Version 1.0
November 29, 2021

November 2021 update on Chicago Group Tasks

Henry Frisch[1,2], Tobias Andelmann[1], Kepler Domurat-Sousa[1], Jacky Li[1], Marek Michulka[1], João Shida[1], Eric Spieglan[2]
1: Physics Dept. and College; 2: Enrico Fermi Institute

1 Supporting the Fermilab upgrade to the Test Beam Facility

Fermilab has embarked on upgrading the Time-of-Flight (TOF) system at the Fermilab Test Beam Facility (FTBF) with the goal of improving the time resolution to better than 10 psec, with coverage over the whole beam profile. The initial installation was to be Evan Angelico's Ph.D thesis [1]; Evan had just installed inside the enclosure and taken first data when the Lab closed due to the pandemic. The effort has now been revived with the hire of Joe Pastika to lead the project. The PSEC group at Chicago, with Evan's help, is in the process of transferring the technology to the Lab.

1.1 Upgraded digitizing electronics

Two students, Toby Abelmann and Marek Michulka.,have been working closely with Pastika and Paul Rubinov from Fermilab, Evan (now at Stanford), and Frisch on commissioning the Rev C ACDC front end waveform sampling cards. Rev C, which like its predecessor has 30 channels of PSEC4 chips sampling at 10-15 GS/sec at 10.5 bits, differs in that it provides six independent trigger thresholds per chip rather than only one, and has redesigned power supplies for significantly lower power consumption.

Sixteen Rev C cards have been stuffed. Abelmann and Michulka, supervised by Pastika and Rubinov, have been debugging the new power sections, and are now ready to implement code for the multiple trigger thresholds. In addition to use at the FTBF, these cards may be useful to the ANNIE experiment where self-triggering plays an important role.

Figure 1 shows the Rev C cards and the test setup in the Institute Electronics Development Group shop.

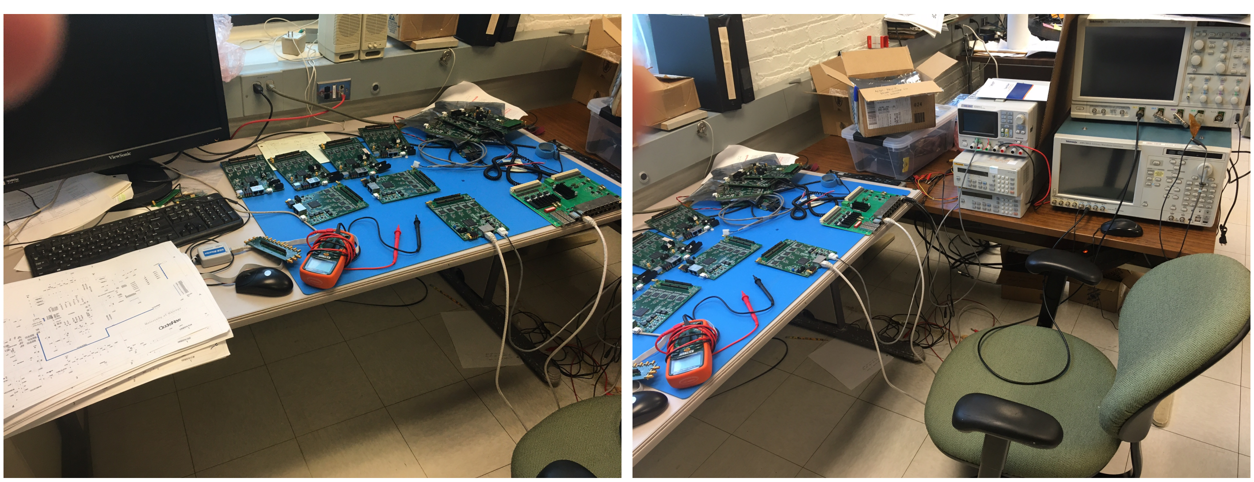

Figure 1: The REV C cards and test setup in the EFI EDG (Abelmann, Michulka).

1.2 3Ghz sub-mm resolution 8-inch pad-based anodes

The LAPPD detector development used a strip-line readout of 50-ohm RF striplines for excellent time and spatial resolution [2, 3]. The pad development is recent and is intended for calorimeters and similar high-occupancy applications. The original (Incom 'Gen-I') LAPPD design was with an internal anode; the Test Beam installation uses capacitively-coupled 'Gen-II' LAPPDs, in which an external signal pickup anode board is capacitively coupled to a monolithic internal metal anode plane[4]. This allows the MCP-PMTs to be produced independent of the specific needs of each application for anode segmentation and RF characteristics (e.g. pads vs strips).

The 8-by-8 arrays of 1-in pads (64 pads total) for a rectangular pad (Left) and a sub-mm spatial resolution patterned pad (Right) are shown in Figure 2. The patterned anode enhances the sharing of charge, enabling a sub-mm spatial resolution over the full area [5].

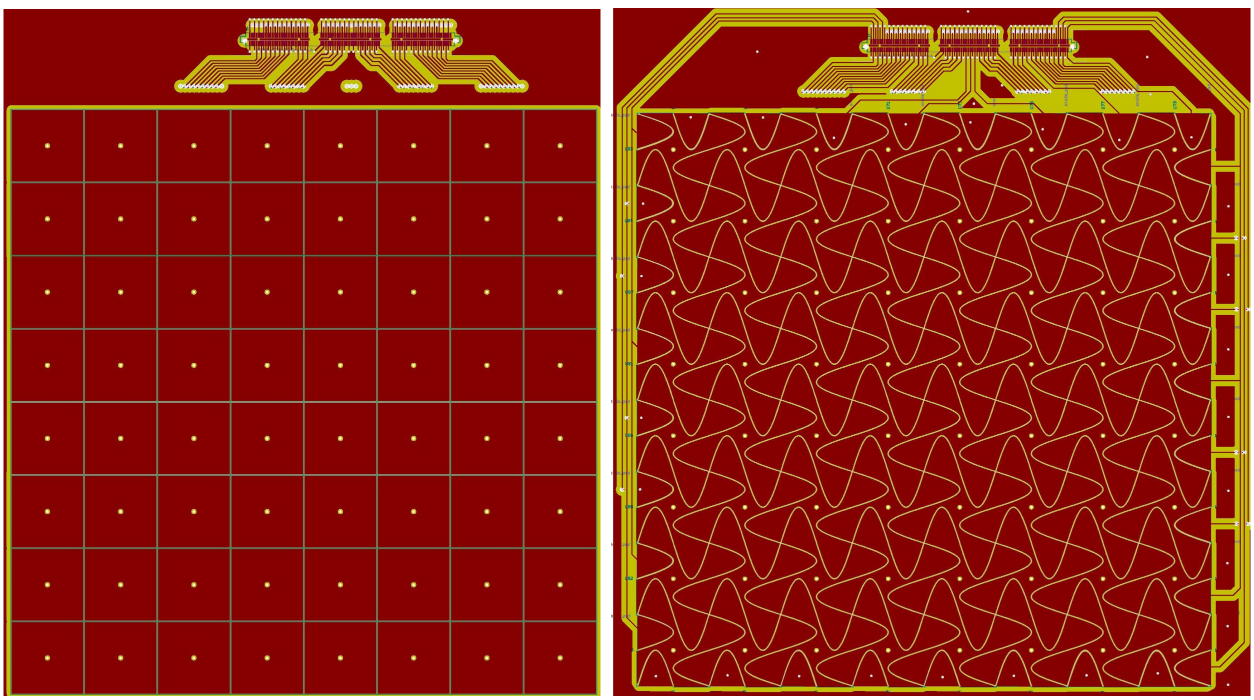

Figure 2: The layout of the top layer of an 8 by 8 array of signal pickup pads for a capacitively-coupled LAPPD^{TM} [4]. The left-hand plot shows 1-inch square pads; the right-hand plot shows one implementation of a patterned anode that enhances the sharing of charge for improved spatial resolution [5] (J. Li, J. Park, E. Spieglan)

.

Figure 3 shows a map of the resolution of the sinusoidally patterned anode, given by the color bar on the right. With pads on a 1-inch pitch we expect sub-mm resolution for the noise levels of our current PSEC4 electronics [5].

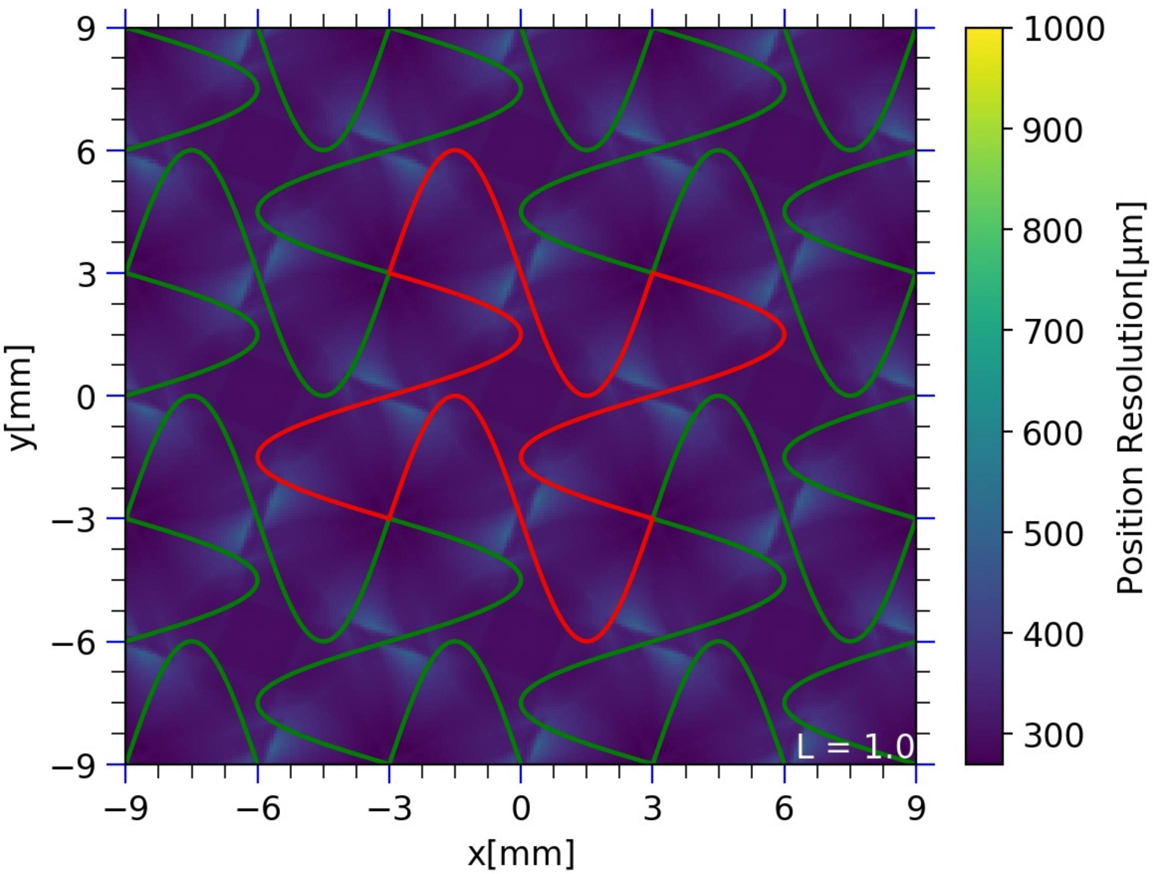

Figure 3: A map of the predicted position resolution of the 8-by-8 anode signal pickup board with patterned 1-inch pads for enhanced signal sharing [5]. A single pad is outlined in red. (J. Park)

1.3 3Ghz Sub-mm resolution 200mm strip-based anodes

Impedance-matched RF strip-lines are a highly efficient anode pattern in terms of channel count, and also may be implemented to exploit an elegant method of optimizing time and space resolution.

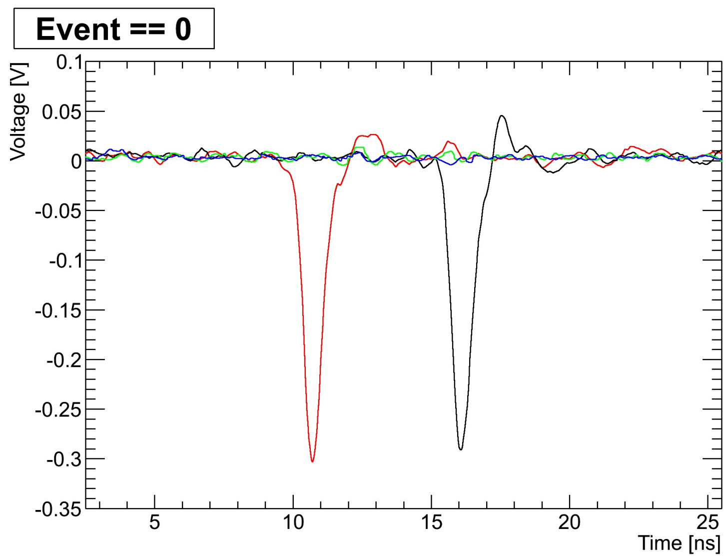

Figure 4: A PSEC4 waveform trace of an LAPPD pulse measured at one end of a 50-ohm RF stripline. The far end of the stripline was extended by cable and left unterminated; the 2nd pulse is the reflection. The distance between the first and second appearances of the pulse maps onto the position of the pulse on the stripline; the average time of the two is the time [2]. Having both pulses travel on the same strip and through the same network, and digitized by the same PSEC4 channel eliminates the need for channel-to-channel calibrations (E. Oberla, A. Elagin.)

Figure 5 shows the layout for the 50-ohm RF stripline anode. The strips double back on themselves on an internal layer with the same impedance as the top layer to provide the needed separation of the direct and reflected pulses when the shower is close to the far end of the strip [3].

1.4 Submission for fabrication; testing

The designs for the three patterns, square 1-inch pads, sine-wave pads on a 1-inch pitch, and 50-ohm striplines [2] are ready for submission to PC houses. The square and sine-wave pick-up boards are six layers. We will go out for quotes shortly after an internal 'Godparent' review with (among others) Pastika, Rubinov, Angelico, and F. Tang (EFI-EDG).

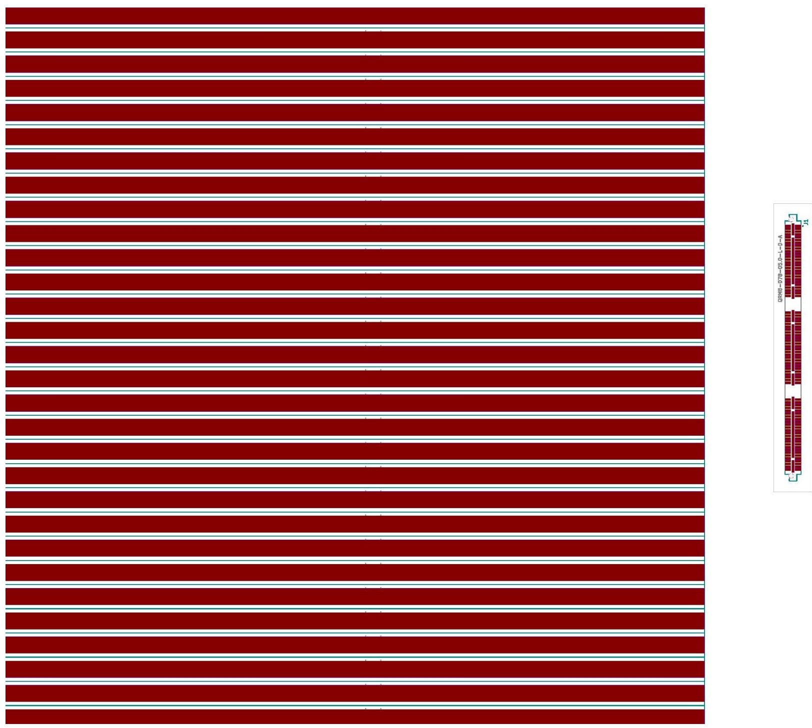

Figure 5: The 50-ohm RF stripline anode. The strips double back on themselves on an internal layer with the same impedance as the top layer to provide the needed separation of the direct and reflected pulses when the shower is close to the far end of the strip. (J. Li)

1.5 3Gz bandwidth, few picosecond resolution, waveform sampling

The PSEC4 15 GS/sec ASIC was made in the130nm IBM 8RF process that is now completely obsolete. Waveform sampling is the gold-standard of fast timing [6]. We have opened discussions with Fermilab on developing a multi-channel 3GHz band-width ASIC. A draft of the specs is given in Table 1.5

Front-end				
Parameter	Min Value	Max Value	Units	Comment
Analog Bandwidth	3	–	GHz	For 1ps res. per S. Ritt [7]
Input	–	-	–	Single-ended (bypass gd to MCP2-out)
Input impedance	50	200	Ohms	50 for current strips
Voltage Range	300	1000	mv	Max signal: S/N>>100
Noise	–	1	mv	For 1ps res. per S. Ritt [7]
Charge Range	3.2	160	pC	Max integrated charge
Charge Resolution	10	10	bits	set by 10% of 1% sharing
Cross-talk	–	0.1	%	?? channel-channel
Linearity	–	0.1	%	after calibration
2-pulse separation	1	–	nsec	(CFD) 1-foot unterminated strip far end
Trigger threshld	1	FS	mv	one per channel
Trigger latency	–	10	nsec	WAG- negotiable if needed
Temperature Coeff.	–	10^{-6}	%/degC	1ps FS for 10 degC
Max Time Recorded	–	12	μs	5 muon lifetimes??
Readout Buffers	4	–	–	parallel buffers
Channels/ASIC	8	–	–	negotiable
Power	==	???	mW	per chip, full rate
System and DAQ				
Digitization Time	–	20	μs ???	multiple buffers, 200 KHz
Readout Rate	200	–	kHz	Set by MTest
Strips or Pads	–	–	–	Either: Capacitive Coupling Pickup
MCP Current return	–	–	–	Bypass caps to MCP-2 out
Channels/FE card	32	64	channels	30 strips or 64 pads??
Local Sparsification	–	–	–	Yes
System # of channels	30	384	channels	1 strip MCP to 6 pad MCPs
Clock	–	–	–	External; White Rabbit compatible
Clock Jitter	–	10^{-12}	–	1 ps/s; e.g. WR PPS

Table 1: A draft of specs for the 1-ps upgrade to the FTFB TOF system. FE refers to a possible Front-End card; BE refers to a Back-End card. The implemented architecture may differ. Note that the 3 GHz analog bandwidth spec refers to the complete FE signal path and not just the ASIC.

2 Batch Production of Capacitively Coupled LAPPD^{TM}MCP-PMTs

We have developed an air-transfer process for MCP-PMT production that closely follows the steps used in batch production of standard bialkali-photocathode photomultipliers [8, 9, 10]. We later learned that our process is both well-supported theoretically and is being used by the Russian PMT firm MELZ to make commercial photomultipliers.

At the start of the LAPPD project we hired a young SULI student at ANL, Camden Ertley, who after working with us for a year went on to get his Ph.D in space sciences at UNH. After working with O. Siegmund at SSL at Berkeley and Incom, Dr. Ertley is now at Southwest Research Institutes, and, like us, is convinced that the original concept of a low-cost high-yield batch-produced 'frugal tile' is achievable. Figure 6 shows the two 'Margherita' single-tile fabrication prototypes for batch production that would provide the basis for the SWRI design. Current collaborative design efforts are on exploiting the air-transfer technique to produce photocathodes with QE's substantially higher than industry best for alkali cathodes, on simplifying the stack-up and hermetic housing, and on enhanced amplification stacks.

Figure 6: The two Margherita single-tile fabrication prototypes for batch production [9, 10]. With C. Ertley of Southwest Research Institutes we are developing a design of 6 stacks of 3 LAPPDs each per cart, with a 1 week cycle. Six carts would produce 100 tiles per week.

3 Energy-separated TOF-tagged Neutrino Beams

An idea for simultaneously running neutrino oscillation experiments with multiple neutrino energy spectra grew out of a joint Fermilab-Chicago workshop on the uses of fast timing held at the University [11]. The precise localization of ionization by the LAr TPCs allows a one-parameter fit to the time at the neutrino detector even with very small coverage [12]. With Matt Wetstein (ISU) and Evan Angelico (Stanford) we continue to pursue this idea with several young scientists interested in Early Career Awards at Fermilab. While not a major time sink, a number of us believe it's an important set of ideas and needs to be kept active during the construction of the Fermilab neutrino detectors for reduction of systematics in a competitive environment.

4 Neutrinoless Double-Beta Decay, charged particle tracking, low-energy electron energy and direction measurement, PET

In addition to our DOE-supported effort on the TOF upgrade at the FTFB, with University financial support Shida, Spieglan, Domurat-Sousa, and Frisch are collaborating with A. Squires (Molecular Engineering), V. Rawal (Chemistry), and Patrick LaRiviere (Radiology) to develop a non-cryogenic liquid medium to measure charged particle tracks at 10-micron spatial resolution and 1-2% energy resolution for 1 MeV electrons [13, 14]. The motivation is to develop a cheap large high-precision detector for neutrinoless double-beta decay [15]. Current work is focusing on Positron-emission Tomography (PET), which has a similar signature of multiple low-energy electrons, but a faster time scale, better pay-off, and larger market. An attractive spin-off is the introduction to the TOPAS [16] wrapper for the Geant4 package, suggested to us by LaRiviere and being implemented for Compton scatters in PET by Domurat-Sousa. It is intended for use by the medical imaging community, but we see that it is very useful for detector development, and hope that we can participate in introducing it to the HEP detector community.

5 Acknowledgements

We thank Mary Heintz for invaluable technical and computational support. We thank Eric Oberla and Jinseo Park for key technical contributions and advice.

References

[1] E. Angelico; *Development of Large-Area MCP-PMT Photo-Detectors for a Precision Time-Of-Flight System at the Fermilab Test Beam Facility*; Ph.D thesis, The University of Chicago. ProQuest Dissertations Publishing, 2020. 28023552.

[2] B.W. Adams, A. Elagin, H. Frisch, R. Obaid, E. Oberla, A. Vostrikov, R. Wagner, J. Wang, M. Wetstein; *Timing Characteristics of Large Area Picosecond Photodetectors*; Nucl. Inst. Meth. Phys. Res. A. , Vol. 795, pp 1-11 (Sept. 2015)

[3] E. Oberla and H.J. Frisch;
Charged particle tracking in a water Cherenkov optical time-projection chamber;
Nucl. Inst. Meth. Phys. Res. A. Volume 814, 19-32, (April 2016) ISSN 0168-9002. arXiv:1510.00947

[4] E. Angelico, T. Seiss, B. W, Adams, A. Elagin, H. J. Frisch, E. Spieglan;
Capacitively coupled pickup in MCP-based photo-detectors using a conductive, metallic anode;
Nucl. Inst. Meth. Phys. Res. A. (Oct. 2016)

[5] Jinseo Park, Fangjian Wu, Evan Angelico, Henry J. Frisch, Eric Spieglan; *Patterned anodes with sub-millimeter spatial resolution for large-area MCP-based photodetector systems* Nuclear Inst. and Methods in Physics Research, A 985 (2021) 164702; 22 Sept, 2020

[6] *Signal Processing for Pico-second Resolution Timing Measurements*, J.-F. Genat,G. Varner, F. Tang, H. Frisch; Nucl.Instrum.Meth.A607:387-393,Oct., 2009. e-Print: arXiv:0810.5590

[7] See S. Ritt in Session 5 of the Workshop *The Factors that Limit Time Resolution in Photodetectors*, Univ. of Chicago; April 2011; https://psec.uchicago.edu/workshops/fast_timing_conf_2011/

[8] E. Angelico, A. Elagin, H. J. Frisch, E. Spieglan, B. W. Adams, M. R. Foley, and M. J. Minot;
"Air-transfer production method for large-area picosecond photodetectors;
Review of Scientific Instruments 91, no. 5 (2020): 053105; 28 April 2020

[9] *Dual Low Vacuum-UltraHigh Vacuum System for Large-Scale Production of Micro-Channel Plate Photomultipliers*;
US Patent 62928598; filed Oct. 31, 2019 (Pending)
Evan Angelico; Eric Spieglan; Andrey Elagin; Henry Frisch; Bernhard Adams, Inventors

[10] *Methods of Fabricating Vacuum Housing with Hermetic Solder Seals Using Capillary Wicks*;
US Patent 62/831.474, filed March 19, 2019 (Pending)
Eric Spieglan; Evan Angelico; Andrey Elagin; Henry J. Frisch, Inventors

[11] E. Angelico, J. Eisch, A. Elagin, H.J. Frisch, S. Nagaitsev, and M. Wetstein;
Energy and Flavor Discrimination Using Precision Time Structure in On-Axis Neutrino Beams; Phys. Rev. D, 100, 032008. 26 Aug 2019.

[12] E Angelico, A Elagin, HJ Frisch, M Wetstein;
Measuring the Neutrino Event Time in Liquid Argon by a Post-Reconstruction One-parameter Fit
Whitepaper submitted to Snowmass2021, https://snowmass21.org/submissions/nf
arXiv preprint 2004.00580 1 April, 2020

[13] E. Spieglan; *Using Switchable Fluorescent Molecules to Image Tracks and Measure Energy in Large Liquid Double Beta Decay Detectors*; CPAD 2019;

https://agenda.hep.wisc.edu/event/1391/timetable/#20191209.detailed. Also available at: http://lappddocs.uchicago.edu/documents/361

[14] H. J. Frisch, E. J. Oberla, H.-J. Kim, M. Yeh; *Positron-Emission Tomography Detector Systems Based On Low-Density Liquid Scintillators And Precise Time-Resolving Photodetectors*// U.S. Patent 10,132,94, Filed April 8, 2016; Issued Nov. 20, 2018

[15] C. Aberle, A. Elagin, H.J. Frisch, M. Wetstein, L. Winslow; *Measuring Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors*; JINST, Volume 9 (2014); arXiv:1307.5813

[16] B. Faddegon, J. Ramos-Mndez, J. Schuemann, J. Shin, J. Perl, H. Paganetti
The TOPAS tool for particle simulation, a Monte Carlo simulation tool for physics, biology and clinical research
European Journal of Medical Physics; Volume 72, P114-121, April (2020); DOI:https://doi.org/10.1016/j.ejmp.2020.03.019