This document was prepared by the DUNE collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

The DUNE collaboration also acknowledges the international, national, and regional funding agencies supporting the institutions who have contributed to completing this Technical Design Report.

Authors

B. Abi,[129] R. Acciarri,[56] Mario A. Acero,[8] G. Adamov,[59] D. Adams,[15] M. Adinolfi,[14] Z. Ahmad,[163] J. Ahmed,[166] T. Alion,[153] S. Alonso Monsalve,[18] C. Alt,[49] J. Anderson,[4] C. Andreopoulos,[109] M. P. Andrews,[56] F. Andrianala,[2] S. Andringa,[103] A. Ankowski,[143] J. Anthony,[28] M. Antonova,[72] S. Antusch,[9] A. Aranda Fernandez,[36] A. Ariga,[10] L. O. Arnold,[39] M. A. Arroyave,[48] J. Asaadi,[157] A. Aurisano,[34] V. Aushev,[101] D. Autiero,[81] F. Azfar,[129] H. Back,[130] J. J. Back,[166] C. Backhouse,[161] P. Baesso,[14] L. Bagby,[56] R. Bajou,[1] S. Balasubramanian,[170] P. Baldi,[23] B. Bambah,[70] F. Barao,[103, 105] G. Barenboim,[72] G. J. Barker,[166] W. Barkhouse,[123] C. Barnes,[116] G. Barr,[129] J. Barranco Monarca,[64] N. Barros,[103, 106] J. L. Barrow,[155, 56] A. Bashyal,[128] V. Basque,[114] F. Bay,[122] J. L. Bazo Alba,[137] J. F. Beacom,[127] E. Bechetoille,[81] B. Behera,[38] L. Bellantoni,[56] G. Bellettini,[135] V. Bellini,[74] O. Beltramello,[18] D. Belver,[19] N. Benekos,[18] F. Bento Neves,[104] J. Berger,[136] S. Berkman,[56] P. Bernardini,[144] R. M. Berner,[10] H. Berns,[22] S. Bertolucci,[73] M. Betancourt,[56] Y. Bezawada,[22] M. Bhattacharjee,[86] B. Bhuyan,[86] S. Biagi,[152] J. Bian,[23] M. Biassoni,[76] K. Biery,[56] B. Bilki,[11] M. Bishai,[15] A. Bitadze,[114] A. Blake,[107] B. Blanco Siffert,[55] F. D. M. Blaszczyk,[56] G. C. Blazey,[124] E. Blucher,[32] J. Boissevain,[110] S. Bolognesi,[17] T. Bolton,[98] M. Bonesini,[76] M. Bongrand,[102] F. Bonini,[15] A. Booth,[153] C. Booth,[146] S. Bordoni,[18] A. Borkum,[153] T. Boschi,[47] N. Bostan,[90] P. Bour,[41] S. B. Boyd,[166] D. Boyden,[124] J. Bracinik,[12] D. Braga,[56] D. Brailsford,[107] A. Brandt,[157] J. Bremer,[18] C. Brew,[142] E. Brianne,[114] S. J. Brice,[56] C. Brizzolari,[76] C. Bromberg,[117] G. Brooijmans,[39] J. Brooke,[14] A. Bross,[56] G. Brunetti,[131] N. Buchanan,[38] H. Budd,[140] D. Caiulo,[81] P. Calafiura,[108] J. Calcutt,[117] M. Calin,[16] S. Calvez,[38] E. Calvo,[19] L. Camilleri,[39] A. Caminata,[75] M. Campanelli,[161] D. Caratelli,[56] G. Carini,[15] B. Carlus,[81] P. Carniti,[76] I. Caro Terrazas,[38] H. Carranza,[157] A. Castillo,[145] C. Castromonte,[89] C. Cattadori,[76] F. Cavalier,[102] F. Cavanna,[56] S. Centro,[131] G. Cerati,[56] A. Cervelli,[73] A. Cervera Villanueva,[72] M. Chalifour,[18] C. Chang,[25] E. Chardonnet,[1] A. Chatterjee,[136] S. Chattopadhyay,[163] J. Chaves,[132] H. Chen,[15] M. Chen,[23] Y. Chen,[10] D. Cherdack,[69] C. Chi,[39] S. Childress,[56] A. Chiriacescu,[16] K. Cho,[97] S. Choubey,[66] A. Christensen,[38] D. Christian,[56] G. Christodoulou,[18] E. Church,[130] P. Clarke,[50] T. E. Coan,[150] A. G. Cocco,[78] J. A. B. Coelho,[102] E. Conley,[46] J. M. Conrad,[115] M. Convery,[143] L. Corwin,[147] P. Cotte,[17] L. Cremaldi,[119] L. Cremonesi,[161] J. I. Crespo-Anadón,[39] E. Cristaldo,[6] R. Cross,[107] C. Cuesta,[19] Y. Cui,[25] D. Cussans,[14] M. Dabrowski,[15] H. da Motta,[30] L. Da Silva Peres,[55] Q. David,[81] G. S. Davies,[119] S. Davini,[75] J. Dawson,[1] K. De,[157] R. M. De Almeida,[58] P. Debbins,[90] I. De Bonis,[20] M. P. Decowski,[122] A. de Gouvêa,[125] P. C. De Holanda,[29] I. L. De Icaza Astiz,[153] A. Deisting,[85] P. De Jong,[122] A. Delbart,[17] D. Delepine,[64] M. Delgado,[3] A. Dell'Acqua,[18] P. De Lurgio,[4] J. R. T. de Mello Neto,[55] D. M. DeMuth,[162] S. Dennis,[109] C. Densham,[142] G. Deptuch,[56] A. De Roeck,[18] V. De Romeri,[72] J. J. De Vries,[28] R. Dharmapalan,[68] F. Diaz,[137] J. S. Díaz,[88] S. Di Domizio,[75] L. Di Giulio,[18] P. Ding,[56] L. Di Noto,[75] C. Distefano,[152] R. Diurba,[160] M. Diwan,[15] Z. Djurcic,[4] N. Dokania,[151] M. J. Dolinski,[45] L. Domine,[143] D. Douglas,[117] F. Drielsma,[143] D. Duchesneau,[20] K. Duffy,[56] P. Dunne,[85] T. Durkin,[142] H. Duyang,[149] O. Dvornikov,[68] D. A. Dwyer,[108] A. S. Dyshkant,[124] M. Eads,[124] D. Edmunds,[117] J. Eisch,[91] S. Emery,[17] A. Ereditato,[10] C. O. Escobar,[56] L. Escudero Sanchez,[28] J. J. Evans,[114] K. Ewart,[88] A. C. Ezeribe,[146] K. Fahey,[56] A. Falcone,[76] C. Farnese,[131] Y. Farzan,[82] J. Felix,[64] E. Fernandez-Martinez,[113] P. Fernandez Menendez,[72] F. Ferraro,[75] L. Fields,[56] A. Filkins,[168] F. Filthaut,[122] R. S. Fitzpatrick,[116] W. Flanagan,[43] B. Fleming,[170] R. Flight,[140] J. Fowler,[46] W. Fox,[88] J. Franc,[41] K. Francis,[124] D. Franco,[170] J. Freeman,[56] J. Freestone,[114] J. Fried,[15] A. Friedland,[143] S. Fuess,[56] I. Furic,[57] A. P. Furmanski,[160] A. Gago,[137] H. Gallagher,[159] A. Gallego-Ros,[19] N. Gallice,[77, 76] V. Galymov,[81] E. Gamberini,[18] T. Gamble,[146] R. Gandhi,[66] R. Gandrajula,[117] S. Gao,[15] D. Garcia-Gamez,[62] M. Á. García-Peris,[72] S. Gardiner,[56] D. Gastler,[13] G. Ge,[39] B. Gelli,[29] A. Gendotti,[49] S. Gent,[148] Z. Ghorbani-Moghaddam,[75] D. Gibin,[131] I. Gil-Botella,[19] C. Girerd,[81] A. K. Giri,[87] D. Gnani,[108] O. Gogota,[101] M. Gold,[120] S. Gollapinni,[110] K. Gollwitzer,[56] R. A. Gomes,[52] L. V. Gomez Bermeo,[145] L. S. Gomez Fajardo,[145] F. Gonnella,[12] J. A. Gonzalez-Cuevas,[6] M. C. Goodman,[4] O. Goodwin,[114] S. Goswami,[134] C. Gotti,[76] E. Goudzovski,[12] C. Grace,[108] M. Graham,[143] E. Gramellini,[170] R. Gran,[118] E. Granados,[64] A. Grant,[44] C. Grant,[13] D. Gratieri,[58] P. Green,[114] S. Green,[28] L. Greenler,[169] M. Greenwood,[128] J. Greer,[14] W. C. Griffith,[153] M. Groh,[88] J. Grudzinski,[4] K. Grzelak,[165] W. Gu,[15] V. Guarino,[4] R. Guenette,[67] A. Guglielmi,[131] B. Guo,[149] K. K. Guthikonda,[65] R. Gutierrez,[3] P. Guzowski,[114] M. M. Guzzo,[29] S. Gwon,[33] A. Habig,[118] A. Hackenburg,[170] H. Hadavand,[157] R. Haenni,[10] A. Hahn,[56] J. Haigh,[166] J. Haiston,[147] T. Hamernik,[56] P. Hamilton,[85] J. Han,[136] K. Harder,[142] D. A. Harris,[172, 56] J. Hartnell,[153] T. Hasegawa,[96] R. Hatcher,[56] E. Hazen,[13] A. Heavey,[56] K. M. Heeger,[170] K. Hennessy,[109] S. Henry,[140] M. A. Hernandez Morquecho,[64] K. Herner,[56] L. Hertel,[23] A. S. Hesam,[18] J. Hewes,[34] A. Higuera,[69] T. Hill,[83] S. J. Hillier,[12] A. Himmel,[56] J. Hoff,[56] C. Hohl,[9] A. Holin,[161] E. Hoppe,[130] G. A. Horton-Smith,[98] M. Hostert,[47] A. Hourlier,[115] B. Howard,[88] R. Howell,[140] J. Huang,[158] J. Huang,[22] J. Hugon,[111] G. Iles,[85] A. M. Iliescu,[73] R. Illingworth,[56] A. Ioannisian,[171] R. Itay,[143]

A. Izmaylov,[72] E. James,[56] B. Jargowsky,[23] F. Jediny,[41] C. Jesús-Valls,[71] X. Ji,[15] L. Jiang,[164] S. Jiménez,[19] A. Jipa,[16] A. Joglekar,[25] C. Johnson,[38] R. Johnson,[34] B. Jones,[157] S. Jones,[161] C. K. Jung,[151] T. Junk,[56] Y. Jwa,[39] M. Kabirnezhad,[129] A. Kaboth,[142] I. Kadenko,[101] F. Kamiya,[54] G. Karagiorgi,[39] A. Karcher,[108] M. Karolak,[17] Y. Karyotakis,[20] S. Kasai,[100] S. P. Kasetti,[111] L. Kashur,[38] N. Kazaryan,[171] E. Kearns,[13] P. Keener,[132] K.J. Kelly,[56] E. Kemp,[29] W. Ketchum,[56] S. H. Kettell,[15] M. Khabibullin,[80] A. Khotjantsev,[80] A. Khvedelidze,[59] D. Kim,[18] B. King,[56] B. Kirby,[15] M. Kirby,[56] J. Klein,[132] K. Koehler,[169] L. W. Koerner,[69] S. Kohn,[21,108] P. P. Koller,[10] M. Kordosky,[168] T. Kosc,[81] U. Kose,[18] V. A. Kostelecký,[88] K. Kothekar,[14] F. Krennrich,[91] I. Kreslo,[10] Y. Kudenko,[80] V. A. Kudryavtsev,[146] S. Kulagin,[80] J. Kumar,[68] R. Kumar,[139] C. Kuruppu,[149] V. Kus,[41] T. Kutter,[111] A. Lambert,[108] K. Lande,[132] C. E. Lane,[45] K. Lang,[158] T. Langford,[170] P. Lasorak,[153] D. Last,[132] C. Lastoria,[19] A. Laundrie,[169] A. Lawrence,[108] I. Lazanu,[16] R. LaZur,[38] T. Le,[159] J. Learned,[68] P. LeBrun,[81] G. Lehmann Miotto,[18] R. Lehnert,[88] M. A. Leigui de Oliveira,[54] M. Leitner,[108] M. Leyton,[71] L. Li,[23] S. Li,[15] S. W. Li,[143] T. Li,[50] Y. Li,[15] H. Liao,[98] C. S. Lin,[108] S. Lin,[38] A. Lister,[169] B. R. Littlejohn,[84] J. Liu,[23] S. Lockwitz,[56] T. Loew,[108] M. Lokajicek,[40] I. Lomidze,[59] K. Long,[85] K. Loo,[95] D. Lorca,[10] T. Lord,[166] J. M. LoSecco,[126] W. C. Louis,[110] K.B. Luk,[21,108] X. Luo,[26] N. Lurkin,[12] T. Lux,[71] V. P. Luzio,[54] D. MacFarland,[143] A. A. Machado,[29] P. Machado,[56] C. T. Macias,[88] J. R. Macier,[56] A. Maddalena,[61] P. Madigan,[21,108] S. Magill,[4] K. Mahn,[117] A. Maio,[103,106] J. A. Maloney,[42] G. Mandrioli,[73] J. C. Maneira,[103,106] L. Manenti,[161] S. Manly,[140] A. Mann,[159] K. Manolopoulos,[142] M. Manrique Plata,[88] A. Marchionni,[56] W. Marciano,[15] D. Marfatia,[68] C. Mariani,[164] J. Maricic,[68] F. Marinho,[53] A. D. Marino,[37] M. Marshak,[160] C. Marshall,[108] J. Marshall,[166] J. Marteau,[81] J. Martin-Albo,[72] N. Martinez,[138] D.A. Martinez Caicedo,[147] S. Martynenko,[151] K. Mason,[159] A. T. Mastbaum,[141] M. Masud,[72] S. Matsuno,[68] J. Matthews,[111] C. Mauger,[132] N. Mauri,[73] K. Mavrokoridis,[109] R. Mazza,[76] A. Mazzacane,[56] E. Mazzucato,[17] E. McCluskey,[56] N. McConkey,[114] K. S. McFarland,[140] C. McGrew,[151] A. McNab,[114] A. Mefodiev,[80] P. Mehta,[94] P. Melas,[7] M. Mellinato,[76] O. Mena,[72] S. Menary,[172] L. Mendes Santos,[29] H. Mendez,[138] A. Menegolli,[79] G. Meng,[131] M. D. Messier,[88] W. Metcalf,[111] M. Mewes,[88] H. Meyer,[167] T. Miao,[56] G. Michna,[148] T. Miedema,[122] J. Migenda,[146] R. Milincic,[68] W. Miller,[160] J. Mills,[159] C. Milne,[83] O. Mineev,[80] O. G. Miranda,[35] S. Miryala,[15] C. S. Mishra,[56] S. R. Mishra,[149] A. Mislivec,[160] D. Mladenov,[18] I. Mocioiu,[133] K. Moffat,[47] N. Moggi,[73] R. Mohanta,[70] T. A. Mohayai,[56] N. Mokhov,[56] J. Molina,[6] L. Molina Bueno,[49] A. Montanari,[73] C. Montanari,[79] D. Montanari,[56] L. M. Montano Zetina,[35] J. Moon,[115] M. Mooney,[38] A. Moor,[28] D. Moreno,[3] B. Morgan,[166] C. Morris,[69] C. Mossey,[56] E. Motuk,[161] C. A. Moura,[54] J. Mousseau,[116] W. Mu,[56] L. Mualem,[27] J. Mueller,[38] M. Muether,[167] S. Mufson,[88] F. Muheim,[50] A. Muir,[44] M. Mulhearn,[22] H. Muramatsu,[160] S. Murphy,[49] J. Musser,[88] J. Nachtman,[90] S. Nagu,[112] M. Nalbandyan,[171] R. Nandakumar,[142] D. Naples,[136] S. Narita,[92] D. Navas-Nicolás,[19] N. Nayak,[23] M. Nebot-Guinot,[50] L. Necib,[27] K. Negishi,[92] J. K. Nelson,[168] J. Nesbit,[169] M. Nessi,[18] D. Newbold,[142] M. Newcomer,[132] D. Newhart,[56] R. Nichol,[161] E. Niner,[56] K. Nishimura,[68] A. Norman,[56] R. Northrop,[32] P. Novella,[72] J. A. Nowak,[107] M. Oberling,[4] A. Olivares Del Campo,[47] A. Olivier,[140] Y. Onel,[90] Y. Onishchuk,[101] J. Ott,[23] L. Pagani,[22] S. Pakvasa,[68] O. Palamara,[56] S. Palestini,[18] J. M. Paley,[56] M. Pallavicini,[75] C. Palomares,[19] E. Pantic,[22] V. Paolone,[136] V. Papadimitriou,[56] R. Papaleo,[152] A. Papanestis,[142] S. Paramesvaran,[14] S. Parke,[56] Z. Parsa,[15] M. Parvu,[16] S. Pascoli,[47] L. Pasqualini,[73] J. Pasternak,[85] J. Pater,[114] C. Patrick,[161] L. Patrizii,[73] R. B. Patterson,[27] S. J. Patton,[108] T. Patzak,[1] A. Paudel,[98] B. Paulos,[169] L. Paulucci,[54] Z. Pavlovic,[56] G. Pawloski,[160] D. Payne,[109] V. Pec,[146] S. J. M. Peeters,[153] Y. Penichot,[17] E. Pennacchio,[81] A. Penzo,[90] O. L. G. Peres,[29] J. Perry,[50] D. Pershey,[46] G. Pessina,[76] G. Petrillo,[143] C. Petta,[74] R. Petti,[149] F. Piastra,[10] L. Pickering,[117] F. Pietropaolo,[18,131] J. Pillow,[166] R. Plunkett,[56] R. Poling,[160] X. Pons,[18] N. Poonthottathil,[91] S. Pordes,[56] M. Potekhin,[15] R. Potenza,[74] B. V. K. S. Potukuchi,[93] J. Pozimski,[85] M. Pozzato,[73] S. Prakash,[29] T. Prakash,[108] S. Prince,[67] D. Pugnere,[81] K. Qi,[151] X. Qian,[15] J. L. Raaf,[56] R. Raboanary,[2] V. Radeka,[15] J. Rademacker,[14] B. Radics,[49] A. Rafique,[4] E. Raguzin,[15] M. Rai,[166] M. Rajaoalisoa,[34] I. Rakhno,[56] H. T. Rakotondramanana,[2] L. Rakotondravohitra,[2] Y. A. Ramachers,[166] R. Rameika,[56] M. A. Ramirez Delgado,[64] B. Ramson,[56] A. Rappoldi,[79] G. Raselli,[79] P. Ratoff,[107] S. Ravat,[18] H. Razafinime,[2] J.S. Real,[63] B. Rebel,[169,56] D. Redondo,[19] M. Reggiani-Guzzo,[29] T. Rehak,[45] J. Reichenbacher,[147] S. D. Reitzner,[56] A. Renshaw,[69] S. Rescia,[15] F. Resnati,[18] A. Reynolds,[129] G. Riccobene,[152] L. C. J. Rice,[136] K. Rielage,[110] Y. Rigaut,[49] D. Rivera,[132] L. Rochester,[143] M. Roda,[109] P. Rodrigues,[129] M. J. Rodriguez Alonso,[18] J. Rodriguez Rondon,[147] A. J. Roeth,[46] H. Rogers,[38] S. Rosauro-Alcaraz,[113] M. Rossella,[79] J. Rout,[94] S. Roy,[66] A. Rubbia,[49] C. Rubbia,[60] B. Russell,[108] J. Russell,[143] D. Ruterbories,[140] R. Saakyan,[161] S. Sacerdoti,[1] T. Safford,[117] N. Sahu,[87] P. Sala,[77,18] N. Samios,[15] M. C. Sanchez,[91] D. A. Sanders,[119] D. Sankey,[142] S. Santana,[138] M. Santos-Maldonado,[138] N. Saoulidou,[7] P. Sapienza,[152] C. Sarasty,[34] I. Sarcevic,[5] G. Savage,[56] V. Savinov,[136] A. Scaramelli,[79] A. Scarff,[146] A. Scarpelli,[1]

T. Schaffer,[118] H. Schellman,[128,56] P. Schlabach,[56] D. Schmitz,[32] K. Scholberg,[46] A. Schukraft,[56] E. Segreto,[29] J. Sensenig,[132] I. Seong,[23] A. Sergi,[12] F. Sergiampietri,[151] D. Sgalaberna,[18] M. H. Shaevitz,[39] S. Shafaq,[94] M. Shamma,[25] H. R. Sharma,[93] R. Sharma,[15] T. Shaw,[56] C. Shepherd-Themistocleous,[142] S. Shin,[32] D. Shooltz,[117] R. Shrock,[151] L. Simard,[102] N. Simos,[15] J. Sinclair,[10] G. Sinev,[46] J. Singh,[112] J. Singh,[112] R. Sipos,[18] F. W. Sippach,[39] G. Sirri,[73] A. Sitraka,[147] K. Siyeon,[33] D. Smargianaki,[151] A. Smith,[46] A. Smith,[28] E. Smith,[88] P. Smith,[88] J. Smolik,[41] M. Smy,[23] P. Snopok,[84] M. Soares Nunes,[29] H. Sobel,[23] M. Soderberg,[154] C. J. Solano Salinas,[89] S. Söldner-Rembold,[114] N. Solomey,[167] V. Solovov,[104] W. E. Sondheim,[110] M. Sorel,[72] J. Soto-Oton,[19] A. Sousa,[34] K. Soustruznik,[31] F. Spagliardi,[129] M. Spanu,[15] J. Spitz,[116] N. J. Spooner,[146] K. Spurgeon,[154] R. Staley,[12] M. Stancari,[56] L. Stanco,[131] H. M. Steiner,[108] J. Stewart,[15] B. Stillwell,[32] J. Stock,[147] F. Stocker,[18] T. Stokes,[111] M. Strait,[160] T. Strauss,[56] S. Striganov,[56] A. Stuart,[36] D. Summers,[119] A. Surdo,[144] V. Susic,[9] L. Suter,[56] C. M. Sutera,[74] R. Svoboda,[22] B. Szczerbinska,[156] A. Szelc,[114] R. Talaga,[4] H. A. Tanaka,[143] B. Tapia Oregui,[158] A. Tapper,[85] S. Tariq,[56] E. Tatar,[83] R. Tayloe,[88] A. M. Teklu,[151] M. Tenti,[73] K. Terao,[143] C. A. Ternes,[72] F. Terranova,[76] G. Testera,[75] A. Thea,[142] J. L. Thompson,[146] C. Thorn,[15] S. C. Timm,[56] A. Tonazzo,[1] M. Torti,[76] M. Tortola,[72] F. Tortorici,[74] D. Totani,[56] M. Toups,[56] C. Touramanis,[109] J. Trevor,[27] W. H. Trzaska,[95] Y. T. Tsai,[143] Z. Tsamalaidze,[59] K. V. Tsang,[143] N. Tsverava,[59] S. Tufanli,[18] C. Tull,[108] E. Tyley,[146] M. Tzanov,[111] M. A. Uchida,[28] J. Urheim,[88] T. Usher,[143] M. R. Vagins,[99] P. Vahle,[168] G. A. Valdiviesso,[51] E. Valencia,[168] Z. Vallari,[27] J. W. F. Valle,[72] S. Vallecorsa,[18] R. Van Berg,[132] R. G. Van de Water,[110] D. Vanegas Forero,[29] F. Varanini,[131] D. Vargas,[71] G. Varner,[68] J. Vasel,[88] G. Vasseur,[17] K. Vaziri,[56] S. Ventura,[131] A. Verdugo,[19] S. Vergani,[28] M. A. Vermeulen,[122] M. Verzocchi,[56] H. Vieira de Souza,[29] C. Vignoli,[61] C. Vilela,[151] B. Viren,[15] T. Vrba,[41] T. Wachala,[121] A. V. Waldron,[85] M. Wallbank,[34] H. Wang,[24] J. Wang,[22] Y. Wang,[24] Y. Wang,[151] K. Warburton,[91] D. Warner,[38] M. Wascko,[85] D. Waters,[161] A. Watson,[12] P. Weatherly,[45] A. Weber,[142,129] M. Weber,[10] H. Wei,[15] A. Weinstein,[91] D. Wenman,[169] M. Wetstein,[91] M. R. While,[147] A. White,[157] L. H. Whitehead,[28] D. Whittington,[154] M. J. Wilking,[151] C. Wilkinson,[10] Z. Williams,[157] F. Wilson,[142] R. J. Wilson,[38] J. Wolcott,[159] T. Wongjirad,[159] K. Wood,[151] L. Wood,[130] E. Worcester,[15] M. Worcester,[15] C. Wret,[140] W. Wu,[56] W. Wu,[23] Y. Xiao,[23] G. Yang,[151] T. Yang,[56] N. Yershov,[80] K. Yonehara,[56] T. Young,[123] B. Yu,[15] J. Yu,[157] J. Zalesak,[40] L. Zambelli,[20] B. Zamorano,[62] A. Zani,[77] L. Zazueta,[168] G. P. Zeller,[56] J. Zennamo,[56] K. Zeug,[169] C. Zhang,[15] M. Zhao,[15] E. Zhivun,[15] G. Zhu,[127] E. D. Zimmerman,[37] M. Zito,[17] S. Zucchelli,[73] J. Zuklin,[40] V. Zutshi,[124] and R. Zwaska[56]

(The DUNE Collaboration)

[1] *APC - Université de Paris, CNRS/IN2P3, CEA/lrfu, Observatoire de Paris, 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France*
[2] *University of Antananarivo, BP 566, Antananarivo 101, Madagascar*
[3] *Universidad Antonio Nariño, Cra 3 Este No 47A-15, Bogotá, Colombia*
[4] *Argonne National Laboratory, Argonne, IL 60439, USA*
[5] *University of Arizona, 1118 E. Fourth Street Tucson, AZ 85721, USA*
[6] *Universidad Nacional de Asunción, San Lorenzo, Paraguay*
[7] *University of Athens, University Campus, Zografou GR 157 84, Greece*
[8] *Universidad del Atlantico, Carrera 30 Número 8- 49 Puerto Colombia - Atlántico, Colombia*
[9] *University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*
[10] *University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland*
[11] *Beykent University, Istanbul*
[12] *University of Birmingham, Edgbaston, Birmingham B15 2TT, United Kingdom*
[13] *Boston University, Boston, MA 02215, USA*
[14] *University of Bristol, H. H. Wills Physics Laboratory, Tyndall Avenue Bristol BS8 1TL, United Kingdom*
[15] *Brookhaven National Laboratory, Upton, NY 11973, USA*
[16] *University of Bucharest, Faculty of Physics, Bucharest, Romania*
[17] *CEA/Saclay, IRFU Institut de Recherche sur les Lois Fondamentales de l'Univers, F-91191 Gif-sur-Yvette CEDEX, France*
[18] *CERN, European Organization for Nuclear Research 1211 Genève 23, Switzerland, CERN*
[19] *CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Av. Complutense, 40, E-28040 Madrid, Spain*
[20] *Laboratoire d'Annecy-le-Vieux de Physique des Particules, CNRS/IN2P3 and Université Savoie Mont Blanc, CNRS/IN2P3 and Université Savoie Mont Blanc, 74941 Annecy-le-Vieux, France*
[21] *University of California Berkeley, Berkeley, CA 94720, USA*
[22] *University of California Davis, Davis, CA 95616, USA*
[23] *University of California Irvine, Irvine, CA 92697, USA*
[24] *University of California Los Angeles, Los Angeles, CA 90095, USA*
[25] *University of California Riverside, 900 University Ave, Riverside CA 92521*
[26] *University of California Santa Barbara, Santa Barbara, California 93106 USA*

[27]California Institute of Technology, Pasadena, CA 91125, USA
[28]University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom
[29]Universidade Estadual de Campinas, Campinas - SP, 13083-970, Brazil
[30]Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ 22290-180, Brazil
[31]Institute of Particle and Nuclear Physics of the Faculty of Mathematics and Physics of the Charles University in Prague, V Holešovičkách 747/2, 180 00 Praha 8-Libeň, Czech Republic
[32]University of Chicago, Chicago, IL 60637, USA
[33]Chung-Ang University, Dongjak-Gu, Seoul 06974, South Korea
[34]University of Cincinnati, Cincinnati, OH 45221, USA
[35]Centro de Investigacion y de Estudios Avanzados del IPN (Cinvestav), Mexico City
[36]Universidad de Colima, 340 Colonia Villa San Sebastian Colima, Colima, Mexico
[37]University of Colorado Boulder, Boulder, CO 80309, USA
[38]Colorado State University, Fort Collins, CO 80523, USA
[39]Columbia University, New York, NY 10027, USA
[40]Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 182 21 Praha 8, Czech Republic
[41]Czech Technical University in Prague, Břehová 78/7, 115 19 Prague 1, Czech Republic
[42]Dakota State University, Madison, SD 57042, USA
[43]University of Dallas, Irving, TX 75062-4736, USA
[44]Daresbury Laboratory, Daresbury Warrington, Cheshire WA4 4AD, United Kingdom
[45]Drexel University, Philadelphia, PA 19104, USA
[46]Duke University, Durham, NC 27708, USA
[47]Durham University, South Road, Durham DH1 3LE, United Kingdom
[48]Universidad EIA, Via José María Córdoba #km 2 + 200, Envigado, Antioquia
[49]ETH Zurich, Institute for Particle Physics, Zurich, Switzerland
[50]University of Edinburgh, Edinburgh EH8 9YL, United Kingdom
[51]Universidade Federal de Alfenas, Poços de Caldas - MG, 37715-400, Brazil
[52]Universidade Federal de Goias, Goiania, GO 74690-900, Brazil
[53]Universidade Federal de São Carlos, Araras - SP, 13604-900, Brazil
[54]Universidade Federal do ABC, Av. dos Estados 5001, Santo André - SP, 09210-580 Brazil
[55]Universidade Federal do Rio de Janeiro, Rio de Janeiro - RJ, 21941-901, Brazil
[56]Fermi National Accelerator Laboratory, Batavia, IL 60510
[57]University of Florida, PO Box 118440 Gainesville, FL 32611-8440, USA
[58]Fluminense Federal University, Rua Miguel de Frias, 9 Icaraí Niterói - RJ, 24220-900, Brazil
[59]Georgian Technical University, 77 Kostava Str. 0160, Tbilisi, Georgia
[60]Gran Sasso Science Institute, Viale Francesco Crispi 7, L'Aquila, Italy
[61]Laboratori Nazionali del Gran Sasso, I-67010 Assergi, AQ, Italy
[62]University of Granada & CAFPE, Campus Fuentenueva (Edif. Mecenas), 18002 Granada, Spain
[63]University Grenoble Alpes, CNRS, Grenoble INP, LPSC-IN2P3, 38000 Grenoble, France
[64]Universidad de Guanajuato, Gto., C.P. 37000, Mexico
[65]Department of Physics, K L E F, Green Fields, Guntur - 522 502, AP, India
[66]Harish-Chandra Research Institute, Jhunsi, Allahabad 211 019, India
[67]Harvard University, 17 Oxford St. Cambridge, MA 02138, USA
[68]University of Hawaii, Honolulu, HI 96822, USA
[69]University of Houston, Houston, TX 77204, USA
[70]University of Hyderabad, Gachibowli, Hyderabad - 500 046, India
[71]Institut de Fìsica d'Altes Energies, Barcelona i.e. Catalan ersitat Autonoma de Barcelona, Campus UAB, Facultat Ciències Nord, 08193 Bellaterra, Barcelona, Spain
[72]Instituto de Fisica Corpuscular, Catedratico Jose Beltran, 2 E-46980 Paterna (Valencia), Spain
[73]Istituto Nazionale di Fisica Nucleare Bologna, 40127 Bologna BO, Italy
[74]Istituto Nazionale di Fisica Nucleare Sezione di Catania, Via Santa Sofia 64, I-95123 Catania, Italy
[75]Università degli studi di Genova, Istituto Nazionale di Fisica Nucleare Genova, 16126 Genova GE, Italy
[76]Istituto Nazionale di Fisica Nucleare Sezione di Milano Bicocca and University of Milano Bicocca, Piazza della Scienza, 3 - I-20126 Milano, Italy
[77]Istituto Nazionale di Fisica Nucleare Milano, I-20133 Milano, Italy
[78]Istituto Nazionale di Fisica Nucleare - Sezione di Napoli, Complesso Universitario di Monte S. Angelo, I-80126 Napoli, Italy
[79]Università degli studi di Pavia, Istituto Nazionale di Fisica Nucleare Sezione di Pavia, I-27100 Pavia, Italy
[80]Institute for Nuclear Research of the Russian Academy of Sciences , prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
[81]Institut de Physique des 2 Infinis de Lyon, Rue E. Fermi 4 69622 Villeurbanne, France
[82]Institute for Research in Fundamental Sciences , Farmanieh St. Tehran, 19538-33511, Iran
[83]Idaho State University, Department of Physics, Pocatello, ID 83209, USA
[84]Illinois Institute of Technology, Chicago, IL 60616, USA
[85]Imperial College of Science Technology and Medicine, Blackett Laboratory Prince Consort Road, London SW7 2BZ, United Kingdom
[86]Indian Institute of Technology Guwahati, Guwahati, 781 039, India

[87]*Indian Institute of Technology Hyderabad, Hyderabad, 502285, India*
[88]*Indiana University, Bloomington, IN 47405, USA*
[89]*Universidad Nacional de Ingeniería, Av. Tupac Amaru 210, Lima 25, Perú*
[90]*University of Iowa, Department of Physics and Astronomy 203 Van Allen Hall Iowa City, IA 52242, USA*
[91]*Iowa State University, Ames, Iowa 50011, USA*
[92]*Iwate University, Morioka, Iwate 020-8551, Japan*
[93]*University of Jammu, Physics Department, JAMMU-180006, India*
[94]*Jawaharlal Nehru University, School of Physical Sciences, New Delhi 110067, India*
[95]*University of Jyvaskyla, P.O. Box 35, FI-40014, Finland*
[96]*High Energy Accelerator Research Organization (KEK), Ibaraki, 305-0801, Japan*
[97]*Korea Institute of Science and Technology Information, Daejeon, 34141, South Korea*
[98]*Kansas State University, Manhattan, KS 66506, USA*
[99]*Kavli Institute for the Physics and Mathematics of the Universe , Kashiwa, Chiba 277-8583, Japan*
[100]*National Institute of Technology, Kure College, Hiroshima, 737-8506, Japan*
[101]*Kyiv National University, 64, 01601 Kyiv, Ukraine*
[102]*Laboratoire de l'Accélérateur Linéaire , Bâtiment 200, 91440 Orsay, France*
[103]*Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal*
[104]*Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Coimbra, Portugal*
[105]*Instituto Superior Técnico - IST, Universidade de Lisboa, Portugal*
[106]*Faculdade de Ciências - FCUL, Universidade de Lisboa, Portugal*
[107]*Lancaster University, Bailrigg, Lancaster LA1 4YB, United Kingdom*
[108]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[109]*University of Liverpool, L69 7ZE, Liverpool, United Kingdom*
[110]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[111]*Louisiana State University, Baton Rouge, LA 70803, USA*
[112]*University of Lucknow, Lucknow 226007, Uttar Pradesh, India*
[113]*Madrid Autonoma University and IFT UAM/CSIC, Ciudad Universitaria de Cantoblanco 28049 Madrid, Spain*
[114]*University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom*
[115]*Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[116]*University of Michigan, Ann Arbor, MI 48109, USA*
[117]*Michigan State University, East Lansing, MI 48824, USA*
[118]*University of Minnesota Duluth, Duluth, MN 55812, USA*
[119]*University of Mississippi, P.O. Box 1848, University, MS 38677 USA*
[120]*University of New Mexico, 1919 Lomas Blvd. N.E. Albuquerque, NM 87131, USA*
[121]*H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*
[122]*Nikhef National Institute of Subatomic Physics, Science Park, Amsterdam, Netherlands*
[123]*University of North Dakota, 3501 University Ave Grand Forks, ND 58202-8357, USA*
[124]*Northern Illinois University, Department of Physics, DeKalb, Illinois 60115, USA*
[125]*Northwestern University, Evanston, Il 60208, USA*
[126]*University of Notre Dame, Notre Dame, IN 46556, USA*
[127]*Ohio State University, 191 W. Woodruff Ave. Columbus, OH 43210, USA*
[128]*Oregon State University, Corvallis, OR 97331, USA*
[129]*University of Oxford, Oxford, OX1 3RH, United Kingdom*
[130]*Pacific Northwest National Laboratory, Richland, WA 99352, USA*
[131]*Universtà Degli Studi di Padova, Dip. Fisica e Astronomia G. Galilei and INFN Sezione di Padova, I-35131 Padova, Italy*
[132]*University of Pennsylvania, Philadelphia, PA 19104, USA*
[133]*Pennsylvania State University, University Park, PA 16802, USA*
[134]*Physical Research Laboratory, Ahmedabad 380 009, India*
[135]*Università di Pisa, Theor. Division; Largo B. Pontecorvo 3, Ed. B-C, I-56127 Pisa, Italy*
[136]*University of Pittsburgh, Pittsburgh, PA 15260, USA*
[137]*Pontificia Universidad Católica del Perú, Apartado 1761, Lima, Perú*
[138]*University of Puerto Rico, Mayaguez, 00681, USA*
[139]*Punjab Agricultural University, Department of Math. Stat. & Physics, Ludhiana 141004, India*
[140]*University of Rochester, Rochester, NY 14627, USA*
[141]*Rutgers University, Piscataway, NJ, 08854, USA*
[142]*STFC Rutherford Appleton Laboratory, OX11 0QX Harwell Campus, Didcot, United Kingdom*
[143]*SLAC National Acceleratory Laboratory, Menlo Park, CA 94025, USA*
[144]*Università del Salento and Istituto Nazionale Fisica Nucleare, Via Provinciale per Arnesano, 73100 Lecce, Italy*
[145]*Universidad Sergio Arboleda, Cll 74 -14 -14, 11022 Bogotá, Colombia*
[146]*University of Sheffield, Department of Physics and Astronomy, Sheffield S3 7RH, United Kingdom*
[147]*South Dakota School of Mines and Technology, Rapid City, SD 57701, USA*
[148]*South Dakota State University, Brookings, SD 57007, USA*
[149]*University of South Carolina, Columbia, SC 29208, USA*
[150]*Southern Methodist University, Dallas, TX 75275, USA*

[151] *Stony Brook University, SUNY, Stony Brook, New York 11794, USA*
[152] *INFN - Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, 95123 Catania, Italy*
[153] *University of Sussex, Brighton, BN1 9RH, United Kingdom*
[154] *Syracuse University, Syracuse, NY 13244, USA*
[155] *University of Tennessee at Knoxville, TN, 37996, USA*
[156] *Texas A&M University (Corpus Christi), Corpus Christi, TX 78412, USA*
[157] *University of Texas at Arlington, Arlington, TX 76019, USA*
[158] *University of Texas at Austin, Austin, TX 78712, USA*
[159] *Tufts University, Medford, MA 02155, USA*
[160] *University of Minnesota Twin Cities, Minneapolis, MN 55455, USA*
[161] *University College London, London, WC1E 6BT, United Kingdom*
[162] *Valley City State University, Valley City, ND 58072, USA*
[163] *Variable Energy Cyclotron Centre, 1/AF, Bidhannagar Kolkata - 700 064 West Bengal, India*
[164] *Virginia Tech, Blacksburg, VA 24060, USA*
[165] *University of Warsaw, Faculty of Physics ul. Pasteura 5 02-093 Warsaw, Poland*
[166] *University of Warwick, Coventry CV4 7AL, United Kingdom*
[167] *Wichita State University, Physics Division, Wichita, KS 67260, USA*
[168] *William and Mary, Williamsburg, VA 23187, USA*
[169] *University of Wisconsin Madison, Madison, WI 53706, USA*
[170] *Yale University, New Haven, CT 06520, USA*
[171] *Yerevan Institute for Theoretical Physics and Modeling, Halabian Str. 34, Yerevan 0036, Armenia*
[172] *York University, Physics and Astronomy Department, 4700 Keele St. Toronto M3J 1P3, Canada*

Contents

Contents i

List of Figures ii

List of Tables 1

A Roadmap of the DUNE Technical Design Report 1

1 DUNE Far Site Technical Coordination 2
- 1.1 Overview . . . 2
- 1.2 Global Project Organization . . . 3
  - 1.2.1 Global Project Partners . . . 3
  - 1.2.2 Coordinated Global Project Functions . . . 4
  - 1.2.3 Coordinated Safety Program . . . 5
  - 1.2.4 Detector Integration . . . 6
  - 1.2.5 Schedule and Milestones . . . 6
  - 1.2.6 Partner Agreements and Financial Reporting . . . 6
- 1.3 DUNE Far Detector Organization . . . 7
  - 1.3.1 Detector Design and Construction . . . 7
  - 1.3.2 Detector Installation and Commissioning . . . 9
- 1.4 Facility Description . . . 10
- 1.5 Far Detector Construction Management . . . 12
- 1.6 Integration Engineering . . . 14
- 1.7 Reviews . . . 15
- 1.8 Quality Assurance . . . 15
- 1.9 Environment, Safety, and Health . . . 16

Glossary 18

References 23

List of Figures

1.1 Global project organization . . . 3
1.2 JPO functions . . . 4
1.3 LBNF/DUNE ES&H . . . 5
1.4 DUNE technical coordination organization . . . 8
1.5 Integration office installation team org chart . . . 9
1.6 Underground campus . . . 11
1.7 DUNE far detector consortia . . . 12
1.8 DUNE WBS at level 2 . . . 13
1.9 Integration nodes and interfaces . . . 14
1.10 Quality assurance flowdown . . . 15

List of Tables

Chapter 1

DUNE Far Site Technical Coordination

This chapter provides a brief introduction to the DUNE far site technical coordination. The text below closely follows that found in the introductory chapters of Volume III, DUNE Far Detector Technical Coordination, where many more details may be found.

1.1 Overview

The Deep Underground Neutrino Experiment (DUNE) collaboration has responsibility for the design and construction of the DUNE far detector (FD). Groups of collaboration institutions, referred to as consortia, assume responsibility for the different detector subsystems. The activities of the consortia are overseen and coordinated through the DUNE technical coordination organization headed by the DUNE technical coordinator (TC). The technical coordination organization provides project support functions such as safety coordination, engineering integration, change control, document management, scheduling, risk management, and technical review planning. DUNE technical coordination manages internal, subsystem-to-subsystem interfaces, and is responsible for ensuring the proper integration of the different subsystems.

DUNE technical coordination works closely with the support teams of its LBNF and DUNE project (LBNF/DUNE) partners within the framework of a Joint Project Office (JPO) to ensure coherence in project support functions across the entire global enterprise. To ensure consistency of the DUNE environment, safety and health (ES&H) and quality assurance (QA) programs with those across LBNF/DUNE, the LBNF/DUNE ES&H and QA managers, who sit within the JPO, are embedded within the DUNE technical coordination organization.

The LBNF/DUNE integration office under the direction of the project integration director incorporates the on-site team responsible for coordinating integration and installation activities at the Sanford Underground Research Facility (SURF). Detector integration and installation activities are supported by the DUNE consortia, which maintain responsibility for ensuring proper installation and commissioning of their subsystems. External DUNE interfaces with the on-site integration

and installation activities are managed through the JPO.

1.2 Global Project Organization

1.2.1 Global Project Partners

The Long-Baseline Neutrino Facility (LBNF) project is responsible for providing both the conventional facilities (CF) and supporting infrastructure (cryostats and cryogenics systems) that house the DUNE FD modules. The international DUNE collaboration under the direction of its management team is responsible for the detector components. The DUNE FD construction project encompasses all activities required for designing and fabricating the detector elements and incorporates contributions from a number of international partners. The organization of LBNF/DUNE, which encompasses both project elements, is shown in Figure 1.1.

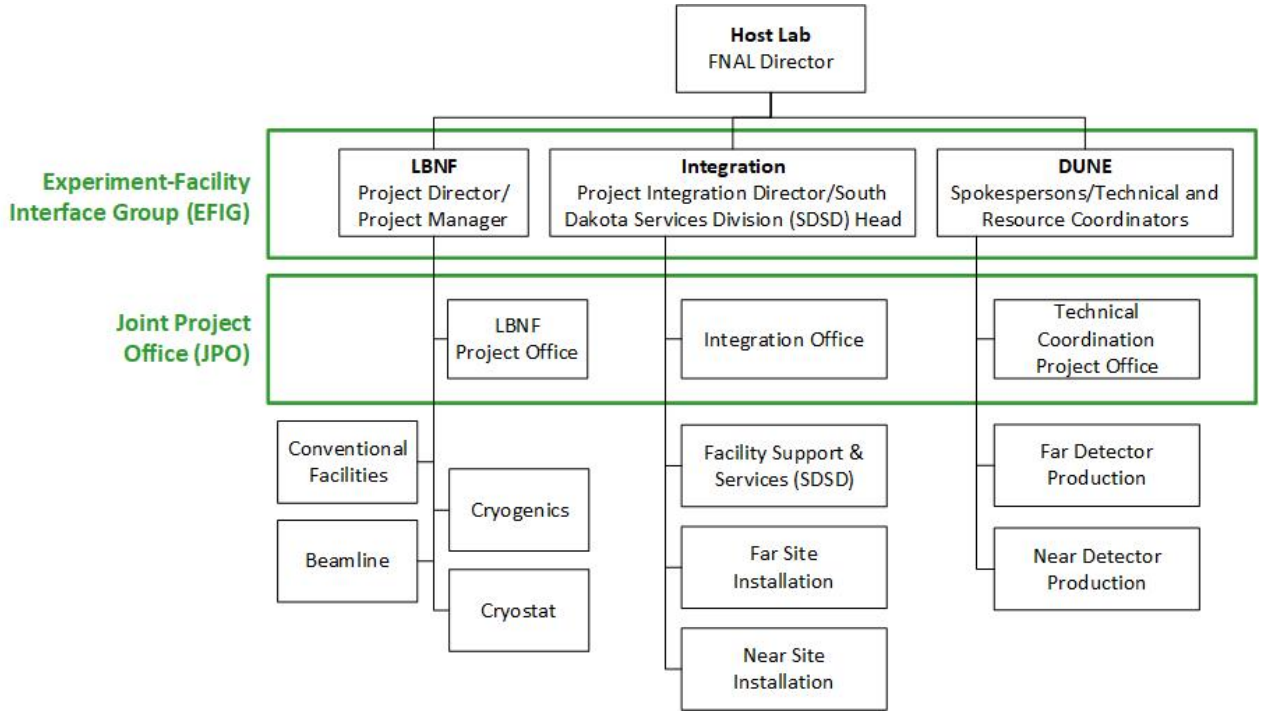


Figure 1.1: The global LBNF/DUNE organization.

The overall coordination of installation activities in the underground caverns is managed as a separate element of LBNF/DUNE under the responsibility of the project integration director, who is appointed by and reports to the Fermi National Accelerator Laboratory (Fermilab) director. To ensure coordination across all elements of LBNF/DUNE, the project integration director connects to both the facilities and detector construction projects through ex-officio positions on the LBNF project management board and DUNE executive board (EB), respectively. The project integration director receives support from the Fermilab South Dakota Services Division (SDSD), a Fermilab division established to provide the necessary supporting infrastructure for installation, commissioning, and operation of the DUNE far detector.

The Experimental Facilities Interface Group (EFIG) is the body responsible for the required high-level coordination between the LBNF and DUNE construction projects. The EFIG is augmented by the JPO that supports both the LBNF and DUNE projects as well as the integration effort that connects the two together. The JPO combines project support functions that exist within the different elements of the global project to ensure proper coordination across the entire LBNF/DUNE enterprise. Project functions coordinated globally through the JPO are shown in Figure 1.2 along with the team members currently supporting these functions within the JPO framework. These team members are drawn from the LBNF project office, DUNE technical coordination, and LBNF/DUNE integration office personnel.

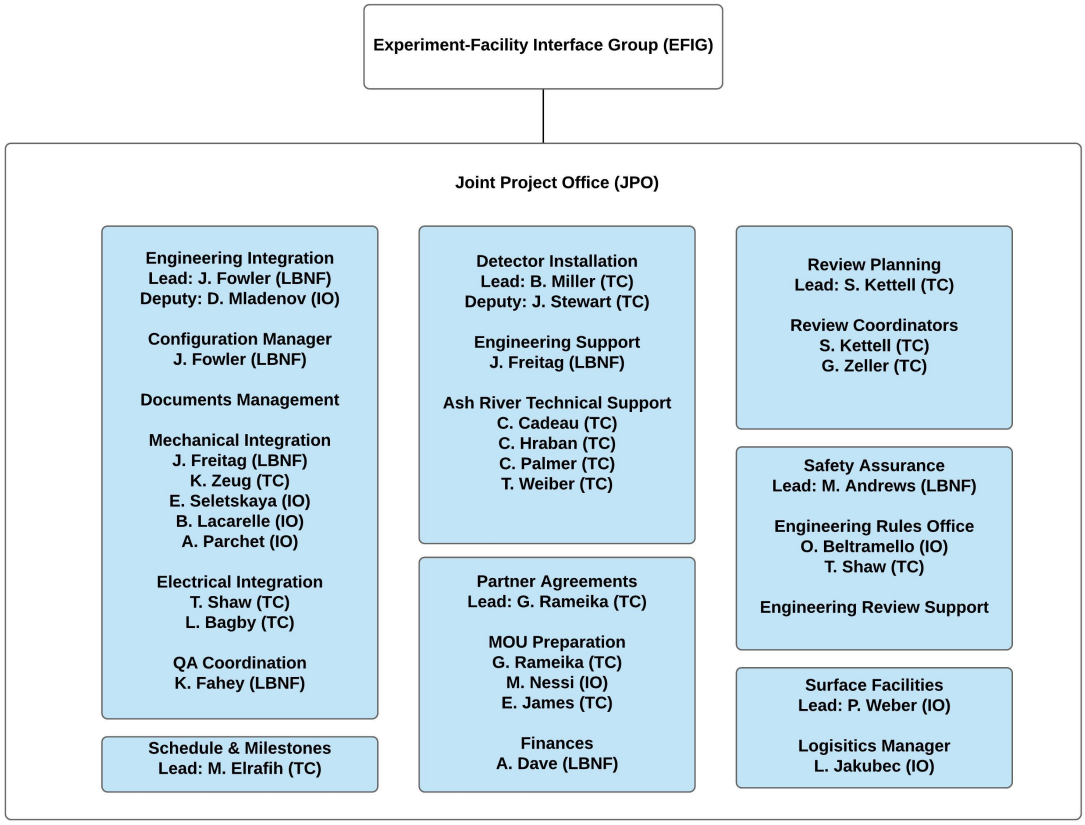


Figure 1.2: JPO global support functions and teams

1.2.2 Coordinated Global Project Functions

Project support functions requiring JPO coordination include safety, engineering integration, change control and document management, scheduling, review planning and oversight, and development of partner agreements.

Planning activities related to detector installation and the provision of surface facilities are also currently embedded within the framework of the JPO to ensure that all project elements are properly incorporated. At the time when LBNF far site conventional facilities (FSCF) delivers acceptance for use and possession (AUP) of the underground detector caverns at SURF, the co-

ordination of on-site activities associated with detector installation and the operation of surface facilities will be fully embedded within the LBNF/DUNE integration office under the direction of the project integration director.

1.2.3 Coordinated Safety Program

To ensure a consistent approach to safety across LBNF/DUNE, a single LBNF/DUNE ES&H manager reports to the LBNF project director, the project integration director, and DUNE management (via the DUNE TC). This individual directs separate safety teams responsible for implementing the LBNF/DUNE ES&H program within the individual LBNF and DUNE projects as well as the coordinated LBNF/DUNE installation activities at SURF. The safety organization is shown in Figure 1.3.

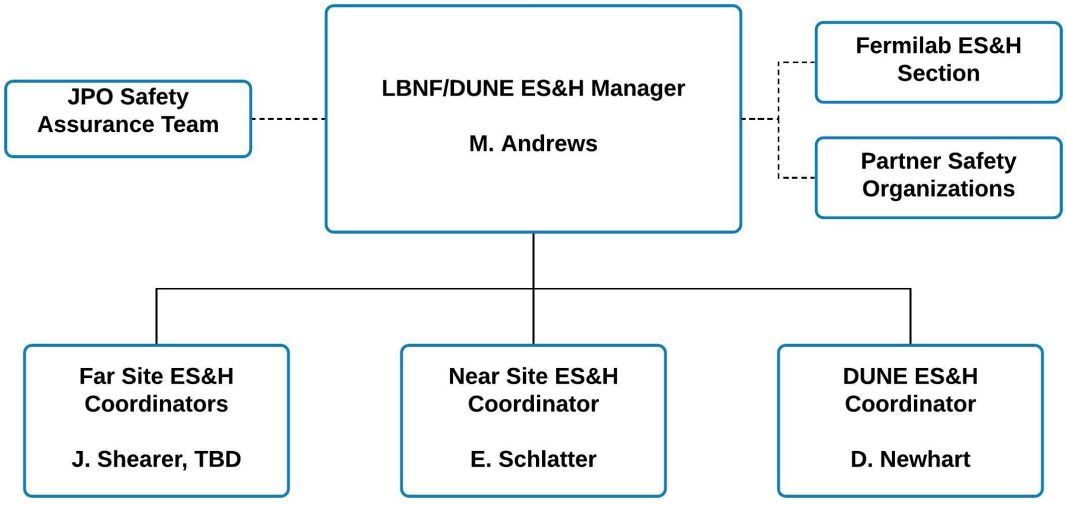


Figure 1.3: High level LBNF/DUNE ES&H organization.

The LBNF/DUNE ES&H manager works with the Fermilab and SURF safety organizations to ensure that all project-related activities comply with the rules and regulations of the host organizations.

The JPO engineering safety assurance team defines a common set of design and construction rules (mechanical and electrical) to ensure consistent application of engineering standards and engineering documentation requirements across LBNF/DUNE. Following lessons learned from the processes used for the ProtoDUNE detectors, an important mandate of the engineering safety assurance team is to ensure that safety issues related to component handling and installation are incorporated within the earliest stages of the design review process.

1.2.4 Detector Integration

A central JPO engineering team is responsible for building an integrated model of the detectors within their supporting infrastructure and the FSCF that house them. This team incorporates approved changes as they are received and checks to ensure that no errors or space conflicts are introduced into the model. After receiving the appropriate sign-offs from all parties, the team tags a new frozen release of the model and makes it available to the design teams as the current release against which the next set of design changes will be generated.

Electrical engineers are incorporated within this team to ensure proper integration of the detector electrical components.

The JPO engineering team is also responsible for documenting and controlling the interfaces between the LBNF and DUNE projects as well as the interfaces between these projects and the LBNF/DUNE installation activities at SURF.

The LBNF/DUNE project partners have agreed to adopt the formal change control process developed previously for the LBNF project. The change control process applies to proposed modifications of requirements, technical designs, schedule, overall project scope, and assigned responsibilities for individual scope items.

1.2.5 Schedule and Milestones

The JPO team is responsible for creating a single project schedule for LBNF/DUNE that incorporates all LBNF and DUNE activities together with the installation activities at SURF, incorporating all interdependencies. This schedule will be used to track the status of the global enterprise. DOE activities will be tracked using the formal earned value management system (EVMS) procedures required for the DOE project activities; non-DOE activities will be tracked through regular assessments of progress towards completion by the management teams responsible for those activities.

1.2.6 Partner Agreements and Financial Reporting

Partner contributions to all project elements will be detailed in a series of written agreements. In the case of LBNF, these contributions will be spelled out in bilateral agreements between the DOE and each of the contributing partners. In the case of DUNE, a memorandum of understanding (MoU) will detail the contributions of all participating partners. A series of more technical agreements describing the exact boundaries between partner contributions and the terms and conditions under which they will be delivered will accompany the primary agreements.

1.3 DUNE Far Detector Organization

1.3.1 Detector Design and Construction

The DUNE FD construction project refers collectively to the activities associated with the design and construction of necessary detector components. DUNE collaboration management is responsible for overseeing this portion of LBNF/DUNE and ensuring its successful execution. The high-level DUNE collaboration management team consisting of the co-spokespersons, TC, and resource coordinator (RC) is responsible for the management of the construction project.

Construction of the FD modules is carried out by consortia of collaboration institutions who assume responsibility for detector subsystems. Each consortium plans and executes the construction, installation, and commissioning of its subsystem.

Each consortium is managed by an overall consortium leader and a technical lead. The consortium leader chairs an institutional board composed of one representative from each of the institutions contributing to the activities of the consortium. Major consortium decisions such as technology selections and assignment of responsibilities among the institutions pass through its institutional board. These decisions are then passed as recommendations to the DUNE EB for formal collaboration approval.

Because the consortia operate as self-managed entities, a strong technical coordination organization is required to ensure overall integration of the detector elements and successful execution of the detector construction project. Technical coordination areas of responsibility include general project oversight, systems engineering, QA, and safety. Technical coordination also supports the planning and execution of integration and installation activities at SURF. The TC manages the overall detector construction project through regular technical and project board meetings with the consortium leadership teams and members of the technical coordination organization.

The technical coordination organization, headed by the TC, supports the work of the consortia and has responsibility for a number of major project support functions prior to the delivery of detector components to SURF, including

- ensuring that each consortium has a well defined and complete scope, that interactions between consortia are sufficiently well defined, and that any missing scope outside of the consortia is provided through other sources such as collaboration common funds;
- defining and documenting scope boundaries and technical interfaces both between consortia and with LBNF;
- developing an overall schedule with appropriate dependencies between activities covering all phases of the project;
- ensuring that appropriate engineering and safety standards are developed, understood, and agreed to by all key stakeholders and that these standards are conveyed to and understood by each consortium;
- ensuring that all DUNE requirements on LBNF for FSCF, cryostat, and cryogenics are clearly

defined and agreed to by each consortium;

- ensuring that each consortium has well developed and reviewed component designs, construction plans, quality control (QC) processes, and safety programs; and
- monitoring the overall project schedule and the progress of each consortium towards delivering its assigned scope.

The DUNE technical coordination organizational structure is shown in Figure 1.4.

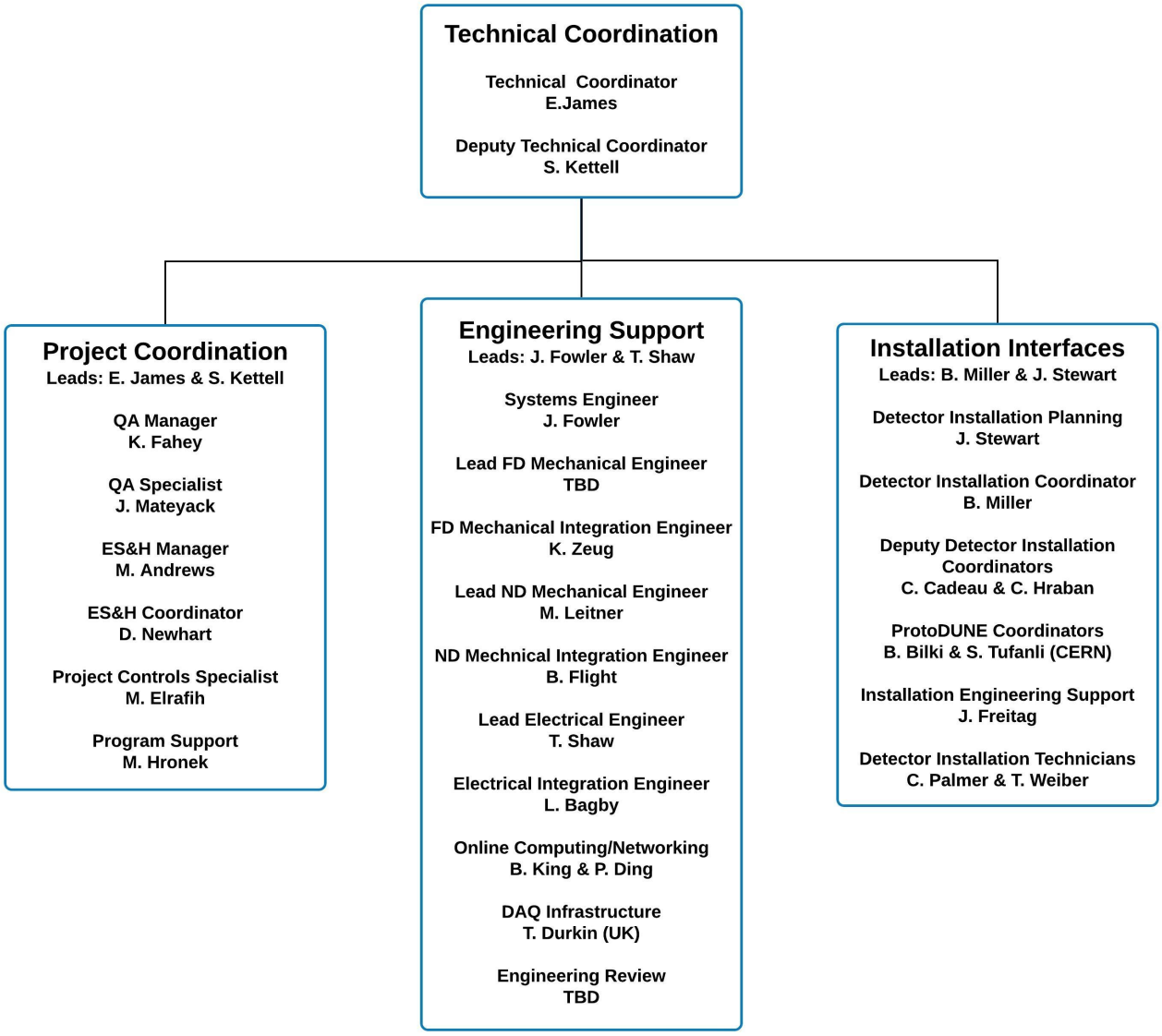


Figure 1.4: DUNE technical coordination organizational chart.

The technical coordination project coordination team incorporates ES&H, QA, and project controls specialists. Overall integration of the detector elements is coordinated through the technical coordination engineering support team headed by the LBNF/DUNE systems engineer and lead DUNE electrical engineer. Planning coordinators for integration and installation activities at SURF (who sit within the LBNF/DUNE integration office) also head the technical coordination installation

interfaces team. The dual placement of these individuals facilitates the required coordination of integration and installation planning efforts between the core team directing these activities and the DUNE consortia.

1.3.2 Detector Installation and Commissioning

The project integration director has responsibility for coordinating the planning and execution of the LBNF/DUNE installation activities, both in the underground detector caverns at SURF and in nearby surface facilities.

The LBNF/DUNE integration office will evolve over time to incorporate the team in South Dakota responsible for the overall coordination of on-site installation activities. In the meantime, the installation planning team within the integration office works with the DUNE consortia and LBNF project team members to plan these activities. This installation team is responsible for specification and procurement of common infrastructure items associated with installation of the detectors. The organization of the on-site team is shown in Figure 1.5.

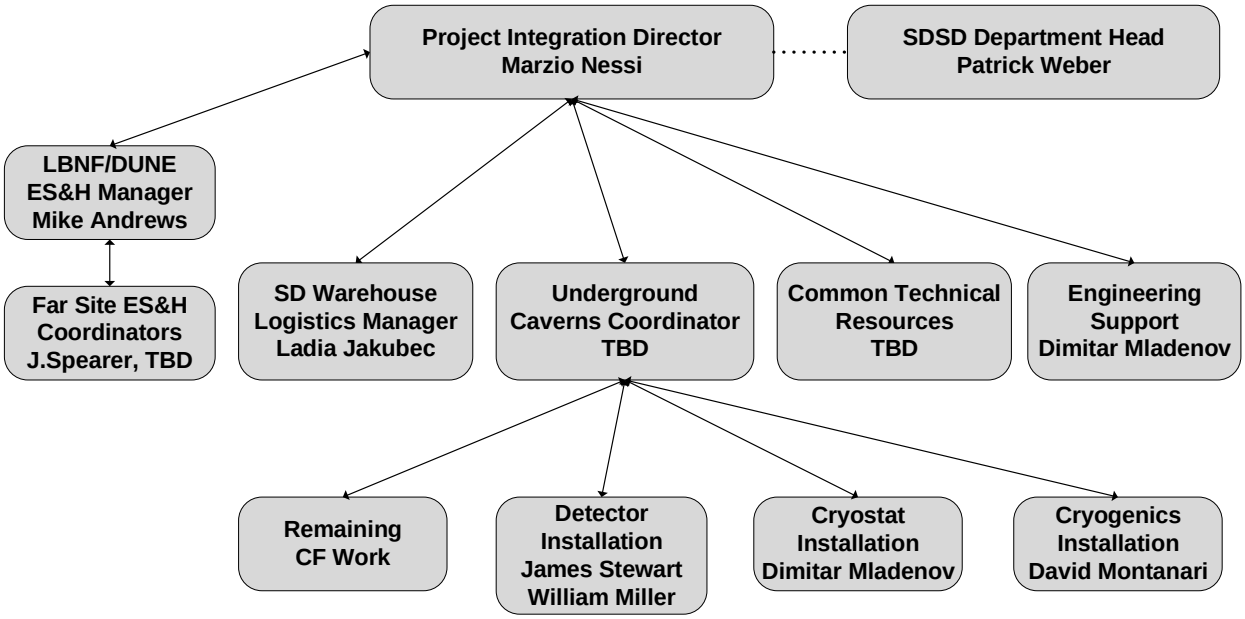


Figure 1.5: Integration office installation team organization chart

The full on-site integration office team includes rigging teams responsible for moving materials in and out of the shaft, through the underground drifts, and within the detector caverns, and personnel responsible for overseeing safety and logistics planning.

The underground caverns coordinator is responsible for managing all activities in the two underground detector caverns and the central utility cavern (CUC). The detector installation teams, distinct from the integration office installation team, incorporate a substantial number of scientific and technical personnel from the DUNE consortia. Integration office coordinators of the detector installation effort are jointly placed within DUNE technical coordination to facilitate consortia

involvement in detector installation activities. Any modifications to the facilities occurring after AUP are managed by the underground cavern coordinator under the direction of the project integration director.

The LBNF/DUNE ES&H manager heads the on-site safety organization and reports to the project integration director to support the execution of this responsibility. The far site ES&H coordinators oversee the day-to-day execution of the installation work.

1.4 Facility Description

The DUNE underground campus at the SURF 4850L is shown in Figures **??** and 1.6. The primary path for both personnel and material access to the underground excavations is through the Ross Shaft.

LBNF will provide facilities and services, on the surface and underground, to support the DUNE FD. This includes logistical, cryogenics, electrical, mechanical, cyber, and environmental facilities and services. All of these facilities are provided for the safe and productive operation of the detector modules.

On the surface, a new compressor building is being constructed adjacent to the Ross headframe. This building will house the cryogenics systems for receiving cryogenic fluids and preparing them for delivery down the Ross Shaft. New piping is being installed down the shaft compartment to transport gaseous argon (GAr) and nitrogen underground where they will be reliquefied.

Two large detector caverns are being excavated. Each of these caverns will support two 17.5 kt-capacity cryostats. The caverns, labeled north and south, are 144.5 m long, 19.8 m wide, and 28.0 m high. The tops of the cryostats are approximately aligned with the 4850L of SURF, with the bottoms resting at the 4910L. A 12 m space between the cryostats will be used for the detector installation process, for placement of cryogenic pumps and valves, and for access to the 4910L. The CUC, between the north and south caverns, is 190 m long, 19.3 m wide, and 10.95 m high.

The South Dakota Warehouse Facility (SDWF) is planned as a leased 5000 m^2 facility, hosted by SDSD, to be located within a maximum one-day roundtrip of SURF. It must be in place for receiving cryostat and detector components approximately six months before AUP of the underground detector caverns is received. Laydown space near the Ross headframe is extremely limited. For this reason, the transportation of materials from the SDWF to the top of the Ross shaft requires careful coordination. The LBNF/DUNE logistics manager works with the construction manager/general contractor (CMGC) through the end of excavation activities and with other members of the integration office team to coordinate transport of materials into the underground areas. Since no detector materials or equipment can be shipped directly to SURF, the SDWF will be used for both short- and long-term storage, as well as for any re-packaging of items required prior to transport into the underground areas.

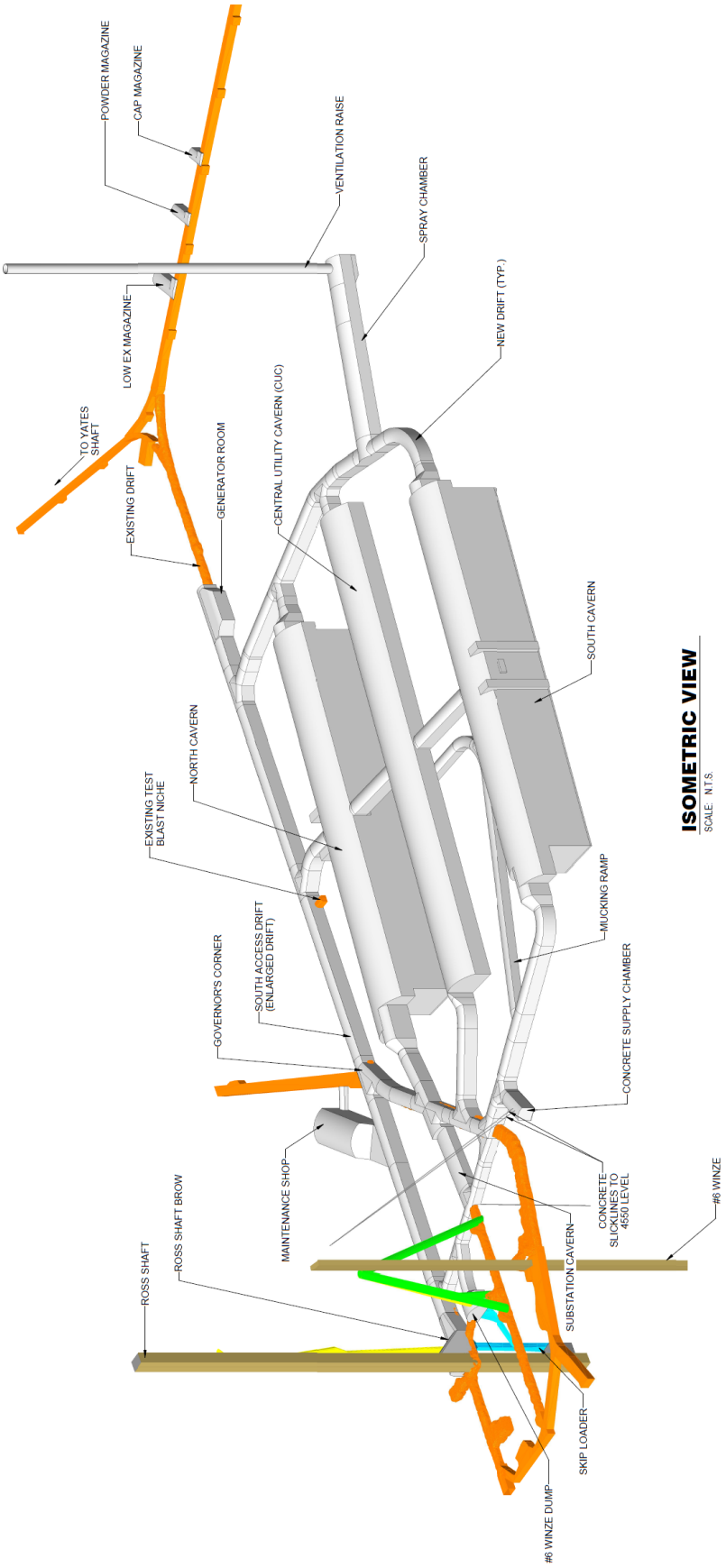


Figure 1.6: Underground campus at the 4850L.

1.5 Far Detector Construction Management

Eleven FD consortia have been formed to cover the subsystems required for the single-phase (SP) and dual-phase (DP) detector technologies (Figure 1.7). Three consortia (SP-APA, SP-TPC Electronics and SP-Photon Detection) pursue subsystems specific to the SP design and another three consortia (DP-CRP, DP-TPC Electronics, and DP-Photon Detection) pursue designs for DP-specific subsystems. Five consortia (HV System, data acquisition (DAQ), cryogenic instrumentation and slow controls (CISC), Calibration, and Computing) have responsibility for subsystems common to both detector technologies.

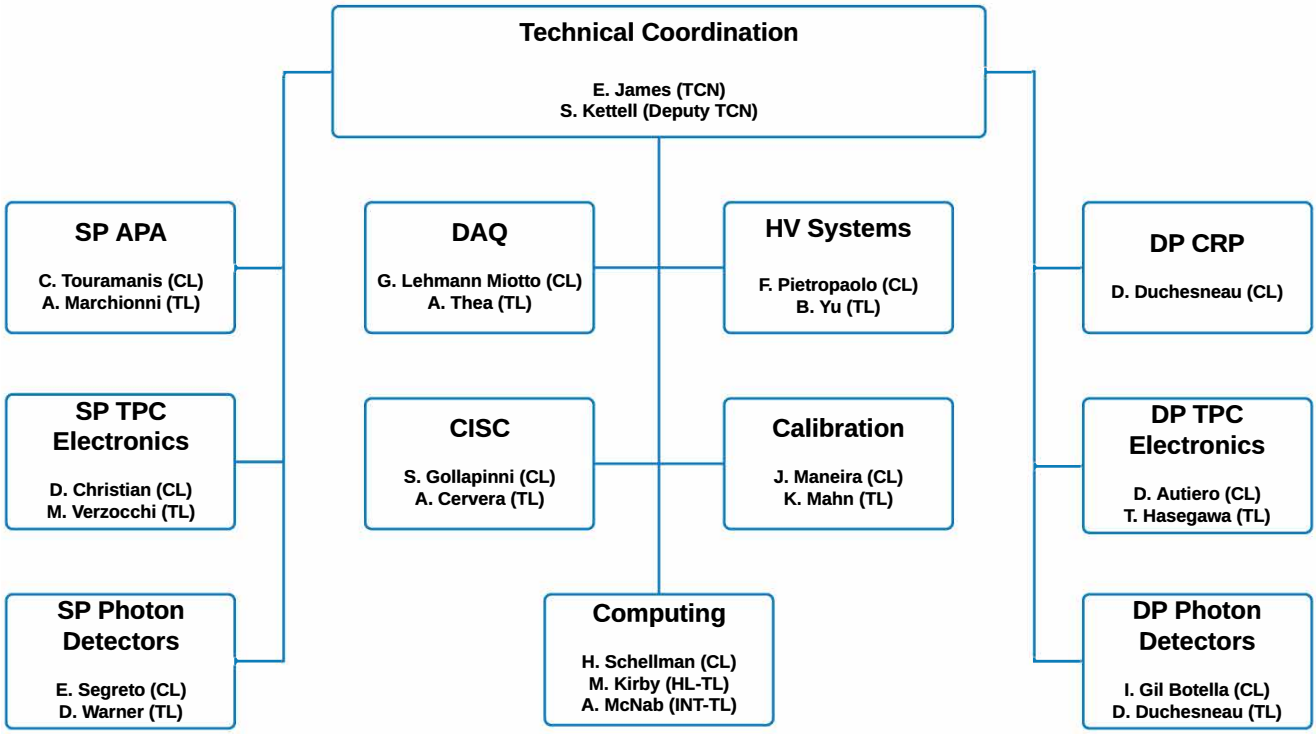


Figure 1.7: Consortia associated with the FD construction effort along with their current leadership teams. CL refers to consortium leader and TL refers to technical lead.

The complete scope of the DUNE construction project is captured in a work breakdown structure (WBS) to define and document the distribution of deliverables among the consortia. In combination with interface documentation, the WBS is used to validate that all necessary scope is covered. The WBS is also used as a framework for building DUNE detector cost estimates.

The highest-level layers of the DUNE WBS are summarized in Figure 1.8. At level 1 the WBS is broken down into six elements, which correspond to technical coordination (TC in the figure), four FD modules, and a near detector (ND). The scope documented in this technical design report (TDR) is fully contained within the elements of level-1 items 1 through 3, the technical coordination, a SP FD module, and a DP FD module.

WBS	WBS name
	DUNE
1	DUNE Technical Coordination (TC)
2	Single Phase Far Detector (DUNE-SP)
2.1	SP Installation (SP-Install)
2.2	SP Anode Plane Assemblies (SP-APA)
2.3	SP TPC Electronics (SP-ELE)
2.4	SP Photon Detection System (SP-PD)
2.8	High Voltage System (SP-HVS)
2.9	DAQ (SP-DAQ)
2.10	Cryogenic Instrumentation & Slow Control (SP-CISC)
2.11	Calibration (SP-CAL)
3	Dual Phase Far Detector (DUNE-DP)
3.1	DP Installation (DP-Install)
3.5	Charge Readout Plane (DP-CRP)
3.6	DP TPC Electronics (DP-ELE)
3.7	DP Photon Detection System (DP-PD)
3.8	High Voltage System (DP-HVS)
3.9	DAQ (DP-DAQ)
3.10	Cryogenic Instrumentation & Slow Control (DP-CISC)
3.11	Calibration (DP-CAL)
4	Reserved for future far detectors
5	Reserved for future far detectors
6	Reserved for near detector

Figure 1.8: High level DUNE WBS to level 2.

1.6 Integration Engineering

Integration engineering for DUNE encompasses three principal focus areas. First, it covers configuration of the mechanical and electrical systems of each detector module and management of the interfaces within them; this includes verifying that subassemblies and their interfaces conform to the approved design of each detector element. A second area is assurance that the detector modules can be integrated and installed into their final configurations. Third, it covers integration of the necessary services provided by FSCF with the detector modules. The overall effort involves the JPO engineering team, who maintains subsystem component documentation for detector configuration management, and the consortia, who provide engineering data for their detector subsystems to the JPO team for incorporation into the global configuration files.

An integration mechanism has been developed to manage and create an overall model of interfaces both within a detector module and between a detector module and facilities. The mechanism defines integration nodes, between which the JPO engineering team carries out and manages interfaces. Figure 1.9 shows the interfaces and nodes between a detector module and the facilities it requires. The JPO engineering team also ensures that the interfaces are appropriately defined and managed for the DAQ room in the CUC and the surface control and network rooms. Interfaces with LBNF are managed at the boundaries of each integration node. Interface documents are developed and maintained to manage the interfaces between consortia and between each consortium and LBNF.

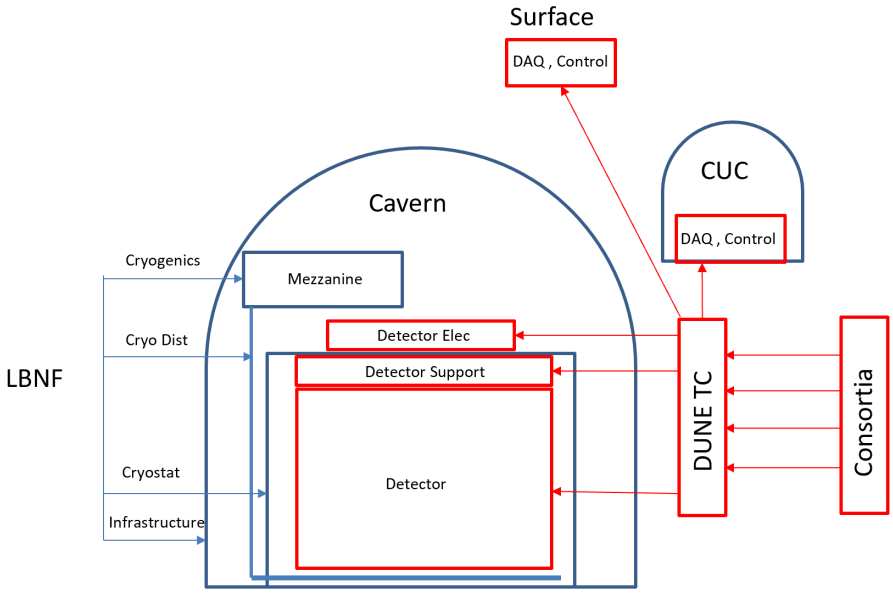


Figure 1.9: Overall integration nodes and interfaces. The items provided by LBNF within the cavern are shown on the left and the items provided by DUNE are on the right.

1.7 Reviews

The integration office and technical coordination review all stages of detector development and work with each consortium to arrange reviews of the design (conceptual design review, preliminary design review and final design review), production (production readiness review and production progress review), installation (installation readiness review), and operation (operational readiness review) of their system. The reviews are organized by the JPO review office. These reviews provide information to the technical board (TB), EB, and EFIG in evaluating technical decisions.

Review reports are tracked by the JPO review office and technical coordination and provide guidance on key issues that require engineering oversight by the JPO engineering team. The review office maintains a calendar of DUNE reviews.

1.8 Quality Assurance

DUNE technical coordination monitors technical contributions from collaborating institutions and provides centralized project coordination functions. One part of this project coordination is standardizing quality assurance (QA)/quality control (QC) practices, a facet of which is to assist consortia in defining and implementing QA/QC plans that maintain uniform, high standards across the entire detector construction effort. Figure 1.10 shows how DUNE technical coordination derives its QA program from the principles of the Fermilab QA program: requirements flow down through the LBNF/DUNE QA program into the QC plans developed for consortium fabrication of detector components and integration and installation of the detector.

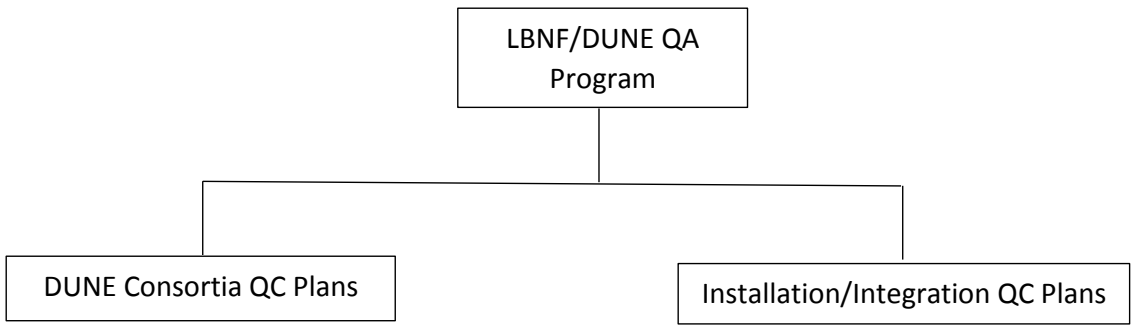


Figure 1.10: Flow-down of Fermilab QA to consortia

The QA effort includes design, production readiness, and progress reviews as appropriate for the DUNE detector subsystems, as was done for ProtoDUNE-SP under technical coordination oversight.

The primary objective of the LBNF/DUNE QA program is to assure quality in the construction of the LBNF facility and DUNE experiment while providing protection of LBNF/DUNE personnel, the public, and the environment. The QA plan aligns LBNF/DUNE QA activities, which are spread around the world, with the principles of the Fermilab Quality Assurance Manual. The

manual identifies the Fermilab Integrated Quality Assurance Program features that serve as the basis for the LBNF/DUNE QA plan.

A key element of the LBNF/DUNE QA plan is the concept of graded approach; that is, applying a level of analysis, controls, and documentation commensurate with the potential for an environmental, safety, health, or quality impact. To promote continuous improvement, DUNE technical coordination will develop a lessons learned program based on the Fermilab Office of Project Support Services lessons learned program.

The QA plan defines the QA roles and responsibilities of the DUNE project. The DUNE consortium leaders are responsible for identifying the resources to ensure that their team members are adequately trained and qualified to perform their assigned work. All consortium members are responsible for the quality of the work that they do and for using guidance and assistance that is available. All have the authority to stop work and report adverse conditions that affect quality of DUNE products to their respective DUNE consortium leader and the LBNF/DUNE QA manager.

1.9 Environment, Safety, and Health

LBNF/DUNE is committed to protecting the health and safety of staff, the community, and the environment, as stated in the LBNF/DUNE integrated ES&H plan [1].

The LBNF/DUNE ES&H program complies with applicable standards and local, state, federal, and international legal requirements through the Fermilab Work Smart set of standards and the contract between Fermi Research Alliance (FRA) and the DOE Office of Science (FRA-DOE). Fermilab, as the host laboratory, established the SDSD to provide facility support. SDSD is responsible for support of LBNF/DUNE operations at SURF.

The TC and project integration director have responsibility for implementation of the DUNE ES&H program for the construction and installation activities, respectively. The LBNF/DUNE ES&H manager reports to the TC and project integration director and is responsible for providing ES&H support and oversight for development and implementation of the LBNF/DUNE ES&H program.

The DUNE ES&H coordinator reports to the LBNF/DUNE ES&H manager and has primary responsibility for ES&H support and oversight of the DUNE ES&H program for activities at collaborating institutions. The far and near site ES&H coordinators are responsible for providing daily field support and oversight for all installation activities at the SURF and Fermilab sites.

The LBNF/DUNE ES&H plan defines the ES&H requirements applicable to installation activities at the SURF site. A key element of an effective ES&H program is the hazard identification process. Hazard identification allows production of a list of hazards within a facility, so these hazards can be screened and managed through a suitable set of controls. All work activities are subject to work planning and hazard analysis (HA). All work planning documentation is reviewed and approved by the DUNE ES&H coordinator and the DUNE installation readiness review or operational readiness

review committees prior to the start of work activities.

A Safety Data Sheet (SDS) will be available for all chemicals and hazardous materials that are used on-site. All chemicals and hazardous materials brought to the SURF site must be reviewed and approved by the DUNE ES&H coordinator and the SURF ES&H department before arriving at the site.

South Dakota Science and Technology Authority (SDSTA) will maintain an emergency response incident command system and an emergency response team (ERT) on all shifts that can access the underground sites with normal surface fire department response times. This team provides multiple response capabilities for both surface and underground emergencies.

Fire and life safety requirements for LBNF/DUNE areas were analyzed in the LBNF/DUNE Far Site Fire and Life Safety Assessment. All caverns will be equipped with fire detection and suppression systems, with both visual and audible notification. All fire alarms and system supervisory signals will be monitored in the SURF Incident Command Center. The SURF ERT will respond with additional support from the Lead and Deadwood Fire Departments and the county's emergency management department. The caverns will be equipped with an oxygen deficiency hazard (ODH) monitoring and alarm system, with independent visual and audible notification systems.

All workers on the DUNE project have the authority to stop work in any situation that presents an imminent threat to safety, health, or the environment. Work may not resume until the circumstances are investigated and the deficiencies corrected, including the concurrence of the DUNE project integration director and LBNF/DUNE ES&H manager.

Glossary

4850L The depth in feet (1480 m) of the top of the cryostats underground at SURF; used more generally to refer to the DUNE underground area. Called the "4850 level" or "4850L". 10, 11

acceptance for use and possession (AUP) Required for beneficial occupancy of the underground areas at SURF for LBNF and DUNE. 4, 10

conventional facilities (CF) Pertaining to construction and operation of buildings and conventional infrastructure, and for LBNF and DUNE project (LBNF/DUNE), CF includes the excavation caverns. 3

cryogenic instrumentation and slow controls (CISC) Includes equipment to monitor all detector components and liquid argon (LAr) quality and behavior, and provides a control system for many of the detector components. 12

construction manager/general contractor (CMGC) The organizational unit responsible for management of the construction of conventional facilities at the underground area at the SURF site. 10

conceptual design review A project management device by which a conceptual design is reviewed. 15

central utility cavern (CUC) The utility cavern at the 4850L of Sanford Underground Research Facility (SURF) located between the two detector caverns. It contains utilities such as central cryogenics and other systems, and the underground data center and control room. 9, 10, 14

data acquisition (DAQ) The data acquisition system accepts data from the detector front-end (FE) electronics, buffers the data, performs a trigger decision, builds events from the selected data and delivers the result to the offline secondary DAQ buffer. 12, 14

detector module The entire DUNE far detector is segmented into four modules, each with a nominal 10 kt fiducial mass. 10, 14

DOE U.S. Department of Energy. 6, 16

dual-phase (DP) Distinguishes one of the DUNE far detector technologies by the fact that it operates using argon in both gas and liquid phases. 12

Deep Underground Neutrino Experiment (DUNE) A leading-edge, international experiment for neutrino science and proton decay studies. 2–10, 12–17

executive board (EB) The highest level DUNE decision-making body for the collaboration. 3, 7, 15

Experimental Facilities Interface Group (EFIG) The body responsible for the required high-level coordination between the Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) projects. 4, 15

ERT emergency response team. 17

environment, safety and health (ES&H) A discipline and specialty that studies and implements practical aspects of environmental protection and safety at work. 2, 5, 8, 10, 16, 17

earned value management system (EVMS) Earned Value Management is a systematic approach to the integration and measurement of cost, schedule, and technical (scope) accomplishments on a project or task. It provides both the government and contractors the ability to examine detailed schedule information, critical program and technical milestones, and cost data (text from the US DOE); the EVMS is a system that implements this approach. 6

far detector (FD) The 70 kt total (40 kt fiducial) mass liquid argon time-projection chamber (LArTPC) DUNE detector, composed of four 17.5 kt total (10 kt fiducial) mass modules, to be installed at the far site at SURF in Lead, SD, USA. 2, 3, 7, 10, 12

Fermi National Accelerator Laboratory (Fermilab) U.S. national laboratory in Batavia, IL. It is the laboratory that hosts DUNE and serves as its near site. 3, 5, 15, 16

final design review A project management device by which a final design is reviewed. 15

Fermi Research Alliance (FRA) A joint partnership of the University of Chicago and the Universities Research Association (URA) that manages and operates Fermilab on behalf of the DOE. 16

far site conventional facilities (FSCF) The conventional facilities (CF) at the DUNE far detector site, SURF. 4, 6, 7, 14

gaseous argon (GAr) argon in its gas phase. 10

hazard analysis (HA) A first step in a process to assess risk; the result of hazard analysis is the identification of the hazards present for a task or process. 16

installation readiness review A project management device by which the plan for installation is reviewed. 15, 16

integration office The office that incorporates the onsite team responsible for coordinating integration and installation activities at SURF. 2, 4, 5, 8–10, 15

Joint Project Office (JPO) The framework through which team members from the LBNF project office, integration office, and DUNE technical coordination work together to provide coherence in project support functions across the global enterprise. Its functions include global project configuration and integration, installation planning and coordination, scheduling, safety assurance, technical review planning and oversight, development of partner agreements, and financial reporting. 2–6, 14, 15

Long-Baseline Neutrino Facility (LBNF) The organizational entity responsible for developing the neutrino beam, the cryostats and cryogenics systems, and the conventional facilities for DUNE. 3–7, 9, 10, 14, 15

LBNF and DUNE project (LBNF/DUNE) The overall global project, including LBNF and DUNE. 2–10, 15–17

memorandum of understanding (MoU) A document summarizing an agreement between two or more parties. 6

near detector (ND) Refers to the detector(s) installed close to the neutrino source at Fermilab. 12

oxygen deficiency hazard (ODH) a hazard that occurs when inert gases such as nitrogen, helium, or argon displace room air and thus reduce the percentage of oxygen below the level required for human life. 17

operational readiness review A project management device by which the operational readiness is reviewed. 15, 16

preliminary design review A project management device by which an early design is reviewed. 15

production progress review A project management device by which the progress of production is reviewed. 15

production readiness review A project management device by which the production readiness is reviewed. 15

project integration director Responsible for integration and installation of LBNF and DUNE deliverables in South Dakota. Manages the integration office. 2, 3, 5, 9, 10, 16, 17

ProtoDUNE Either of the two DUNE prototype detectors constructed at European Organization for Nuclear Research (CERN). One prototype implements single-phase (SP) technology and the other dual-phase (DP). 5

ProtoDUNE-SP The SP ProtoDUNE detector at CERN. 15

quality assurance (QA) The set of actions taken to provide confidence that quality requirements are fulfilled, and to detect and correct poor results. 2, 7, 8, 15, 16

quality control (QC) An aggregate of activities (such as design analysis and inspection for defects) performed to ensure adequate quality in manufactured products. 8, 15

resource coordinator (RC) A member of the DUNE management team responsible for coordinating the financial resources of the project effort. 7

review office An office within the integration office that organizes reviews. 15

Fermilab South Dakota Services Division (SDSD) A Fermilab division responsible providing host laboratory functions at SURF in South Dakota. 3, 10, 16

South Dakota Science and Technology Authority (SDSTA) The legal entity that manages SURF, in Lead, S.D. 17

South Dakota Warehouse Facility (SDWF) Warehousing operations in South Dakota responsible for receiving LBNF and DUNE goods and coordinating shipments to the Ross shaft at SURF. 10

single-phase (SP) Distinguishes one of the DUNE far detector technologies by the fact that it operates using argon in its liquid phase only. 12

Sanford Underground Research Facility (SURF) The laboratory in South Dakota where the LBNF far site conventional facilities (FSCF) will be constructed and the DUNE far detector (FD) will be installed and operated. 2, 4–10, 16, 17

technical board (TB) The DUNE organization responsible for evaluating technical decisions. 15

technical coordinator (TC) A member of the DUNE management team responsible for organizing the technical aspects of the project effort; is head of technical coordination. 2, 5, 7, 16

technical design report (TDR) A formal project document that describes the experiment at a technical level. 12

technical coordination The DUNE organization responsible for overall integration of the detector elements and successful execution of the detector construction project; areas of responsibility

include general project oversight, systems engineering, quality assurance (QA) and safety. 2, 4, 7–9, 12, 15, 16

work breakdown structure (WBS) An organizational project management tool by which the tasks to be performed are partitioned in a hierarchical manner. 12, 13

References

[1] M. Andrews, "Integrated Environment, Safety and Health Management Plan," DUNE doc 291, 2016. https://docs.dunescience.org/cgi-bin/private/ShowDocument?docid=291&asof=2019-11-1.