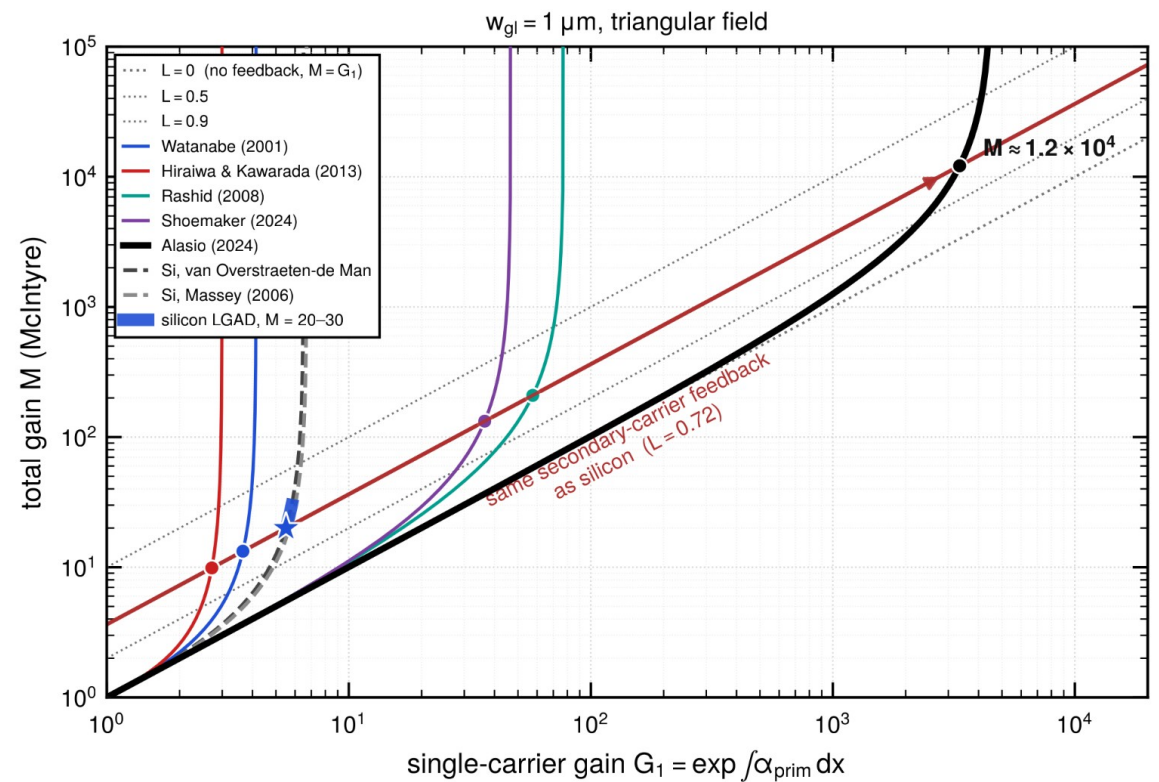
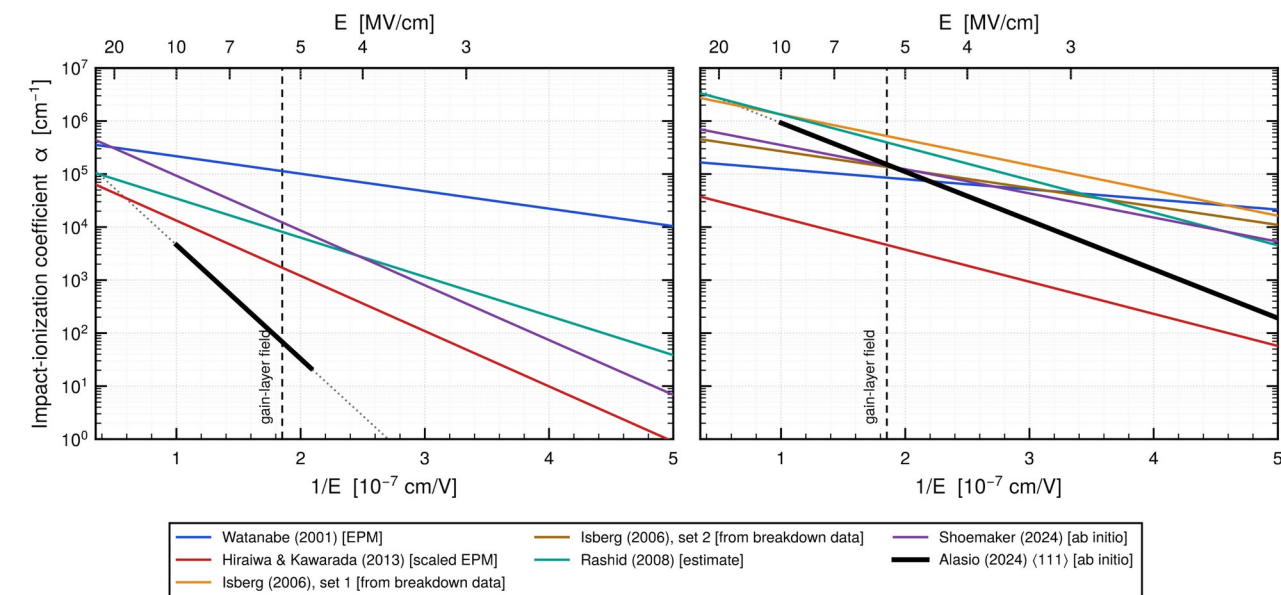
Maximum Gain of Diamond LGADs?

- Maximum gain / avalanche is set by asymmetry btw. e^- and h^+ gain
- Some models predict very low ionization for e^- in diamond $\rightarrow$ high gain?
(similar to gas detectors with $\sim$ zero ionization rates for ions)

$$M_h = \left[1 - \int_0^w \alpha_h(x) \exp\left(-\int_0^x (\alpha_h(x') - \alpha_e(x')) dx'\right) dx \right]^{-1}$$

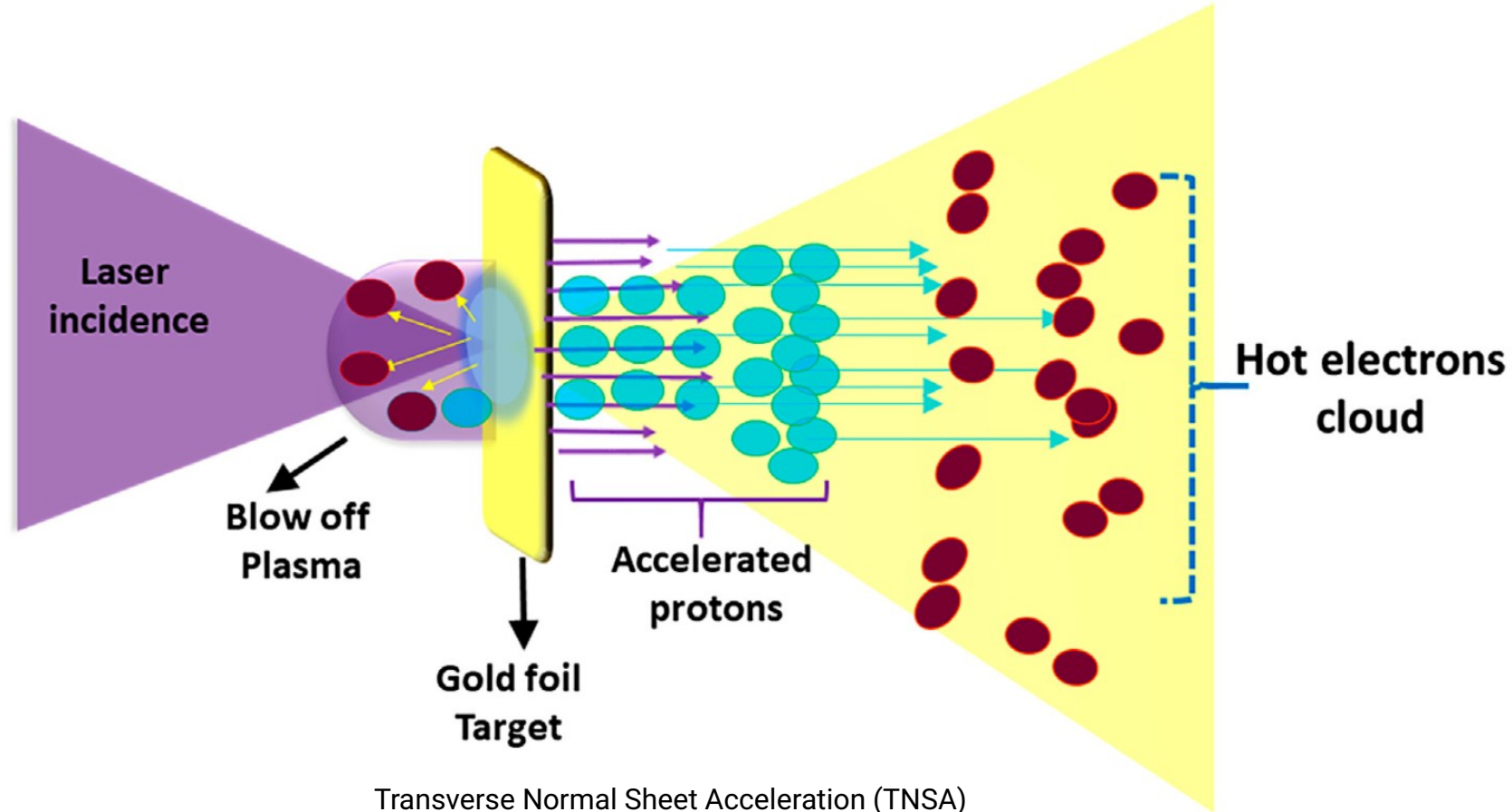
Electrons

Holes



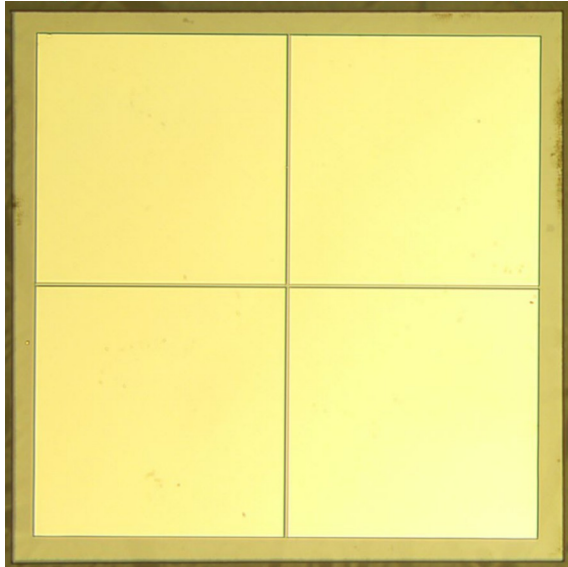
Laser Acceleration

- Transverse normal sheet acceleration (TNSA) is the main acceleration mechanism used at Titan (JLF/LLN)
- Radiation pressure acceleration (RPA) also observed for some thin targets during the MDEC campaign this summer

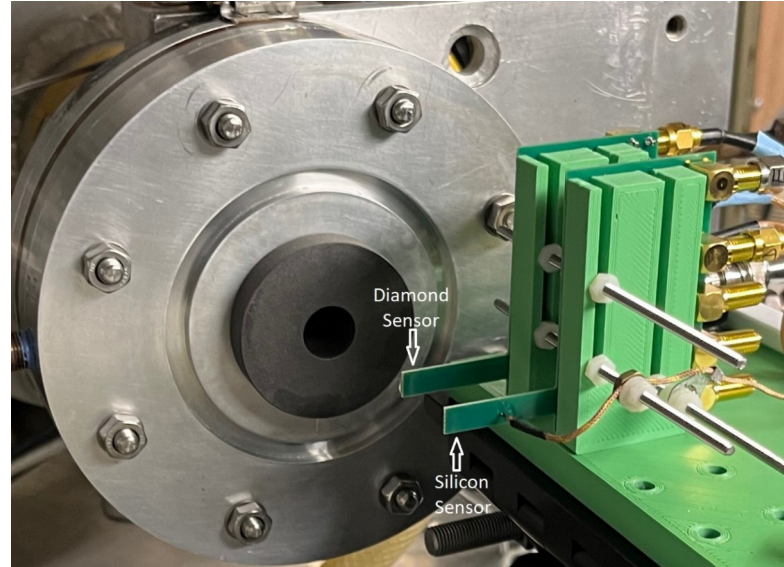


Transverse Normal Sheet Acceleration (TNSA)
[10.3389/fphy.2021.624963](https://doi.org/10.3389/fphy.2021.624963)

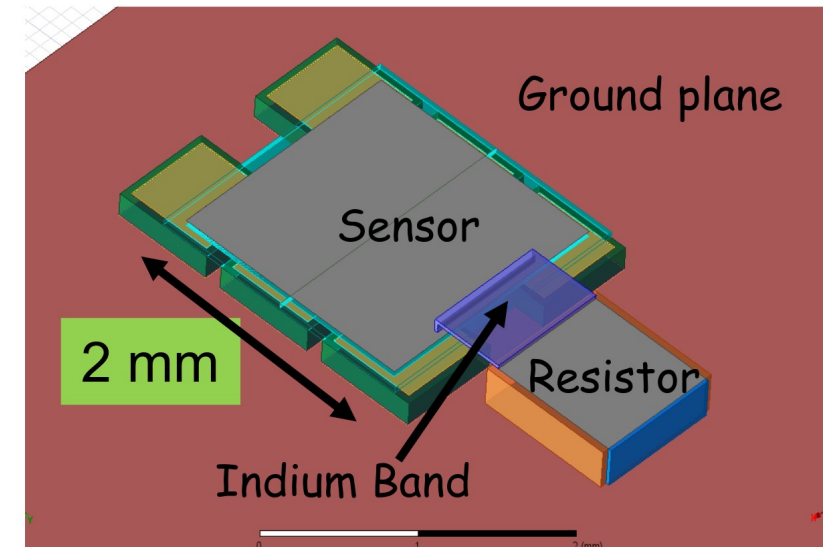
Diamond Instrumentation
for beamlines, XFELs
and fusion



Radiation Damage
extreme fluences, doping



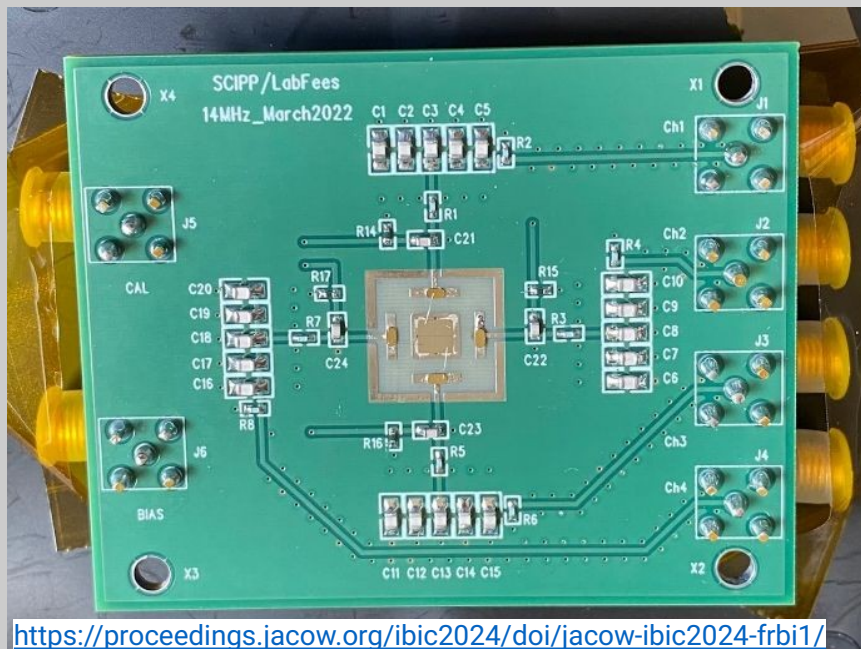
High Bandwidth (> 10 GHz)
using thin diamonds



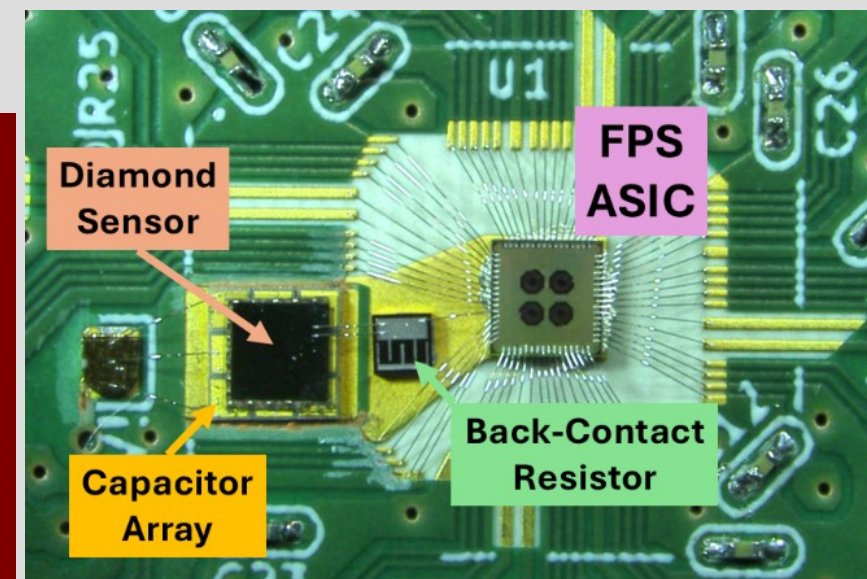
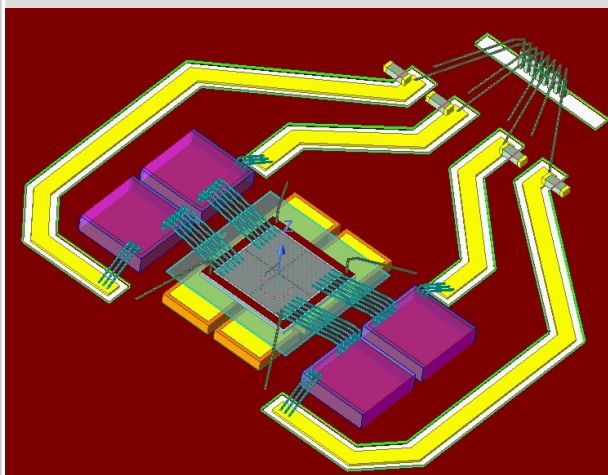
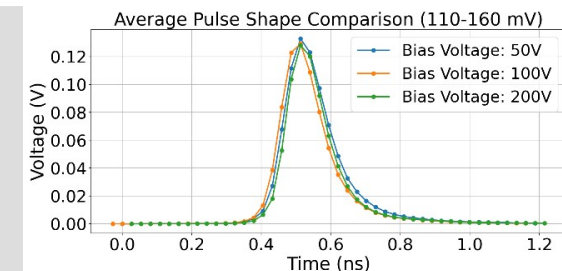
Diamond Beam Monitors

- Motivated by push toward XFELs with repetition rates exceeding 1 GHz
→ demand for fast diagnostics
- Advanced Accelerator Diagnostics collaboration (UCSC, UCD, LANL, LBNL, SLAC)

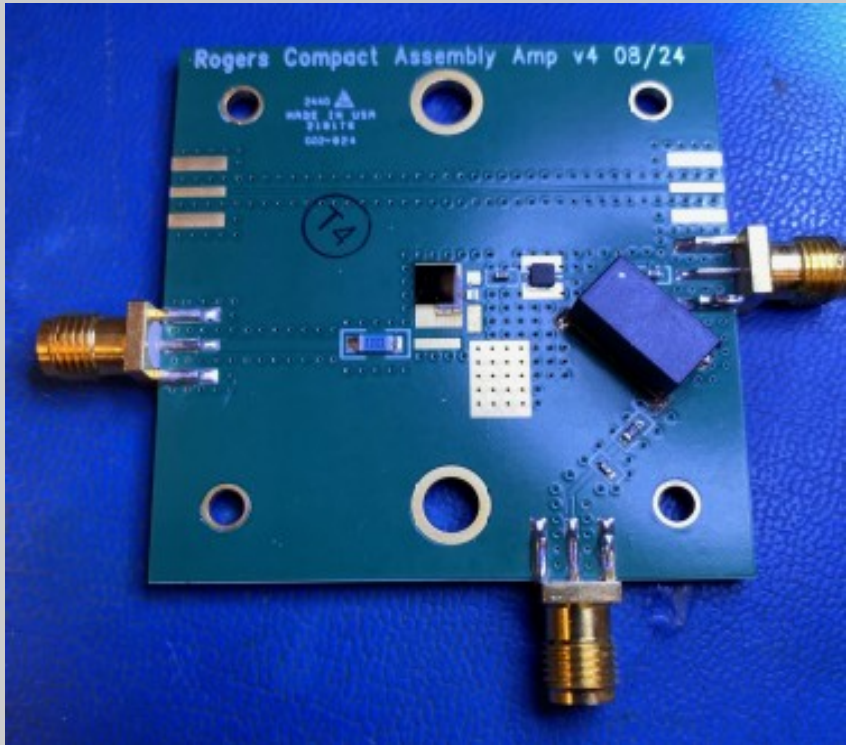
4-quadrant 50 MHz position monitor 3 μm spatial accuracy



ASIC-based beam position monitor FWHM down to 120 ps Tested at NLCTA (SLAC)

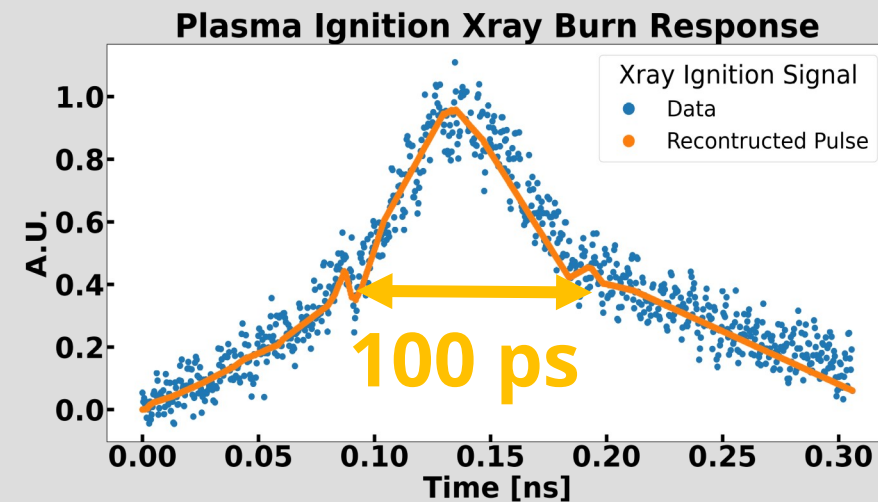


Diamond Spectrometer for ZAP energy Monitoring D-D fusion symmetry



Diagnostics for inertial confinement fusion (ICF)

- UCSC part of new California Center for Fusion Energy
- Ongoing efforts to develop ultra-fast and ultra radiation-hard diamond diagnostics for ICF
- BW : $> 10 \text{ GHz}$, $\phi > 1\text{E}20 \text{ n}_{\text{eq}}/\text{cm}^2$



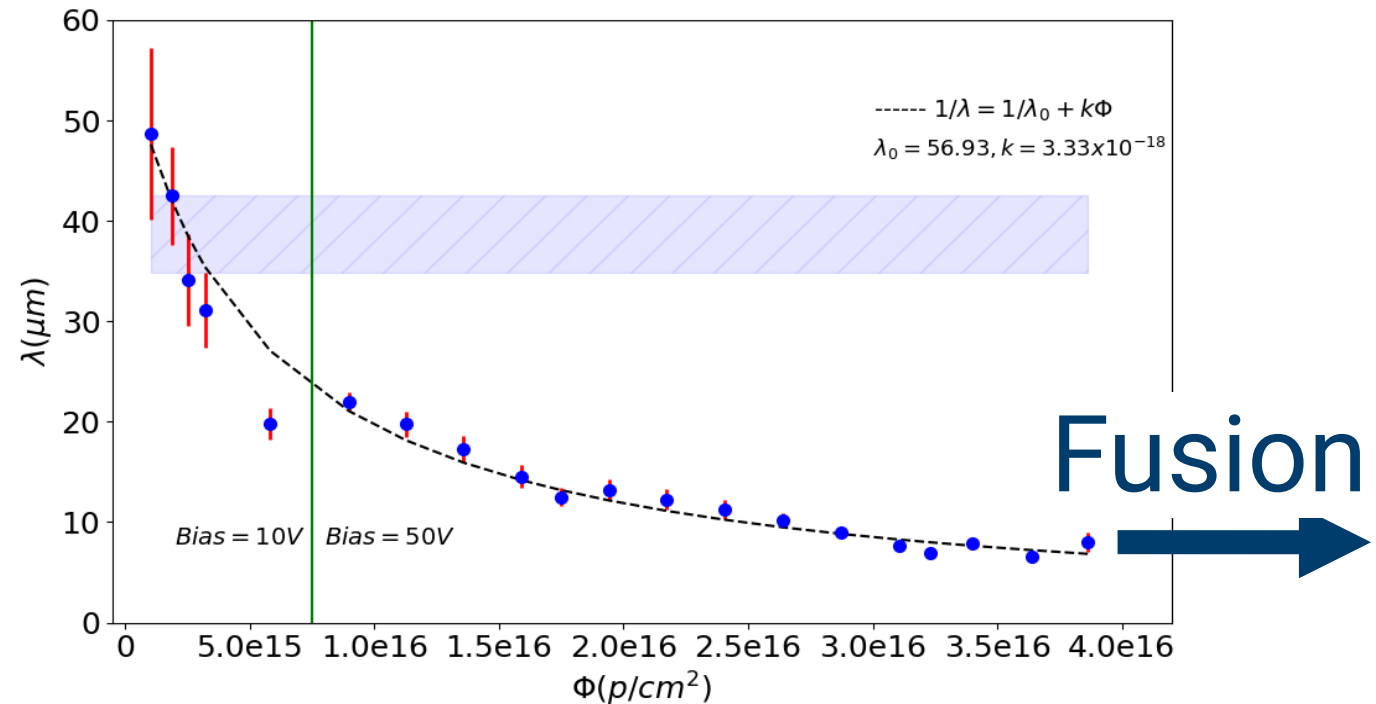
NIF burn measured by a X-ray streak camera, <https://doi.org/10.1063/5.0127438>

Radiation damage in doped diamond



Seed project with ADVENT diamond (AZ) to study radiation damage to doped diamond

In-situ damage study using protons



Charge collection length vs. 67.5 MeV p^+ fluence, 60 μm SCVD
[10.1088/1748-0221/19/09/P09018](https://doi.org/10.1088/1748-0221/19/09/P09018) (AAD Collaboration)

High Bandwidth Electronics

- Many applications demand high bandwidths in excess of 5-10 GHz (beam monitoring, fusion, TCT with thin detectors)
- Developed “compact signal path” using a shunt resistor and single layer capacitors
- BW of ~5 GHz achieved, ongoing push to 10+ GHz

