

DEVELOPMENT OF ULTRA-FAST DIMAOND-SENSOR BASED SYSTEMS FOR ADVANCED ACCELERATOR DIAGNOSTICS*

B. A. Schumm[†], F. Martinez-McKinney, T. Morris, S. Mudford, M. Nizam, R. Padilla, K.-W. Shin, M. Wilder, University of California, Santa Cruz and the Santa Cruz Institute for Particle Physics, Santa Cruz, California, USA

E. Prebys, C. Rowling, University of California, Davis and the Crocker Nuclear Laboratory, Davis, California, USA

J. Bohon, C. Grace, T. Prakash, Lawrence Berkeley National Laboratory, Berkeley, California, USA

B. Jacobson, I. Silva Torrecilla, J. Smedley, SLAC National Accelerator Laboratory, Menlo Park, California, USA

M. Gulley, D. Kim, Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Abstract

The Advanced Accelerator Diagnostics collaboration has been developing diamond-sensor based high bandwidth position-sensitive diagnostics for application at next generation XFELs and other accelerator facilities. A pass-through diagnostic with 50 MHz rate capability has demonstrated pulse-by-pulse position sensitivity of 1% of delivered beam width. Progress has been made in upgrading this diagnostic approach to multi-GHz operation, involving an integrated detection system design making use of a compact signal path and proximate high-bandwidth readout ASIC. Preliminary results are presented on the performance of both the signal path and ASIC. Possible additional applications, including precision event timing and plasma ignition diagnosis, are introduced.

INTRODUCTION

The prospective diagnostic and imaging needs of future X-ray Free Electron Laser (XFEL) facilities [1,2] have driven work in the development of high-bandwidth ionizing particle detection systems that can operate at frame rates in excess of 5 GHz, an order of magnitude greater than existing prototype systems [3]. The Advanced Accelerator Diagnostics (AAD) group, a collaboration involving University of California campuses (Santa Cruz and Davis) and three National Laboratories (Los Alamos, Lawrence Berkeley and SLAC), has been exploring the use of CVD diamond sensors complemented by dedicated readout

systems (including ASICs) to push the limits of readout bandwidth and dynamic range of X-ray detection systems. In this Proceedings, we report on the performance of a moderate speed (50 MHz) position-sensitive pass-through diagnostic and, more importantly, recent progress made in advancing the design of this diagnostic to allow for operation in the multi-GHz RF regime. Such a capability may prove enabling for the operation and exploitation of next-generation XFEL beams, as well as advancing diagnostic capabilities in other fields, including Fusion Energy Science [4].

In this work, the AAD collaboration makes use of monocrystalline diamond sensors, whose superior saturated drift speed of approximately 200 $\mu\text{m}/\text{ns}$ [5] make them ideal for fast-signal applications. The collaboration makes use of diamond substrates purchased from industrial vendors, and fabricated by the Los Alamos National Laboratory group at its Center for Integrated Nanotechnologies.

50 MHz QUAD PASS-THROUGH DIAGNOSTIC

Motivated by the development of the cavity-based XFEL (CBXFEL) [6], the AAD collaboration has developed a quadrant pass-through diagnostic designed to provide intensity and centroid measurements of a moderate-intensity XFEL beam with 50 MHz repetition rate. This diagnostic is depicted in Fig. 1, and features a four-channel quadrant diamond sensor of total area $4 \times 4 \text{ mm}^2$ and thickness 43 μm .

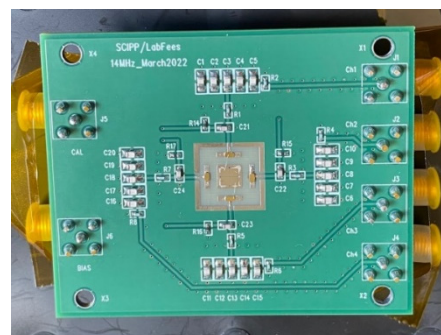


Figure 1: 50 MHz quadrant pass-through diagnostic.

* This work was supported in part by U.S. Dept. of Energy Office of Basic Energy Sciences grant numbers DE-SC0024205 (UC Santa Cruz), DE-AC02 05CH11521 (LBNL), A24-0496-S001 (UC Davis), DE-AC02-76SF00515 (SLAC) and FWP LANLE8AN (LANL), by the Office of High Energy Physics grant number and DE-SC0010107, and by the UC-National Laboratory Fees Research Program grant ID #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. Dept. of Energy (DOE) Office of Science by LANL and Sandia National Laboratories (Contract DE-NA-0003525). LANL is operated by Triad National Security, LLC, for the National Nuclear Security Administration of U.S. Dept. of Energy (Contract No. 89233218CNA000001).

[†] baschumm@ucsc.edu

Each channel's signal is shaped by an independent passive network (Fig. 2), yielding pulses of less than 20 ns duration (Fig. 3), corresponding to a rate capability in excess of 50 MHz.

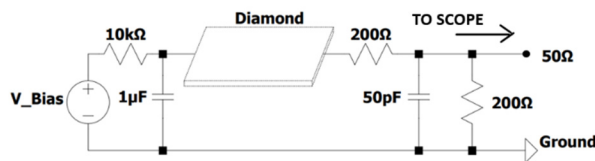


Figure 2: Biasing and per-channel shaping network of the 50 MHz diagnostic.

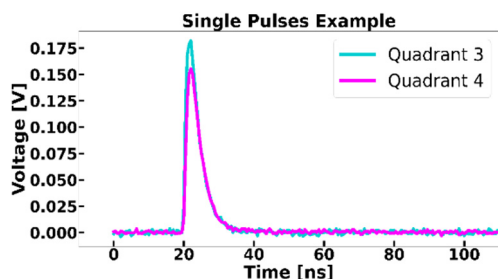


Figure 3: Example pulses from two of the four quadrants of the 50 MHz diagnostic.

Summing the signals from the four channels, the diagnostic is found to be linear for pulses of 12 keV X-rays with intensities of 10s of nJ, the range of interest for the CBXFEL. The beam centroid can be reconstructed as a function of the asymmetry in the observed signal among the different channels. The observed charge resolution of ± 50 fC leads to a pulse-by-pulse position resolution of approximately 1% of the width of the delivered beam¹, or approximately 3 μm for a beam of 300 μm FWHM.

HIGH BANDWIDTH CONSIDERATION AND APPROACHES

Increasing the bandwidth of the quadrant detection system from 50 MHz into the multi-GHz, radio-frequency regime presents a number of challenges, which roughly factorize according to the heuristic of Fig. 4. Achieving high bandwidth performance requires separate attention to the process of charge collection, signal path and signal transport integrity, and signal processing, all four of which contribute independently to the degradation of the signal speed.

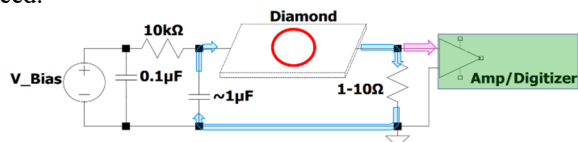


Figure 4: Factorization of the high bandwidth challenge into its contributing considerations of charge collection (red), and signal path (blue), transport (purple), and processing (green).

¹ More details on the content and performance of this diagnostic are expected to become available in [7].

Rapid charge collection is achieved by exploiting the fast drift speed of monocrystalline diamond, for appropriately thinned diamond substrates. Electron-hole plasma density limitations associated with intense instantaneous liberation of signal charge has been explored by the AAD collaboration, with prompt, linear operation generally found for plasma densities less than $10^{16}/\text{cm}^2$ [8]. The work discussed in this Proceedings concerns the other three elements of the high bandwidth challenge.

The strategy employed to explore the development of a multi-GHz ionizing particle detection system is that of compactifying and integrating the signal path and readout functions of the system, guided as closely as possible by state-of-the-art simulation frameworks, especially the HFSS package provided by the ANSYS Corporation [9].

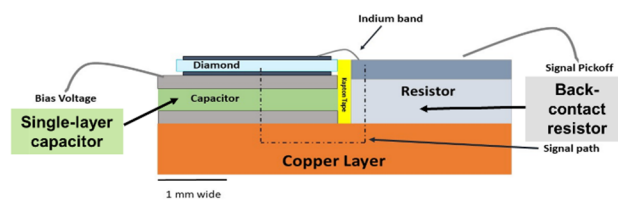


Figure 5: High bandwidth compact signal path concept. Diamond sensors developed for this system are of order 2×2 mm², with thickness in the 10s of μm range.

Figure 5 provides a depiction of the high bandwidth signal path conception, which makes use of commercial RF components to provide a millimeter-scale AC-signal return path that limits dynamic signal impedance, and strives to push LC resonances above the frequency range of interest for the readout. Figure 6 shows how the compact signal path can be integrated with the readout, with the signal-return resistor acting as a sense resistor from which the high bandwidth signal can be picked off using a short bond wire. The bond wire carries the signal to a high bandwidth ASIC, known as the FastPulse Precision Sampler (FPS) chip, currently under development by the AAD collaboration. The next section focuses on the description of this ASIC, and results from characterization of its first prototype.

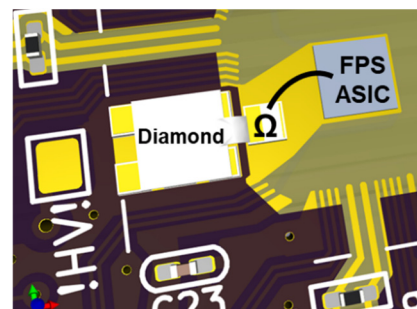


Figure 6: Integration of the compact signal path with the high-bandwidth "FPS" ASIC. A ~ 1 mm diameter hole has been bored underneath the diamond sensor, through which a beam will pass.

SPECIFICATION AND PERFORMANCE OF THE PROTOTYPE FPS ASIC

The four-channel FPS ASIC makes use of a high bandwidth analog amplifier/buffer that feeds into a 45-element switched-capacitor array (SCA) that captures the signal excitation and holds it for later readout. The nominal specifications of the FPS ASIC are enumerated in Table 1.

Table 1: Nominal Specification Table for the FPS ASIC

Spec	Value	Unit
Bandwidth	11	GHz
Sample Rate	50	Gs/s
Capture Window	1-2	ns
Readout Rate	500	MHz
Resolution	10	Bits

The FPS is designed to operate at an analog bandwidth of 11 GHz, with variable sampling rate that results in a signal-trace capture window of 1-2 ns across the 45 elements of the SCA, depending upon the chosen sampling rate. The stored SCA levels can then be clocked out to an external digitizer at rates as fast as 500 MHz, allowing for readout of the captured trace at rates well above 1 MHz.

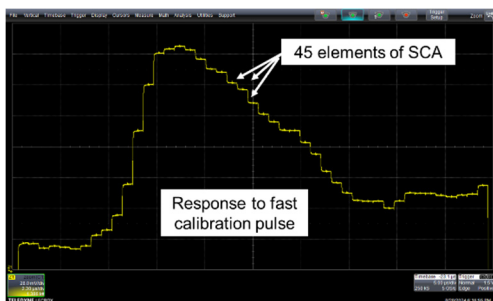


Figure 7: Response of the FPS to a fast calibration pulse, clocked out of the SCA at 2 MHz.

Figure 7 shows a pulse sampled at the maximum sampling rate, introduced by fast pulser and read out by clocking out the SCA elements at 2 MHz into a digital oscilloscope. By sweeping the pulse delay over the full ns capture window, the sampling period was determined to be 28 ps, corresponding to a maximum sampling rate of about 36 Gs/s. Applying this calibration to a series of pulses of steadily increasing size yields the FPS excitation profile of Fig. 8. Linear behavior is observed until the peak response voltage reaches approximately 160 mV, after which the response stops increasing, maintaining its 20-80% rise time of approximately 67 ps while approaching a maximum height of 210 mV and a maximum slew rate of 2.4×10^9 V/s. Using a fast (13 GHz) probe at the input to the ASIC, the 20-80% input signal rise time was determined to be approximately 47 ps; consideration of the difference between the input and output rise time suggests that the FPS readout is operating with a bandwidth of at least 5 GHz.

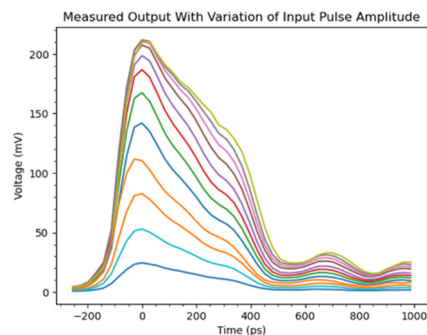


Figure 8: Excitation profile of the FPS ASIC.

By repeatedly triggering the FPS chip when no pulse is introduced, the electronic noise can be measured for each element of the SCA. Figure 9 shows the distribution of noise measured in this manner; a mean value of approximately 550 μ V is obtained, and thus a dynamic range of approximately 300, corresponding to a dynamic range in excess of 8 bits. As an additional application, of the system, considering the maximum slew rate of 2.4×10^9 V/s, this noise performance implies that the electronic jitter contribution to the measurement of the time-of-arrival of an intense ionizing particle pulse could be as little as 230 fs.

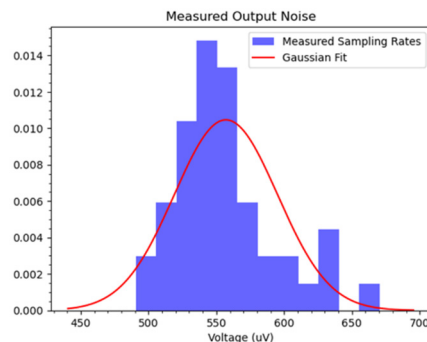


Figure 9: Distribution of electronic noise measured on each of the 45 elements of the SCA.

INTEGRATED MULTI-GHz DETECTION SYSTEM

Figure 10 displays a photograph of the integrated multi-GHz detection system currently under development by the AAD collaboration. The lit area in the center of the board is the region depicted schematically in Fig. 6. The results presented in the previous section were observed for an FPS ASIC loaded onto this board, but as of the writing of these proceedings, the compact signal path (diamond sensors, sense resistor and capacitive signal return path) had not been added to the board. However, the signal path has been modelled in the ANSYS HFSS framework, with the FPS ASIC represented via an idealized ohmic input impedance of value 50 Ω . The signal path has also been studied in isolation, as discussed in the following section. We expect to test the full system in a beam later this year.

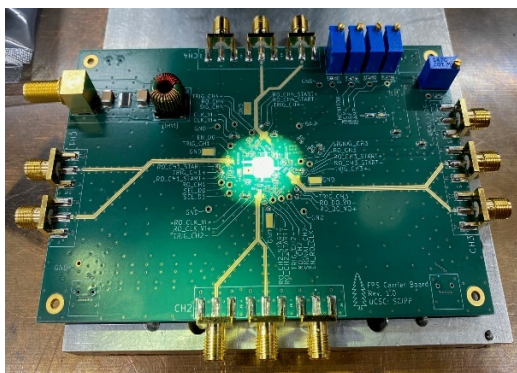


Figure 10: Prototype multi-GHz detection system.

Figure 11 depicts the model used to simulate the compact signal path concept in HFSS. The dimensions and electronic characteristics of the back-contact resistor, single-layer capacitor array, and diamond sensor reflect those of available components (such as those displayed in the following section). The simulated responses of the system at the sensor side of the $10\ \Omega$ sense resistor, and at the $50\ \Omega$ FPS proxy resistor, to a signal expected from a very thin ($10\text{--}20\ \mu\text{m}$) sensor is shown in Fig. 12. The FWHM of the simulated signal response is in the $60\text{--}80\ \text{ps}$ range, corresponding to a simulated system performance in the $5\text{--}10\ \text{GHz}$ range.

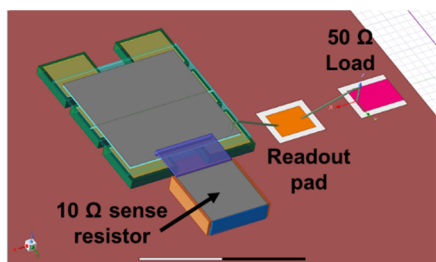


Figure 11: Depiction of the detection system model used to explore the compact signal path concept with the ANSYS HFSS framework.

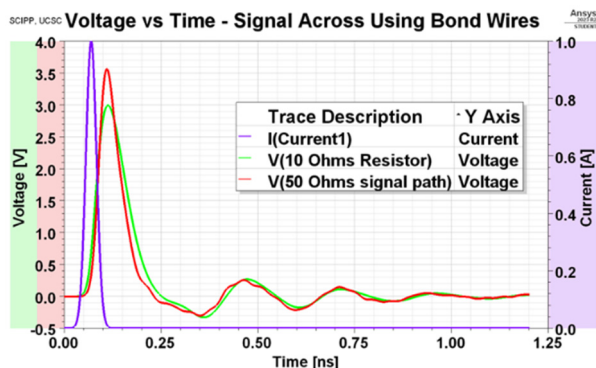


Figure 12: Simulated output traces (red and green) excited by a high-bandwidth excitation (blue).

Since the AAD collaboration has been funded to develop a multi-GHz position-sensitive sensor, a quadrant detection system has also been simulated. Figure 13 shows this system, which includes $50\ \Omega$ traces laid out on top of high-

bandwidth Rogers4350B dielectric that reach the $50\ \Omega$ proxy resistors of the four-channel FPS ASIC. Figure 14 shows the simulated response to an excitation from the $30\ \mu\text{m}$ thick, $3\times 3\ \text{mm}^2$ quadrant diamond sensor that has been prepared for use in the system. Signal response with FWHM in the $100\text{--}120\ \text{ps}$ range indicates an overall performance in the $4\text{--}5\ \text{GHz}$ range. Work continues with the HFSS simulation to understand and mitigate the dominant limitations to the system bandwidth in preparation for the fabrication of the quadrant system in 2025.

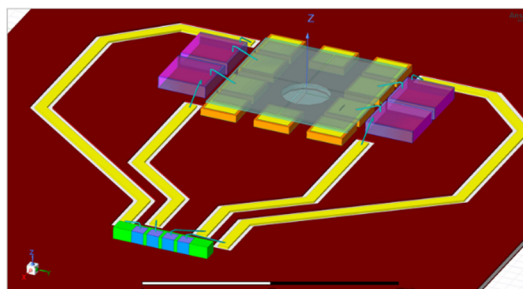


Figure 13: Model used to simulate a quadrant detection system.

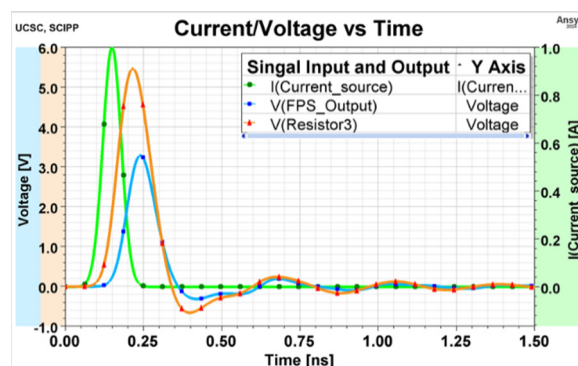


Figure 14: Simulated response (blue, orange) to an excitation (green) from a $30\ \mu\text{m}$ thick quadrant sensor.

ISOLATED SIGNAL PATH STUDIES

In order to explore the performance of the compact signal path independently of that of the FPS ASIC, a high-bandwidth readout system has been developed making use of a commercial $13\ \text{GHz}$ amplifier chip (the Minicircuits EHA-163L+ RF amplifier [10]). This system should allow for the use of alpha particles from standard radiological sources (typical kinetic energy of $5\ \text{MeV}$) to characterize signal-path behaviour, rather than a test beam, the scheduling and use of which takes significant time and effort. A preliminary version of this PC board-based readout system has been fabricated with low bandwidth FR4 dielectric; a high bandwidth version making use of Rogers4350B dielectric is currently in process of submission for fabrication.

Figure 15 (left) shows a picture of this system, with a blow-up of the signal path assembly shown on the right. The assembly makes use of a $33\ \mu\text{m}$ thick, $2\times 2\ \text{mm}^2$ diamond sensor with a single planar electrode. Figure 16 shows the response of the system to excitation by a fully-absorbed alpha particle from an Americium source. The

response sharpens as the detector bias is increased, indicating that charge collection speed, along with the use of low-bandwidth FR4 dielectric, could be limiting the speed of the response. For the highest bias voltage, the 95 ps signal rise time is consistent with 4 GHz performance of the system.

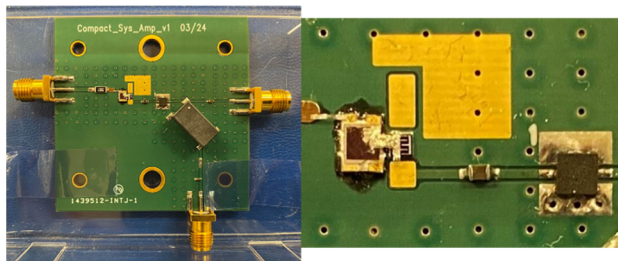


Figure 15: Signal-path test board composed of a compact signal path assembly read out by a 13 GHz commercial amplifier. The right-hand photograph shows a blow-up of the signal assembly; a 33 μm thick, 2 \times 2 mm² diamond sensor is connected by an indium band to a 10 Ω back-contact sense resistor, which is bonded out to a pad that is capacitively coupled to the input of the amplifier. This preliminary version has been implemented on a board composed of low-bandwidth FR4 dielectric.

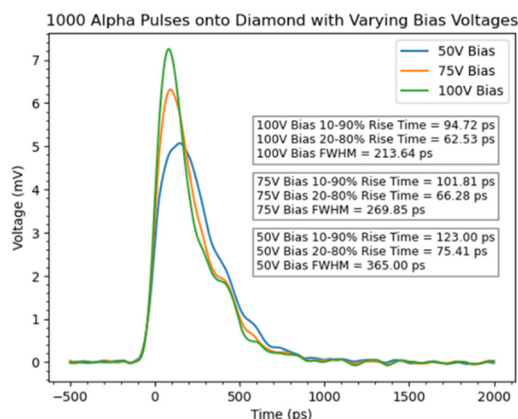


Figure 16: Response of the discrete signal-path system to the absorption of an alpha particle, as a function of sensor bias.

SUMMARY AND OUTLOOK

In summary, the AAD collaboration has made strides towards the development of an integrated multi-GHz ionizing particle detection system, with a goal of producing a four-channel (quadrant) position-sensitive detection system that can operate at or above 5 GHz in late 2026. The work includes the development of the FPS ASIC, intended to be closely integrated with the compact, high-bandwidth signal path. First results, based on calibration pulses for the FPS and alpha particle absorption for the compact signal path, suggest progress is being made towards the 5 GHz target. Overall performance of the first-stage prototype

system will be evaluated in a run in an ionizing particle beam, expected by the end of 2024. A preliminary, intermediate-bandwidth (50 MHz) quadrant pass-through diagnostic has demonstrated position resolution of 1% of delivered beam width. In addition to its intended use as a beam diagnostic, the approaches developed here could have applications in precision timing, and in fusion energy research, especially inertial confinement, for which the event burn duration is of the same order as the target temporal response function of the initiative.

ACKNOWLEDGEMENTS

We acknowledge the generous support of the SLAC National Accelerator Laboratory, through its provision of LCLS beam time and staff support. Use of the LINAC Coherent Light Source (LCLS), SLAC National Accelerator Laboratory, is supported by the U.S. Dept. of Energy, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF00515.

REFERENCES

- [1] F. J. Decker *et al.*, “A demonstration of multi-bunch operation in the LCLS”, in *Proceedings of the 2010 Free Electron Laser Conference*, Malmo, Sweden, Aug. 2010, p. 467-470.
- [2] R. W. Garnett, “The Los Alamos Multi-Probe Facility for matter radiation interactions in extremes”, in *Proceedings of the LINAC2016 Conference*, East Lansing, MI, USA, Sep. 2016, p. 729-733.
doi:10.18429/JACoW-LINAC2016-TH3A02
- [3] Z. Galloway *et al.*, “Use of ‘LGAD’ ultra-fast silicon detectors for time-resolved low-keV X-ray science”, *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 923, 5-7, Apr. 2019.
doi:10.1016/j.nima.2019.01.050
- [4] G. J. Schmid *et al.*, “CVD diamond as a high bandwidth neutron detector for inertial confinement fusion diagnostics”, *Rev. Sci. Instrum.*, vol. 74, 1828-1831, Mar. 2003.
<https://doi.org/10.1063/1.1534899>
- [5] C. J. H. Wort and R. S. Balmer, “Diamond as an electronic material”, *Materials Today*, vol. 11, 22-28, Jan-Feb. 2008,
doi:10.1016/S1369-7021(07)70349-8
- [6] G. Marcus *et al.*, “Cavity-Based Free-Electron Laser Research and Development: A Joint Argonne National Laboratory and SLAC National Laboratory Collaboration.” in *Proc. 39th Free Electron Laser Conf. (FEL'19)*, Hamburg, Germany, Aug. 2019, pp. 282-287.
doi:10.18429/JACoW-FEL2019-TUD04
- [7] “A 50 MHz position sensitive pass-through diagnostic for XFEL applications”, to be submitted.
- [8] J. Bohon *et al.*, “Use of diamond sensors for a high-flux, high-rate X-ray pass-through diagnostic”, *J. Synchrotron. Radiat.*, vol 29, 595-601, May 2022.
doi:10.1107/S1600577522003022.
- [9] Ansys High Frequency Simulation Software (HFSS), ANSYS Incorporated, <https://www.ansys.com/products/electronics/ansys-hfss>
- [10] <https://www.minicircuits.com/WebStore/dashboard.html?model=EHA-163L%2B>