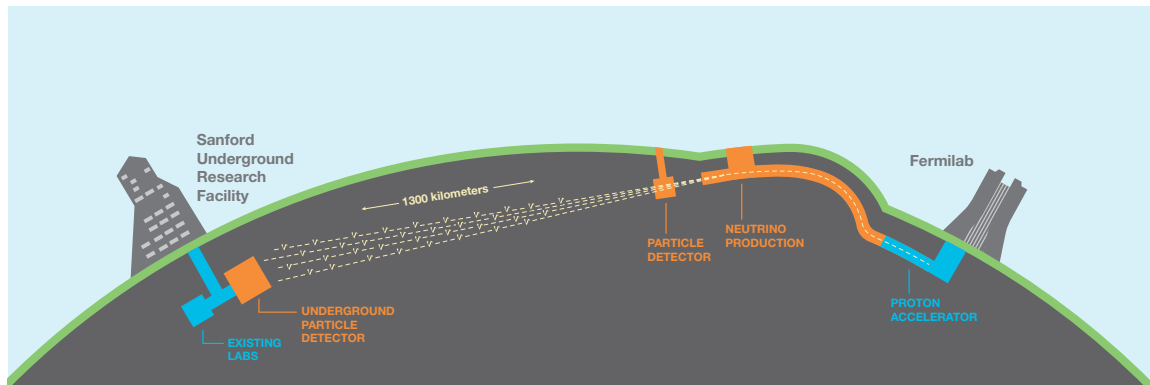


DUNE: Construction Scoping Proposal



DUNE-UK

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1. Context

The Long-Baseline Neutrino Facility (LBNF) will be the world's most intense high-energy neutrino beam. It will fire neutrinos 1300 km from Fermilab in Illinois towards the 68 kt Deep Underground Neutrino Experiment (DUNE) in South Dakota in order to study neutrino oscillations. The DUNE far detector will consist of four vast liquid argon time projection chambers (LAr TPCs), each with an argon mass of 17 kt (approximately 11 kt fiducial mass). DUNE will be the first large-scale US-hosted experiment run as a truly international project. It has broad support from the particle physics community in the US and Europe, with growing interest in developing countries. DUNE currently has almost 940 collaborators from 164 institutions in 30 nations. The highest-level milestones through the ten-year construction period are:

- **2017:** start of construction at the Sanford Underground Research Facility, South Dakota;
- **2018:** operation of the two large-scale “protoDUNE” engineering prototypes at CERN;
- **2020:** start of far detector construction;
- **2024:** start of (non-beam) science exploitation with the first 17 kt far detector module;
- **2026:** start of 1.2 MW beam operation with the first two 17 kt far detector modules.

LBNF/DUNE is now an approved project in the US and the US DOE has legal authority to commit \$300M for construction of the underground far detector facility in South Dakota, starting in US FY17. DUNE represents a major scientific opportunity. The UK particle physics community has responded to this opportunity, with DUNE-UK now numbering over 120 scientists and engineers; forty UK academics from sixteen UK institutes are signatories to this construction scoping proposal.

DUNE-UK has a clear plan for a leading UK participation in the construction of the DUNE far detector. To execute the full scope of this plan will require a UK core capital contribution of £25-30M from the BEIS long-term fund for science capital investment. Although not part of this scoping proposal, a similar level of investment in the LBNF accelerator complex (PIP-II) and the neutrino beam is being pursued.

2. Objectives

The intended outcomes of the DUNE-UK construction proposal are:

- Delivery and installation of 150 out of the 300 anode plane assemblies (APAs) required for the first two DUNE 17 kt far detector modules, which will be commissioned in 2024 and 2026. The remainder of the APAs will be constructed in the US (and possibly Italy).
- Delivery and commissioning of the UK-led data acquisition (DAQ) system for the first two 17 kt far detector modules. This proposal assumes that the UK will take responsibility for the majority of the back-end system.
- Continued UK leadership within the DUNE collaboration.
- UK access to the DUNE data and subsequent scientific exploitation.

3. Project Description

DUNE-UK has pursued a clear strategy for a UK contribution to DUNE, focussed on four key areas: i) scientific exploitation; ii) the development of the critical LAr-TPC automated reconstruction software; iii) a major UK contribution to the far detector DAQ system; and iv) the UK becoming one of the main sites for the construction of the large-scale readout wire planes (APAs) that lie at the heart of the far detector LAr-TPC. This strategy places the UK at the centre of the far detector physics programme: from collection of the ionisation signals in the liquid argon, to data read out, event reconstruction and ultimately data exploitation. This strategy underpins the existing DUNE-UK preparatory-phase grant

(October 2014 – September 2017). In 2016, this plan was reinforced by a capital grant (April 2016 – March 2018) for a UK contribution to the large ($8\times 8\times 8\text{ m}^3$) protoDUNE-SP prototype LAr-TPC at CERN (construction of three of the six APAs and a contribution to the DAQ system). The DUNE-UK pre-construction proposal (October 2017 – September 2019) follows this strategy, focussing on: pre-construction work for the APAs and DAQ and maintaining UK scientific leadership. The pre-construction proposal would allow the UK to move into the construction phase in late 2019, with components of the far detector starting to be produced in 2020.

The construction-phase proposal would comprise four main activities and support for computing:

- **Scientific leadership:** with the aim of retaining UK scientific leadership. This activity builds on the world-leading UK-led VALOR approach to the propagation of constraints on cross section and flux systematic uncertainties (from the near detector) to the oscillation fits to far detector data. Estimated project resources: 4 FTEs for the duration of the project.
- **Advanced reconstruction software:** with the aim of retaining UK leadership of the critical LAr-TPC reconstruction software. This activity builds on the UK-led world-leading Pandora reconstruction development (now used by the MicroBooNE experiment). Bringing this to production-readiness requires further development and optimisation. Estimated project resources: 4 FTEs for the duration of the project.
- **DAQ construction:** with the UK being the lead nation in the back-end DAQ system. This work exploits UK world-leading experience from ATLAS, CMS and T2K. Estimated project resources: a capital investment of £10M and 50 FTE-years of additional staff effort.
- **APA construction:** with the UK providing half of the APAs for the first two 17 kt far detector modules. This work exploits UK expertise developed from the construction of half of the APAs for the SBND and protoDUNE-SP detectors (ongoing work as part of the DUNE-UK preparatory-phase and protoDUNE grants). Estimated project resources: a capital investment of £20M and 25 FTE-years of (non-capital) staff effort.
- **Computing:** to provide grid- or cloud-based computing support to develop the software infrastructure to enable and support UK-based analysis of the large LAr-TPC data samples produced by the DUNE far detector modules. This work exploits existing UK leadership in Grid computing for the LHC experiments. Estimated project resources: 2 FTEs for the duration of the project.

4. Strategic Fit

The STFC 2013 Programmatic Review recognised the progress in neutrino physics, but noted that several key science questions remain. These crucial open questions include: i) are neutrinos Majorana or Dirac particles; ii) what is the absolute scale of neutrino masses; iii) what is the neutrino mass hierarchy (MH); and iv) is CP violated in the leptonic sector? In particular, the observation of CP violation in neutrino oscillations would represent a breakthrough discovery with a possible connection to the matter-antimatter asymmetry in the Universe through a process known as leptogenesis. The strategic importance of the future long-baseline neutrino programme was endorsed by STFC's Science Board through the approval of the existing DUNE-UK preparatory-phase and protoDUNE grants.

The proposed activities will eventually address the following core questions in STFC's scientific roadmap:

- C1: What are the fundamental particles?
- C3: Is there a unified framework?
- C7: What is the origin of the matter anti-matter asymmetry?
- D1: How do the laws of physics work when driven to the extremes?

5. Awareness and Context

DUNE has strong support in the UK particle physics community. Forty UK academics from sixteen institutions are part of DUNE-UK, with almost all major UK experimental particle physics groups represented. DUNE-UK is supported by two current STFC grants (preparatory phase and protoDUNE) with a total value of £3.0M. Two related PRD proposals have also been awarded: development of the MicroBooNE reconstruction software and the prototyping a GAr-TPC that represents a possible route to the DUNE near detector. UK physicists are also playing central roles in the MicroBooNE (running) and SBND (construction-phase) experiments. Involvement in these 100 t-scale LAr-TPC detectors at Fermilab has enabled UK scientists to gain crucial experience with the operation, analysis and construction of detectors using the LAr-TPC technology.

There is strong global support for LBNF/DUNE. The collaboration currently consists of almost 940 scientists and engineers from 164 institutions in 30 nations. The most recent survey of effort (six months ago) indicated that the total level of effort was equivalent to 220 FTEs. The US DOE has a funding profile for LBNF/DUNE with a total project cost of \$1.5B. The plans for the \$300M far site construction costs were given CD-3A approval in September 2016. India has committed \$100M in in-kind contributions to the PIP-II linac, which is the source of protons for the LBNF beam line. Investment in PIP-II and DUNE is currently being considered by Italy. Requests for R&D and construction funds are being pursued elsewhere in Europe and in Latin America.

Support for a long-baseline neutrino programme hosted outside Europe was identified as a key component of the 2013 European Strategy for High-Energy physics. CERN is pursuing this strategy and is a major partner in LBNF and DUNE. The CERN Medium-Term Plan (MTP) includes commitments to provide: i) strong support to the DUNE prototyping programme through the infrastructure at the CERN neutrino platform and ii) the cryostat for the first 17 kt far detector module – the first time CERN will have invested in an experiment outside CERN. The financial investment in the CERN neutrino platform includes the EHN1 building extension, two new tertiary charged-particle beam-lines and two $8 \times 8 \times 8 \text{ m}^3$ cryostats (and associated cryogenic infrastructure) for the large-scale DUNE prototype detectors. Although the CERN neutrino platform also covers other activities, the vast majority of the resources support LBNF/DUNE.

6. Competition

DUNE will undertake a game-changing programme of neutrino physics, making precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. The highest-level scientific goals are:

- Discovery and measurements of neutrino CP violation. DUNE has $>3\sigma$ discovery coverage for 75% of δ_{CP} values. In favourable regions of parameter space, 3σ (5σ) sensitivity can be reached with 3–4 (6–7) years of operation. Ultimately, δ_{CP} can be measured with a precision of between $6\text{--}9^\circ$ (depending on the angle itself), starting to approach the current level for the CP violating angle in the quark sector.
- Precision neutrino physics, including the definitive determination of the mass hierarchy. Because of the very long baseline, DUNE reaches 5σ MH sensitivity within 2–5 years (depending on the values of other parameters).
- Search for new physics beyond the current understanding of neutrino oscillations. The long baseline and the wide-band neutrino beam will enable DUNE to test the current three-flavour paradigm of neutrino oscillations, providing unique sensitivity to non-standard neutrino interactions and sterile neutrinos.

- Observation of the electron neutrino burst from a galactic core-collapse supernova. Unlike in water Čerenkov or liquid scintillator detectors, the main sensitivity in a liquid argon detector is to ν_e (rather than $\bar{\nu}_e$), providing a real-time probe of electron neutrino burst from the initial stage of the neutron star formation phase ($p + e^- \rightarrow n + \nu_e$).
- Search for proton decay. Nucleon decay is expected in most models of new physics but has yet to be observed. A large LAr TPC provides an almost background-free search for many proton decay modes, including decay modes with kaons. For example, DUNE will improve the sensitivity to the SUSY-favoured decay $p \rightarrow K^+ \bar{\nu}_\tau$ by almost an order of magnitude.

6.1 Competing Experiments

Comparing projects at different stages in development is difficult due to potentially large uncertainties in ultimate scope, schedule and any assumptions used in projecting sensitivities. There are several experiments (running, proposed or construction phase) with some potential overlap with the DUNE scientific programme:

- T2K & NOvA: recent results from the T2K and NOvA experiments favour the normal hierarchy with $\delta_{CP} \sim \pi/2$, however, the uncertainties are still very large. Even in optimistic scenarios, the combination of NOvA and T2K-II (the proposed T2K upgrade) might not reach the 3σ level for CP violation and will not approach a 5σ determination of the mass hierarchy.
- JUNO: the Jiangmen Underground Neutrino Observatory (JUNO) is currently being constructed in China. It consists of a 20 kt liquid scintillator detector. JUNO aims to measure the mass hierarchy. Data taking is planned to start in 2020 with a 10 year initial operation. The claimed sensitivity for determining the mass hierarchy is just over 3σ after running for six years. Reaching this sensitivity relies on JUNO achieving its very challenging goal for energy resolution. JUNO is also sensitive to supernova burst neutrinos, primarily $\bar{\nu}_e$ through the inverse beta decay process, which would be complementary to the ν_e measurements from DUNE.
- Hyper-Kamiokande: Hyper-K is a proposed off-axis beam neutrino experiment with a baseline of 295 km. In its most recent configuration, it will consist of two 260 kt water Čerenkov detectors. If it were approved in 2017, Hyper-K would aim to start operation with the first tank in 2026, with the second operational 6 years later. Neutrino oscillation sensitivities assume a 1.3 MW beam from J-PARC – a significant step up from the current operation at 450 kW. With 10 years of operation, Hyper-K can measure δ_{CP} with a precision of $\pm 7^\circ$ ($\pm 20^\circ$) for $\delta_{CP} = 0^\circ$ ($\delta_{CP} = 90^\circ$). The corresponding numbers for 10 years of DUNE operation, with the planned detector staging, are $\pm 7^\circ$ ($\pm 13^\circ$) for $\delta_{CP} = 0^\circ$ ($\delta_{CP} = 90^\circ$). Hyper-K can reach 5σ mass hierarchy sensitivity with between 5–10 years of *atmospheric* neutrino data. Because of the longer baseline, the DUNE *beam* neutrino data will provide a 5σ determination of the mass hierarchy in just 2–5 years. The DUNE and Hyper-K programmes for supernova neutrinos are complementary with Hyper-K having sensitivity to $\bar{\nu}_e$, whereas DUNE is primarily sensitive to ν_e . The situation is similar for proton decay, with the Hyper-K having best sensitivity for final states with light particles, such as $p \rightarrow e^+ \pi^0$, whereas DUNE is most sensitive to SUSY-favoured decays, such as $p \rightarrow K^+ \bar{\nu}_\tau$.
- PINGU: which is part of the proposed IceCube-GEN2 upgrade, would focus on ν_τ appearance and the mass hierarchy but is not sensitive to CP violation. About 3 – 4 years of PINGU data are required to reach 3σ MH sensitivity. However, at this stage it is not clear whether PINGU will be funded and the timescales are uncertain.
- ORCA: could provide sensitivity to the mass hierarchy similar to that of PINGU. A first ORCA string has recently been deployed in the Mediterranean but funding and timescales are uncertain.

6.2 Particular strengths of LBNF/DUNE

LBNF/DUNE is an approved programme with a well-defined funding profile. The project has been extensively reviewed in the US by a series of external expert panels; at this point in time, costs, risks and the schedule are well understood. The particular strengths of LBNF/DUNE are:

- Fermilab has a strong track record in meeting neutrino beam power goals. The NuMI beam for NOvA reached 600 kW this year and 700 kW operation is planned for 2017. Based on this experience, there is confidence that, with the PIP-II upgrade of the Fermilab accelerator complex, LBNF will be able to achieve (or exceed) the goal of 1.2 MW operation.
- The wide-band LBNF beam and the long baseline of 1300 km make DUNE particularly sensitive to BSM effects such as neutrino non-standard interactions; no other planned long-baseline experiment comes close in terms of sensitivity.
- By measuring the neutrino oscillation energy spectrum (appearance and disappearance) in a wide-band beam, DUNE is able to simultaneously extract the parameters governing neutrino oscillations in a single experiment. This is unique to the DUNE scientific programme. Furthermore, if non-standard effects are present, the wide-band provides the potential to disentangle new physics from the measurement of the standard parameters governing neutrino oscillations.
- The LBNF beam is tunable, giving the possibility to study ν_τ appearance in future higher energy operation – the physics sensitivities are currently being studied.
- Unique sensitivity to the ν_e signature of the neutronisation phase from a core-collapse supernova.
- Almost background free searches for proton decay, with good sensitivity to modes with kaons.
- The LAr TPC is the ultimate technology for neutrino physics, providing bubble-chamber-like images of each neutrino interaction. The development of the large-scale DUNE LAr TPC opens up a new era in neutrino physics.

7. Track Record

A construction project of the scale being proposed here requires a large team with deep scientific and technical experience. DUNE-UK brings together world-leading UK experience from previous beam-based neutrino experiments including MicroBooNE, MINOS, NOvA and T2K. This expertise is complemented by the involvement of new groups bringing expertise from ATLAS, CMS and LHCb, particularly in the area of high-speed high-volume DAQ. The assembled team from sixteen UK institutes has the strength and depth necessary to successfully undertake a construction project of this scale.

A non-exhaustive list of previous leadership roles of academic staff on the proposed DUNE-UK project includes: **Andreopoulos** leads the GENIE neutrino interaction generator and the VALOR oscillation fit group; **Barker** played a leading role in the construction of the ECAL for the T2K near detector; **Barr** is the level-3 project manager for the DUNE DAQ system; **Clarke** is an internationally recognised expert in distributed grid computing; **Hartnell** holds an ERC grant that enabled the UK to play a major role in the NOvA experiment; **Newbold** leads the UK-CMS upgrade project and brings deep knowledge of high-speed DAQ/electronics; **Soldner-Remböld** was D0 spokesperson and currently leads the large-scale construction efforts for SuperNEMO wire-based tracking detector; **Spooner** has played leading roles in construction of dark matter detectors; **Thomson** is co-spokesperson of the DUNE collaboration and is a world-leading expert on advanced reconstruction software, he also led the UK ATLAS phase-1 upgrade FEX project; **Touramanis** led the UK construction contribution to the T2K ND280 detector, he is also the co-lead of the protoDUNE-SP prototype detector at CERN; **Waters** has been the UK PI for SuperNEMO; **Watson** has been a

leading figure in the ATLAS level-1 trigger project from its beginning; **Weber** is the PI of the DUNE preparatory-phase proposal and led the electronics work for MINOS and the T2K near detector.

The academic leadership is complemented by a strong engineering/project management team, who have taken leading roles in major detector construction projects, for example, **Cussans** has deep experience of the electronics and DAQ development for multiple experiments, **Grant** is a highly-experienced project engineer, who was responsible for the design and construction of the T2K ND280 detector, and **Preece** is a highly-experienced, internationally-recognised project manager.

8. Project Strategy

LBNF/DUNE has adopted the LHC model for the overall organisation and relationships between the facility (LBNF) and the experiment (DUNE). The US LBNF and DUNE projects have adopted the management tools used for all other major DOE projects. The resource-loaded schedule (RLS) is implemented in the primavera P6 project management system. The RLS is based on the well-defined DOE funding profile. The project is managed by the DUNE International Project Office. Non-US contributions, such as those from the UK, will be embedded in the P6 schedule by the DUNE International Project Office and tracked using a detailed set of milestones. The project management of the UK deliverables will be the responsibility of the UK project. Issues with funding or project deliverables at the national level and their impact on the international project will be resolved within the DUNE Resources Review Board (RRB) which meets twice yearly. The RRB will meet for the third time in November 2016.

8.1 DUNE-UK Project Organisation

The high-level DUNE-UK project management structure is described in the DUNE pre-construction proposal and is indicated in Figure 1. The intention is to build on this structure for the construction-phase proposal. At this stage, it is too early to provide names for the different management positions, but it is reasonable to assume that many of those named in WP0 of the pre-construction proposal will take leading roles in the construction project.

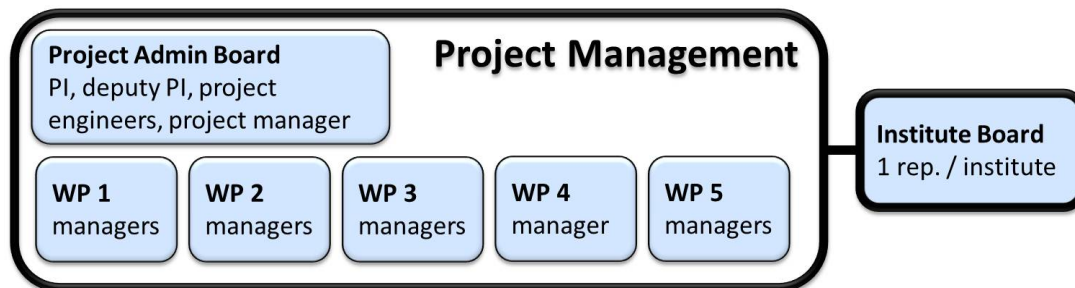


Figure 1: The DUNE-UK project management structure for the pre-construction proposal.

8.2 DUNE-UK WBS

In addition to project management (WP0), the high-level DUNE-UK WBS will be constructed around five work packages:

- **WP1:** DUNE science;
- **WP2:** Advanced LAr-TPC reconstruction software;
- **WP3:** Far Detector DAQ construction;
- **WP4:** Far Detector APA construction;
- **WP5:** DUNE Computing.

At this time, the detailed WBS elements below these top-level categories have not been finalised.

8.3 Major Milestone

The major milestones through the ten-year construction period are:

- **2017:** start of construction at SURF, South Dakota;
- **2018:** operation of the large-scale protoDUNE engineering prototypes at CERN;
- **2019:** provisional international resource matrix for DUNE construction;
- **2019:** technical design report (TDR) for the DUNE detectors (to be reviewed in Q3 2019);
- **2020:** start of production of far detector components;
- **2021:** start of installation the first 17 kt far detector module at SURF;
- **2024:** start of physics operation of the first 17 kt far detector module;
- **2026:** start of 1.2 MW beam operation with the first two 17 kt far detector modules.

9. Project Resources

Table 1 summarises the current estimate of the cost of the proposed UK DUNE construction project. In preparing this breakdown it is assumed that capital will be funded from the BEIS long-term science capital fund and not directly from the STFC allocation. The capital costs of the APAs and DAQ (which include capitalised engineering/technician effort) are based on the current best estimates from the DUNE international project. These estimates have been scrutinised as part of the DOE CD-1R independent project review. Table 1 does not give a breakdown by work package. The approximate distribution of new costs (excluding travel) is: £2M resource in WP1 (Physics); £2M resource in WP2 (Reconstruction); £5M resource and £9M capital in WP3 (DAQ); £5M resource and £19M capital in WP4 (APAs); and £1M resource in WP5 (Computing).

	19/20	20/21	21/22	22/23	23/24	24/25	25/26	Total
RESOURCE (k£)								
New Staff costs	600	1600	1600	1600	1600	1600	1600	10200
Total group costs	600	1600	1600	1600	1600	1600	1600	10200
Laboratory costs								
PPD staff costs	30	70	70	70	70	70	70	450
TD staff costs	50	200	200	150	150	150	150	1050
Travel and subsistence	125	250	300	400	400	400	300	2175
Working allowance	150	400	500	600	600	500	100	2850
Total laboratory costs	355	920	1070	1220	1220	1120	620	6525
CAPITAL (BEIS funded)								
APA Construction	1000	3000	4000	4000	4000	3000	500	19500
DAQ Construction	500	1000	1000	2000	2000	2000	500	9000
Total capital	1500	4000	5000	6000	6000	5000	1000	28500
EXISTING PROJECT COSTS								
Consolidated grant effort	375	750	750	750	750	750	750	4875
RAL PPD baseline staff	75	150	150	150	150	150	150	975
Total existing costs	450	900	900	900	900	900	900	5850
GRAND TOTAL								
Total new cost to STFC	955	2520	2670	2820	2820	2720	2220	16725
Overall project cost	2905	7420	8570	9720	9720	8620	4120	51075

Table 1: Estimates of total costs (k£) for the DUNE-UK construction project (October 2019 – March 2026). The total new cost to STFC does not include capital, which is assumed to be funded by the BEIS long-term science capital fund.

Basis of Estimate

The costs of the APA production for SBND and protoDUNE-SP (in the UK and US) provide a basis for the cost estimate for the DUNE APA production. The DAQ capital cost is the current estimate from the DUNE project office, based on the existing assumptions for the system. The programme of work in the DUNE-UK pre-construction proposal will provide improved cost estimates for the APAs and the DAQ. For this reason, at the time of the construction proposal it is likely that the risks to construction aspects of the UK project will be relatively low. Hence, the likely working allowance at the time of the construction proposal is assumed to be only 10% of the capital cost, with a further 10% contingency held by STFC. Given the modular nature of the APA production, any increase in costs over what is assumed here could be absorbed by a reduction in the UK scope.

New staff costs at the universities are requested at a level that is 50% greater than in the DUNE-UK pre-construction proposal. The funding of one project PDRA at RAL is included. It is assumed that the direct costs for TD staff (mostly STFC Daresbury) are capitalised. The TD staff costs in the table are intended to account for overheads only. CG costs are estimated to be 50% larger than in the pre-construction proposal. There exact division between project new staff costs and CG effort may change with time.

Travel and subsistence costs are based on an extrapolation of the current experience. In the pre-construction phase, a travel budget of £200k per annum is required to support DUNE-UK. During the construction phase, there will be significant additional costs associated with detector installation at SURF, particularly during peak times.

10. Risk Management

Risk management is central to the overall management of the LBNF and DUNE projects. At this stage no UK-specific risk register exists, however the high-level risks are captured by the extensive DUNE international cost and schedule risk register, which has had external expert scrutiny as part of the DOE CD-1 and CD-3A reviews. The UK-specific risk register will be developed following the methodology adopted by the central DUNE project office and members of the UK project team will attend the LBNF/DUNE risk management workshops. In this document, only an initial assessment of the main risks to the proposed UK project are presented.

The main external risks are:

- LBNF/DUNE does not proceed; following the successful CD-3A review this is extremely unlikely. The US DOE and Fermilab are committed to LBNF/DUNE and to maintaining the schedule. There is a well-defined funding profile that will deliver the major milestones.
- Delays due to changes in the planned US funding profile, which could increase UK costs. This risk has been mitigated by recent changes to the US funding profile, which have increased the up-front contingency in order to decrease the risk of schedule slippage.
- Insufficient international resources to build the full scope of LBNF/DUNE, resulting in reduced scientific capability. The most likely impact would be a delay to the construction of the third and fourth far detector modules. This risk is partly mitigated by the contingency built into the US project to cover this eventuality. Furthermore, from the UK is partly insulated from this risk as the UK project will focus on the construction of the first two far detector modules.
- Underestimation of the technical challenges in the construction and operation of large liquid argon detectors. This risk is mitigated through extensive prototyping/testing activities, including the large-scale prototyping programme at CERN (protoDUNE).
- The reconstruction of complex event topologies does not reach the assumed level of performance. This risk is being mitigated through the existing software development for DUNE and

the need for production-ready reconstruction for MicroBooNE.

The main internal UK project risks are:

- Costs and/or complexity of the APA production are underestimated. This risk is being mitigated by the UK construction of three of the six APAs for the protoDUNE-SP detector at CERN. By the time of the construction-phase proposal, costs will be well understood.
- The UK-led DAQ system does not deliver the required performance. This risk will be mitigated by the vertical-slice tests proposed in the DUNE-UK pre-construction proposal.

11. Wider Collaboration

DUNE is an international collaboration. An initial provisional division of responsibilities will be formalised in 2017. The UK is in a very strong position to take a leading role in the construction of the first two 17 kt far detector modules (APAs and DAQ). A capital investment from BEIS would secure this role. The UK is a key partner in DUNE and without a significant contribution from the UK it is difficult to see how the current project timescales could be maintained.

The international funding situation is summarised below:

- **US:** the LBNF/DUNE has CD-1 approval with a total project cost of \$1.5B. LBNF/DUNE is now an approved project in the US and the US DOE has legal authority (CD-3A) to commit the \$300M for construction of the underground far detector facility in South Dakota.
- **CERN:** support for DUNE is included in the CERN's MTP. CERN will provide the infrastructure for the DUNE prototyping programme, as well contributing to the protoDUNE detectors. CERN is also committed to providing the cryostat for the first far detector module.
- **India:** is providing a \$100M in-kind contribution to the PIP-II linac. The Indian scientific community has also put forward a proposal for a major Indian contribution to the DUNE near detector and high-level discussions are ongoing.
- **Italy:** discussions are ongoing in INFN and contributions to the facility (through PIP-II) and the DUNE far detector are foreseen.
- **Switzerland:** has made a significant investment in the development of the dual-phase approach to LAr-TPC readout, which is seen as a possible option for the later far detector modules. The long-term investment in DUNE is currently being discussed with the Swiss funding agency.
- **Brazil:** is providing R&D funding (FAPESP) for the development of the photon detection system. There is the potential for a long-term in-kind contribution, either through Brazil or a consortium of Latin American countries.
- **Rest of Europe:** a number of other European countries are engaged in DUNE (Bulgaria, Czech Republic, Finland, France, Greece, Netherlands, Poland, Romania, Russia, Spain, Sweden, Ukraine). Discussions with funding agencies are at various stages.

12. Other Funding

The UK participation in DUNE is (indirectly) supported by two STFC grants: reconstruction for MicroBooNE (Cambridge) and prototyping of a high-pressure gaseous argon TPC (Imperial, RHUL, Lancaster, Warwick) that could be the basis of the tracking system for the DUNE near detector.

A GCRF grant application is being developed for a partnership between UK universities and institutes across a number of countries in Latin America. The aim is to provide a long-lasting impact on the development of the physics/STEM capability in Latin America and to build a long-term strategic relationship with the UK. This is being coordinated by **Thomson** in the UK and through the Centro

Latino-Americano de Física (CLAF), which is located in Brazil. This initiative has gained strong support in four Latin American countries (Brazil, Columbia, Mexico and Peru) and has been discussed with STFC senior management.

13. Impact

A major UK investment in LBNF/DUNE would have impact in four distinct categories.

i) Strategic Partnerships

- The proposed large-scale investment in DUNE would build a strong UK-US partnership in particle physics, as well as securing the UK's international position in what will almost certainly be the largest new particle physics project in the 2020s. LBNF/DUNE has a high profile in the US and the strategic importance of partnering with the UK is recognised within the highest levels of the US DOE and beyond; letters of support have been sent to the UK Science Minister from representatives of both chambers of US Congress.
- It offers the possibility to build strong partnerships between UK and developing nations, particularly in Latin America and a GCRF bid is planned.

ii) Industrial Impact/Engagement

- The large APA frames would be produced in UK industry. A potential industrial partner has been identified and is already engaged in the prototyping programme. In addition, UK industry has the capability to produce the large number of PCB boards required to mount and position the APA wires.
- The DAQ electronics boards would be manufactured in UK industry, leveraging the existing connections with industry following the industrial engagement work of ATLAS and SKA.
- Although not part of this proposal, a major UK role in the construction of DUNE would open the possibility of a UK contribution to the superconducting SRF for the PIP-II linac and the neutrino beam target station. The business case for this investment has been sent to STFC and a potential UK industrial partner has been identified for manufacture of SRF cavities. Provision of PIP-II cryomodules would drive development of UK industrial capabilities in SRF acceleration. This is the key enabling technology for free electron lasers, next generation light sources, and other accelerator based tools that will lead to the next generation of advancements in soft material, biology, and pharmaceutical sciences. Work on the target station would have strong connections to the UK nuclear industry.

iii) Capability Building/Utilisation and Skills Retention

- Utilisation and retention of the existing skill base at the RAL and Daresbury laboratory.
- The provision of high-speed DAQ boards would enable UK universities to retain their world-leading reputation in high-energy physics, building on similar projects for ATLAS and CMS.

iv) Broader Impact

- The billion-dollar (core) scale LBNF/DUNE project is likely to be the largest global particle physics construction project in the 2020s. A strong UK participation will provide unique and exciting training opportunities for PhD students.
- DUNE offers a remarkable outreach opportunity. The ethereal nature of neutrinos captures the imagination of the public and the concept of firing a beam of neutrinos 1300 km and then detecting them in vast liquid argon detectors, located one mile underground resonates with the public. DUNE is already developing a strong outreach programme. This is currently led by the Fermilab Communications Office, who are producing brochures, informational videos as well as developing a strong social media presence. These materials would form the basis of the UK outreach activities that would accompany the award of a construction-phase grant.

14. Training

LBNF/DUNE is likely to be the largest new particle physics facility/experiment in the 2020s. There are many new and exciting technical challenges associated with the construction and operation of the large far detector LAr TPCs. The existing strong engagement of the UK particle physics community in DUNE is an indication in the interest in this major construction project and the opportunities that it will generate. DUNE will provide a major opportunity for the training of PhD students in hardware construction (APAs), high-speed DAQ and advanced reconstruction software.

15. Alternative Funding Scenarios

The scale of the UK investment in DUNE presented in this document is predicated on a £25–30M capital investment from the BEIS long-term science strategy fund. This would enable the UK to be a major partner in DUNE with a core contribution of 15% of the total construction project (four 17 kt far detector modules and the near detector). An investment at this level would secure the UK a leading and highly-visible position in DUNE. In particular, the UK would be a critical player in the construction of the first two 17 kt far detector modules, which will be installed in time for the first beam operation in 2026.

Options for a lower level of UK investment are not presented here. However, there are possibilities. For example, a total capital investment at the level of £15M would allow the UK to make a significant contribution to DUNE: i) APA production at the level of 75 APAs (half a far detector module); and ii) the back-end DAQ in partnership with another funding source. An investment at this level would still allow the UK access to the DUNE scientific exploitation, but some loss of UK leadership would be inevitable.

16. Summary

Following the US DOE CD-3A approval of the far site construction/excavation at SURF, LBNF/DUNE is established as the next global major construction project in particle physics. DUNE will be the flagship of Fermilab and the US domestic particle physics programme in the 2020s and beyond.

DUNE will offer a world-leading programme in long-baseline neutrino oscillation physics providing: access to CP violation; a definitive determination of the neutrino mass ordering; precise measurements of the parameters governing neutrino oscillation (including the determination of the θ_{23} octant); as well as providing unique sensitivity to new physics effects such as non-standard interactions. DUNE also provides unique opportunities for the discovery of proton decay and the observation of the ν_e burst from a galactic core collapse supernova.

DUNE represents a major scientific opportunity for the UK and the UK particle physics community has responded to this opportunity; DUNE-UK now numbers 126 scientists and engineers and forty UK academics are signatories to this proposal. The UK has secured important leadership roles within the DUNE collaboration.

DUNE-UK has the strength and depth to undertake the major construction project outlined in this scoping document. As well as providing ground-breaking science, a major UK contribution in DUNE would secure the UK's position and reputation in the international particle physics community.