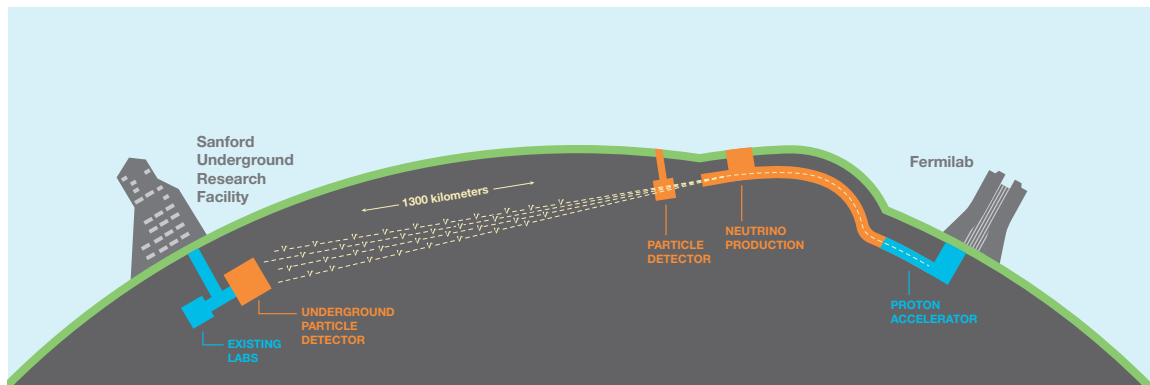# DUNE: Pre-Construction Proposal

DUNE-UK

J. Bracinik, F. Gonnella, E. Goudzovski, S. Hillier, N. Lurkin, A. Sergi, R. Staley, A. Watson, (University of Birmingham); M. Adinolfi, P. Baesso, J. Brooke, D. Cussans, D. Newbold, S. Paramesvaran, K. Petridis, J. Rademacker, (University of Bristol); J. Marshall, L. Escudero, M. Thomson (University of Cambridge); P. Clarke, F. Muheim, M. Needham (University of Edinburgh); K. Long, J. Pasternak, J. Pozimski (Imperial College); S. Pascoli (IPPP, Durham); A. Blake, D. Brailsford, G. Chapman, I. Mercer, J. Nowak (Lancaster University); C. Andreopoulos, C. Mavrokoridis, N. McCauley, K. Hennessy, D. Payne, P. Sutcliffe, C. Touramanis (University of Liverpool); A. Bitadze, J. Freestone, A. Furmanski, J. Evans, D. Garcia Gamez, P. Guzowski, J. Pater, S. Söldner-Rembold, A. Szelc (University of Manchester); B. Abi, F. Azfar, G. Barr, M. Bass, R. Guenette, J. Martin-Albo, A. Weber (University of Oxford); A. Grant, A. Muir, S. Smith (STFC Daresbury Laboratory); R. Preece, A. Weber (STFC Rutherford-Appleton Laboratory); C. Booth, V. Kudryavtsev, N. McConkey, T. Gamble, M. Malek, J. Perkin, M. Robinson, N. Spooner, M. Wright (University of Sheffield); M. Baird, J. Davies, L. Falk, J. Hartnell, S. Peeters, B. Zamorano (University of Sussex); M. Cascella, C. Ghag, A. Holin, R. Nichol, D. Waters (University College London); G. Barker, S. Boyd, M. Haigh, N. Grant, Y. Ramachers (University of Warwick).

1. High-Level Goals

Since the last STFC Programmatic Review, progress with the Deep Underground Neutrino Experiment (DUNE) has been extremely rapid. US Department of Energy approval of the $300M construction of the underground facility for DUNE was granted on September 1st 2016.

LBNF/DUNE is now an approved project with a defined US funding profile. The major milestones through the ten-year construction period are:

- **2017:** start of underground construction at SURF, South Dakota;
- **2018:** operation of the large-scale protoDUNE engineering prototype at CERN;
- **2019:** provisional international resource matrix for DUNE construction;
- **2019:** technical design report (TDR) for the DUNE detectors (to be reviewed in Q4 2019);
- **2020:** start of production of far detector components;
- **2021:** start of installation the first 10 kt far detector module at SURF;
- **2024:** start of physcs operation of the first 10 kt far detector module;
- **2026:** start of 1.2 MW beam operation with the first two 10 kt far detector modules.

DUNE-UK has a clear plan for strong UK participation in the DUNE far detector construction. To execute the full scope of this plan will require a UK core capital contribution of £25-30M. The current UK grant is closely aligned with this long-term goal. This two-year pre-construction proposal, which will run from October 2017 – September 2019 covers the period when the international responsibilities will be defined, with detector construction activities ramping up in 2020. The requested funding supports a UK programme that is aligned with the major milestones of the DUNE collaboration. The proposal has three central goals:

- perform the preparatory work required to start UK far detector construction in 2020;
- enable the UK scientists to play leading roles in the preparations of the DUNE TDR;
- further the already strong UK leadership within DUNE (both technical and scientific).

1.1 Funding Request

A total of £4.0M is requested over a two-year period. This will provide support for the sixteen UK institutes in DUNE-UK and will ensure a leading UK role in the DUNE collaboration. The total existing cost (CG and RAL PPD baseline staff) is £1.3M. Staff and equipment costs are justified in this proposal. The annual travel and subsistence budget represents an increase of 80% compared to the current grant, reflecting the increase in the size of DUNE-UK. Working allowance is estimated at 30% of the equipment budget. The lLTA costs will support SBND and protoDUNE installation and commissioning at Fermilab and CERN respectively. There is some flexibility in the allocation of the requested funds between capital and resource, through capitlisation of engineering effort.

Summary of costs (k£)	FY17	FY18	FY19	Total
New Staff	494	1144	568	2206
RAL PPD	16	32	16	64
STFC TD	57	178	89	323
Travel and subsistence	100	200	100	400
LTA costs	25	35	0	60
Consumables	5	10	5	20
Working Allowance (estimated)	25	100	75	200
Equipment	289	307	94	690
Total new cost to STFC	1010	2006	947	3963

2. Introduction to DUNE

DUNE is the flagship of the future US domestic particle physics programme and forms a major part of the UK strategy for participation in the next generation of neutrino oscillation experiments. The 1.2 MW wide-band neutrino beam, generated by the Long Baseline Neutrino Facility (LBNF) at Fermilab, will be fired 1300 km towards a 40 kt fiducial mass liquid argon (LAr) time projection chamber (TPC), located one mile underground at the Sanford Underground Research Facility (SURF) in South Dakota. The deployment of this huge LAr detector, illustrated in Figure 1, in an intense neutrino beam will represent a game-changing development in the field of neutrino physics.
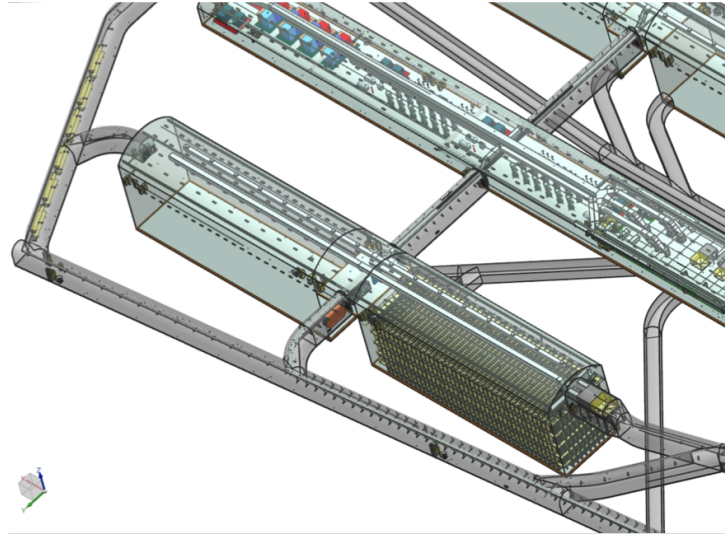

Figure 1: Illustration of of the underground facility at SURF, showing two of the four underground detector chambers and the central utility cavern. Also shown is the first far detector module (bottom left). To set the scale, the detector chambers are approximately 65 m long.

2.1 Status of DUNE

Since the submission of the long-baseline neutrino oscillation SoI in 2013, progress with LBNF/DUNE has been rapid. In 2014, the US Particle Physics Project Prioritisation Panel (P5) called for the formation of LBNF/DUNE as a truly international project with ambitious scientific goals. LBNF/DUNE was also called out as the highest priority for the US domestic particle physics programme. As a result, the scale and scientific scope of the international LBNF/DUNE project is much greater than that of its predecessor, the US-funded LBNE project.

LBNF/DUNE was set up as a truly international endeavour from day one – a first for a US-hosted project of this scale. The international governance model for LBNF and DUNE follows that of the LHC and the LHC experiments. LBNF is the US facility with international contributions at the level of 25%. DUNE is an international experimental collaboration with an expected US contribution of approximately 25%. DUNE has broad support from the global particle physics community in the US and Europe and with growing interest in developing countries; currently DUNE has over 900 collaborators from 158 institutions in 30 nations.

LBNF/DUNE passed its DOE CD-1-R review in July 2015, setting the cost for the US contribution at $1.5B. There is strong support within the US government; both chambers of Congress included authorization and funding for the LBNF construction start in their FY17 appropriations bills. CD-3a

approval for the planned $300M far site construction was granted in September 2016. This significant milestone marked the approval of the LBNF/DUNE construction, with construction/excavation commencing in South Dakota in US FY17.

DUNE is strongly supported by CERN who are investing in a large-scale detector prototyping programme at CERN and though a major contribution to the far detector underground facility in South Dakota – the first time CERN will have invested in an experiment outside CERN.

3. DUNE Science

The last 20 years have seen a revolution in our understanding of neutrinos. We now know that neutrinos have mass and the three associated PMNS matrix "rotation" angles have been measured. As it stands, non-zero neutrino masses cannot be accommodated within the Standard Model. Furthermore, the relatively "flat" PMNS neutrino mixing-matrix differs greatly from the near diagonal CKM quark mixing-matrix, possibly providing a window into flavour symmetry. The advancement in our understanding of neutrinos is one of the highlights of recent particle physics, ranking alongside the discovery of a Higgs boson at CERN.

The STFC 2013 Programmatic Review recognised this major 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 potential to explain the matter-antimatter asymmetry in the Universe through the process of leptogenesis.

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 scientific case for LBNF/DUNE has been presented in detail in volume 2 of the DUNE conceptual design report (arXiv:1512.06148) and only the highest-level scientific goals are repeated here:

- 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 $7-10°$ (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 wide-band neutrino beam will enable DUNE to test the current three-flavour paradigm of neutrino oscillations, providing 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.

4. The DUNE Detectors

The long-term goal of DUNE-UK is to play a leading role in the construction of the vast DUNE LAr-TPC far detector modules. This goal has defined the scientific and technical focus of the existing DUNE preparatory phase grant and the supplemental capital grant for a UK contribution to the large-scale prototype (ProtoDUNE) at CERN. A brief introduction to the DUNE far detector and ProtoDUNE is given below.

4.1 The DUNE Far Detector

In DUNE (and ProtoDUNE) the ionisation produced by charged particles will drift in a uniform 500 V/cm electric field through a volume of pure liquid argon. The ionisation is then detected using three planes of wires separated by ~5 mm. The recorded charge produces separate two-dimensional (wire number versus time) images of from three wire planes, such as that shown in Figure 2. The different views can be combined in software to give a three-dimensional image of the interaction with a point resolution of ~2 mm. In addition to its imaging capability, a LAr TPC provides total absorption calorimetry, whereby all the ionisation is collected, leading to excellent energy resolution. Liquid argon is an excellent scintillator and collection of the scintillation light augments the capabilities of the LAr TPC.
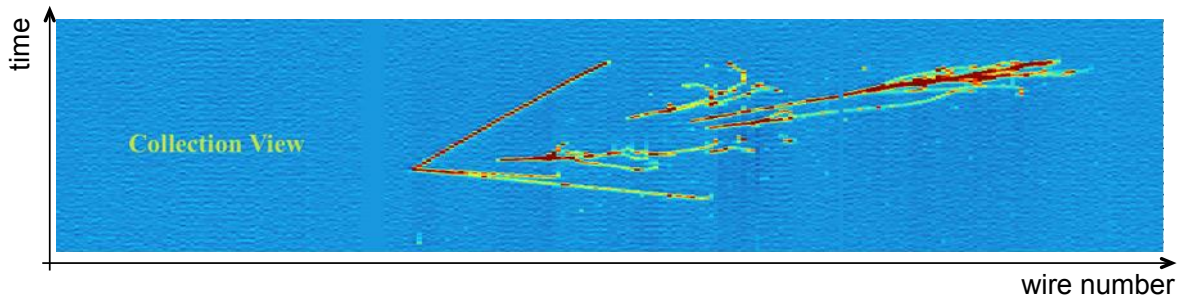

Figure 2: A ν_μ interaction observed in the small ArgoNeuT prototype LAr TPC at Fermilab.

The DUNE far detector will consist of four 10 kt fiducial mass (17 kt total mass) detector modules. The first module(s) will be constructed using the single-phase[1] LAr-TPC technology, described here. The TPC active volume of each module is 12 m high, 14.5 m wide and 58 m long, instrumented with anode-plane assemblies (APAs), which are 6 m high and 2.3 m in width, and cathode-plane assemblies (CPAs), 3 m high by 2.5 m wide. Groups of two APAs and four CPAs are stacked vertically to instrument the 12 m height of the active volume. The 12.5 m width of the detector is spanned by three stacks of APAs and two stacks of CPAs in an APA:CPA:APA:CPA:APA arrangement, with four 3.6 m drift volumes. The 58 m length of the active volume is spanned by 25 such stack arrangements placed edge-to-edge, as indicated in Figure 3. A 10 kt far detector modules consists of 150 APAs and 200 CPAs. The CPAs are held at -185 kV, such that ionization electrons drift a maximum distance of 3.6 m in the electric field of 500 V cm^{-1}. The highly-modular nature of detector design enables manufacturing to be distributed across a number of sites. DUNE-UK has the ambition to set up one of the (three or four) production sites for the APAs, which are the most complex part of the TPC.

4.2 ProtoDUNE at CERN

DUNE is constructing two large prototype detectors in the EHN1 hall in the North Area at at CERN. These are engineering prototypes for the DUNE single- and dual-phase far detector designs. The

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[1]The dual phase LAr-TPC readout, which has yet to be demonstrated on a large scale, is considered as a possible option for later far detector modules.
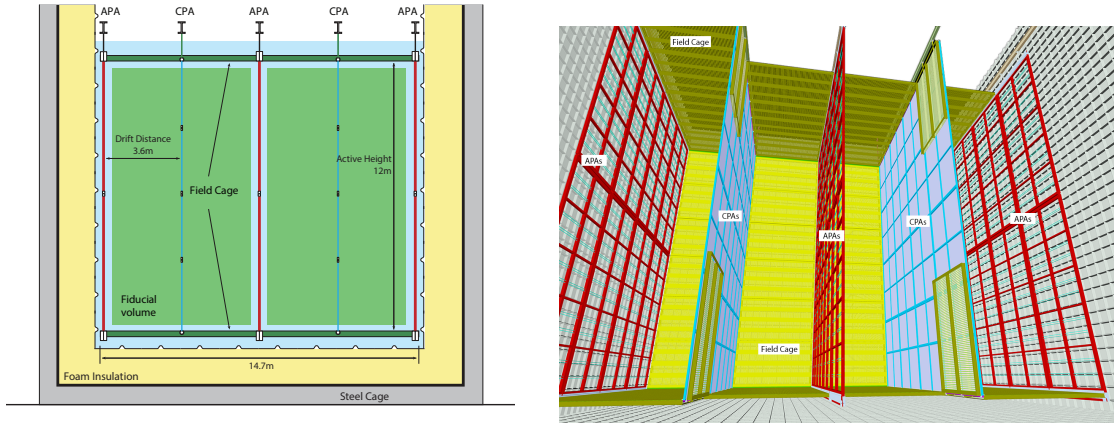
Figure 3: (left) a schematic showing the cross section of the DUNE far detector design with the A:C:A:C:A arrangement of anode and cathode planes. (right) a view from inside the DUNE far detector as it will appear during the construction.

UK is playing a leading role in the construction of ProtoDUNE-SP, which is the large-scale prototype for the first DUNE 10 kt far detector module(s). As indicated in Figure 4, ProtoDUNE-SP is $7 \times 7 \times 6$ m^3 (active volume) LAr TPC. Although ProtoDUNE is a prototype, it is the largest LAr TPC module ever constructed. It will consist of six 6 m $\times$ 2.3 m wire-wrapped APAs, identical in design to those for the far detector. The cathode plane at the centre of the detector is held at -185 kV providing the 500 V m^{-1} drift field in the 3.6 m drift regions between the cathode plane and APAs (identical to the far detector configuration). ProtoDUNE will be exposed in a tertiary tagged charged-particle test beam generated from the SPS primary beam. The tertiary charged-particle beam, which spans the kinetic energy range of approximately 0.5 GeV $-$ 8 GeV, will provide a detailed calibration of the response of ProtoDUNE to electrons, kaons, muons, pions and protons.
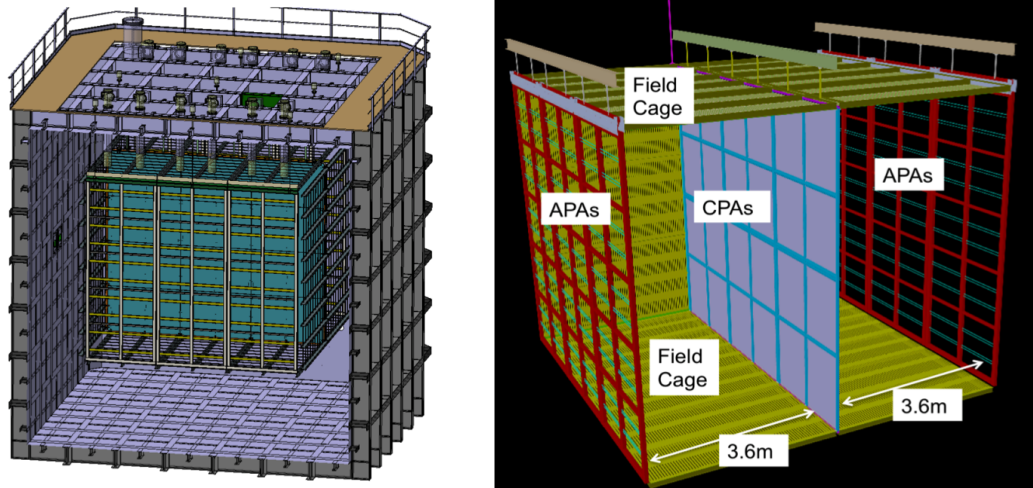

Figure 4: (left) A schematic drawing showing the ProtoDUNE TPC inside the large cryostat that will be constructed at CERN. (right) A schematic of the TPC, showing APAs, the cathode plane and the field cage.

The ProtoDUNE programme serves three essential purposes:

- provides calibration test-beam data that will map out in detail the response of the DUNE far detector design to different particles;
- provides an engineering test of the design of the full-size far detector TPC elements, an essential part of the DUNE risk mitigation strategy prior to the start of far detector construction in 2020;
- allows an early test of the far detector production techniques and sets up/validate the initial production lines for the TPC components.

4.3 The DUNE Near Detector

DUNE will use a high-resolution near detector, located at approximately 500m from the target. The main purpose of the ND is to constrain potential systematic biases in the neutrino oscillation analysis by characterising the unoscillated neutrino beam, including the ν_μ beam spectrum and the ν_e contamination. The design of the ND dictates the manner in which it is used in the oscillation analysis. For example, the ND can provide measurements of neutrino interaction cross sections and kinematics that are then used to tune the neutrino interaction physics simulation.

The reference design for the DUNE ND is a fine-grained tracker, with a $3\,m \times 3\,m \times 3\,m$ straw-tube tracker and electromagnetic calorimeter in a $0.4\,T$ magnetic field, followed by RPC chambers for $\mu^\pm$ detection. However, other ND options are being considered, possibly operated in parallel with the fine-grained tracker. For example, a LAr TPC could be an attractive option, as it would be functionally identical to the far detector, but with the downside of having pile-up from approximately five ν interactions (and five ν-induced muons from the surrounding rock) in a single beam spill, presenting a significant challenge for the pattern recognition software. Another option is a high-pressure gaseous argon (GAr) TPC, combining some of the benefits of a fine-grained tracker but with argon as the target nucleus. Through experience with MINOS, T2K and NOvA, the UK is ideally placed to investigate the scientific merits of the different approaches (see WP1).

5. DUNE-UK: Status, Strategy and Goals

The UK is a leading partner in DUNE, with over 100 collaborating scientists and engineers from sixteen UK institutes. DUNE-UK brings together world-leading experience from neutrino experiments including MicroBooNE, MINOS, NOvA and T2K. This expertise is complemented by the recent involvement of new groups bringing expertise from ATLAS, CMS and LHCb, particularly in the area of high-speed high-volume data acquisition.

UK scientists hold important leadership roles in the collaboration. **Thomson** was elected as co-spokesperson of DUNE (along with Prof A. Rubbia of ETH Zurich). UK academics, scientists and engineers hold key posits within the collaboration. For example, **Touramanis** is the co-leader of the ProtoDUNE-SP detector activities at CERN; **Barr** is the DOE level-3 manager for the DUNE DAQ and is the convenor of the DUNE DAQ working group; **Söldner-Rembold** is chair of the DUNE speakers committee; **Weber** is the coordinator of the DUNE Beam Optimisation Task Force; and **Blake** is a deputy coordinator of the DUNE Far Detector Optimisation Task Force. In addition, UK physicists hold a number of convenor roles within the far detector and ProtoDUNE working groups, including **Nowak** who co-convenes the ProtoDUNE measurement planning group.

5.1 Strategy for UK Participation in DUNE

DUNE-UK has pursued a clear strategy for a UK contribution to DUNE focussing 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 data acquisition (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 aims to place the UK at the centre of the far detector physics programme: from collection of the ionization signals, to data readout, event reconstruction and ultimately data exploitation. The existing funded three-year preparatory phase (October 2014 – September 2017) programme, which was approved in 2014, is closely aligned with the long-term UK goals.

The scale of the UK contribution to the DUNE far detector will depend on the availability of capital funding beyond the current STFC allocation. A capital investment (including capitalized engineering effort) of between £25-£30M would enable the UK to be a leading player in the construction of the first two far 10 kt detector modules, contributing:

- **Far Detector readout APA wire planes:** the UK would provide approximately half of the critical readout planes (APAs) for the first two far detector modules, through a partnership between STFC-DL, industry and several universities (mostly from the NW of England).
- **Far Detector DAQ:** the UK would provide the high-speed DAQ electronics for the first two far detector modules. A consortium of UK universities and STFC-RAL would be responsible for design and firmware, with the electronics boards being manufactured in UK industry.

Based on the current understanding of the detector costs, this would represent an approximately 15% core contribution to the overall DUNE detector construction project.

5.2 The Existing DUNE-UK Programme

The approved DUNE-UK programme of work is divided into six distinct work packages: WP0 Management; WP1 DUNE Physics Simulation and Experiment Design, WP2 Liquid Argon Neutrino Event Reconstruction; WP3 DUNE Data Acquisition; WP4 DUNE Prototypes; and WP5 Liquid Argon TPC Design and Construction. This programme of work is closely aligned with the DUNE-UK long-term aspirations for a major UK contribution to the construction of the DUNE far detector, where the provision of the APAs and DAQ have been identified as the highest priorities. Experience with the operation of a large-scale LAr detector (WP4) and the construction of the APAs for the SBND detector at Fermilab and the ProtoDUNE detector at CERN (WP5) represent major steps towards this long-term goal. The work on reconstruction software and DAQ (WP2 and WP3) build on existing UK expertise and are critical to the success of DUNE and the wider LAr programme; both represent areas of UK intellectual leadership and will result in long-term leadership roles in DUNE.

In parallel with the UK work on DUNE, UK groups have become important contributors of the MicroBooNE and SBND collaborations. MicroBooNE is the largest LAr-TPC currently running and is the first large-scale LAr-TPC to operate in a neutrino beam. There are strong synergies between these activities and those on DUNE, in particular the development of expertise and understanding of the hardware and reconstruction issues in a real detector environment. These experiments also provide experience with neutrino physics analysis with a LAr-TPC detector.

6. Proposed Pre-construction Programme

In early 2019 the international responsibilities for the elements of the construction of the first two 10-kton (fiducial) DUNE far detector modules will be defined, with construction starting early in 2020. Funding is requested from October 2017 (the end of the preparatory phase grant) to September 2019. The scientific and technical work proposed here would cement the leading role that the UK has in DUNE. It would also allow the UK to make a central contribution to DUNE TDR, for the LBNC and DOE CD-2/3 reviews at the end of 2019. At the end of the pre-construction phase, DUNE-UK would be in a position to move rapidly to the start of the DUNE far detector construction. The funding request has three main elements: maintaining UK leadership in the areas of DUNE science (WP1) and advanced reconstruction software (WP2); development and prototyping of a cost-optimised design of the DUNE far detector DAQ boards (WP3); and detector prototyping (WP4), developing of the APA manufacturing process (WP5).

WP0: Management

Work package manager: **Preece** (RAL)

For the pre-construction phase, the DUNE-UK project will adopt a lightweight version of the likely management structure for the anticipated UK construction project. The management structure, which is indicated in Figure 5 consists of the DUNE-UK Project Admininstration Board (PAB), the Project Management team, which includes the WP leaders) and the DUNE-UKInstitute Board.
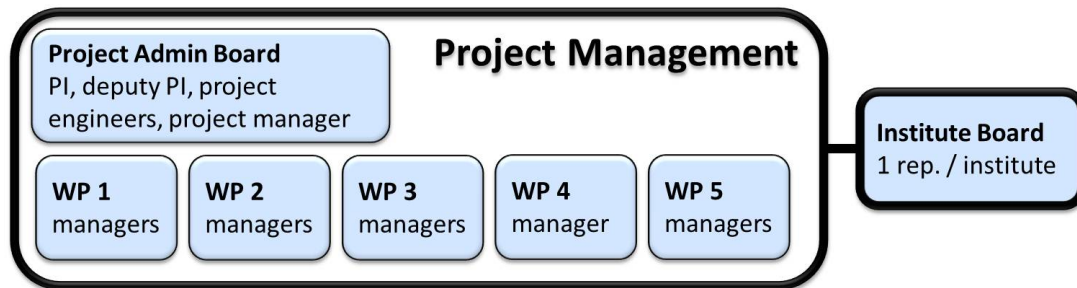

Figure 5: DUNE UK project Management Structure

The role of the PAB, which is chaired by the project PI, is to track the progress of the overall project and to facilitate the reporting to STFC, the DUNE-UK Oversight Committee and the DUNE management. It is consists of the PI (**Weber**) and deputy PI (**Söldner-Rembold**) of the UK project, the Project Manger (**Preece**) and the DAQ and APA project engineers (**Cussans** and **Grant**). The PAB is completed by **Thomson**, who will focus on the strategic and financial preparations for the construction phase. Together with the work package managers, they form the overall Project Management Board (PMB). It will meet monthly to discuss progress and any issues, with the aim of ensuring effective communication within the UK project. All non-WP specific resources, such as travel and working allowance, are held under WP0. Allocation of these resources will be agreed by the PMB, with the DUNE-UK Project Manager taking responsibility for tracking the overall progress of the project and monitoring cost and schedule.

DUNE-UK now consists of sixteen institutes and we believe this is right time to set up a formal DUNE-UK Institute Board (IB), with one representative from each collaborating institute participating. The role of the IB is to approve the main management positions and agree on the allocation of project resources. Any change of resource allocation or management positions proposed by the PAB will have to be ratified by the Institute Board. The IB will elect its own chair.

WP1: Physics

Work package manager: Andreopoulos (Liverpool, RAL)

Key deliverable: Physics sensitivity results based on full detector simulation and full event reconstruction for the DUNE Physics TDR.

Key people: **Andeopoulos** (Liverpool, RAL), **Dennis** (Liverpool), **Escudero** (Cambridge), **Grant** (Warwick), **Kaboth** (RAL), **Martin-Albo** (Oxford)

Strategic goals: i) Retain the UK leadership at the heart of the DUNE physics programme; ii) Ensure a strong UK voice in key decision-making process for the design of the DUNE experiment; and iii) Retain the option of the UK taking a role in construction of the DUNE near detector, building on the existing (non-DUNE) UK gaseous argon TPC prototyping work.

UK groups are leading the work in DUNE on producing a first realistic oscillation sensitivity simulation (see Figure 6). This work provides a full treatment of near detector, far detector and physics uncertainties, implemented in UK-led VALOR fit (developed for T2K). This detailed end-to-end analysis simultaneously uses multiple topological event samples from both near and far DUNE detectors, as well as a detailed picture of prior uncertainties on the determination of the neutrino flux and interaction characteristics. This has been a step change in the DUNE sensitivity calculation – previously only a simple assessment of overall flux/cross-section uncertainties were used. This analysis will form a central part of the DUNE physics case presented in the DUNE TDR.

The above analysis is interfaced to the full simulation and reconstruction chain of the three different near detector designs under consideration by DUNE, including the concept where a gaseous argon TPC (GAr-TPC) is used as the central tracker for the near detector. There is considerable interest in the UK in a GAr-TPC (which extends beyond DUNE). Such a detector would be sensitive to low-energy particles exiting the nucleus in neutrino-Argon interactions and would provide rich information for constraining neutrino interaction systematics. Within DUNE, the UK is playing the leading role developing the GAr-TPC concept and in evaluating its potential benefits.

WP1 aims to retain and exploit the existing UK intellectual leadership in these two connected areas.
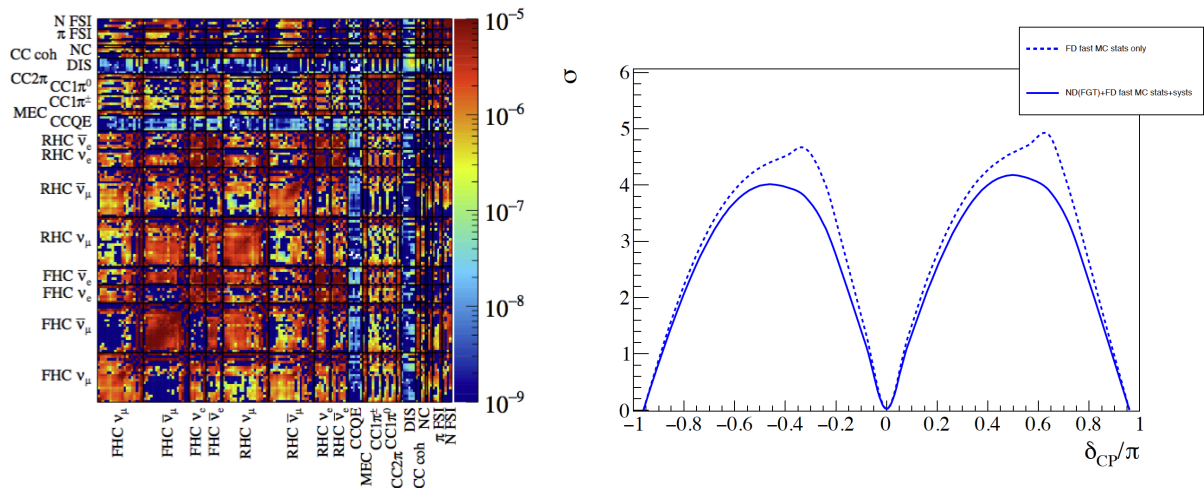
Figure 6: (left) An example of the correlation matrix output from the VALOR fit performed with simulated samples for the DUNE fine-grained-tracker near detector and right, the resulting CP sensitivity for an exposure of 300 kton·MW·year incorporating these constraints on systematic uncertainties. Because the far detector reconstruction is still at a very preliminary stage, the sensitivity plot only provides a technical demonstration of the tools, not the true experimental sensitivity.

Programme of Work

This work package has two main goals:

- realistic sensitivity studies for the proposed DUNE experimental configurations;
- the development and optimization of the GAr-TPC concept for the DUNE near detector design.

The outcome of WP1 will directly feed into the neutrino oscillation sensitivity studies for the physics volume of the DUNE TDR.

WP1.1: Near Detector Constraints and Oscillation Sensitivity (Andreopoulos)

The UK will continue the development of the VALOR analysis and will use it in the neutrino oscillation sensitivity studies for the DUNE TDR. The different potential near detector concepts (NOMAD-inspired fine-grained tracker, LAr-TPC and GAr-TPC) will be considered on an equal footing, with VALOR fit variants designed to take into account unique aspects of each detector technology, with the possibility of exploring hybrid detector options.

Systematic uncertainties in the modeling of neutrino interaction physics will be implemented in VALOR, parameterizing the nature and size of possible data/MC discrepancies, which could impact the DUNE physics reach (**Andreopoulos**, **Escudero**, **Jones**, **Roda**). A large part of this work is making comparisons to existing data to ensure that prior uncertainties used in the analysis are conservative. As part of the validation of the overall procedure, more extreme, but physically motivated, scenarios will be simulated and used as alternative inputs to the neutrino physics modeling. This will ensure that the oscillation sensitivity simulation is robust and also will probe the potential benefits of the different near detector concepts in disentangling unexpected systematic effects. Liason with the DUNE near detector groups will ensure that detector systematics for each option are correctly included in the analysis (**Andreopoulos** and **Dennis**).

Deliverable D1.1 (Q2 2019): Oscillation sensitivity results for the DUNE TDR, based on full simulation and reconstruction for all detector and beam options considered by DUNE.

WP1.2: Near Detector Design and Optimisation (Kaboth)

The UK (RHUL, Imperial, Warwick, Lancaster) are prototyping the concept of a high-pressure GAr-TPC as part of a recently awarded STFC PRD grant (which is not directly associated with DUNE). This task will connect this activity to the possibility of a GAr-TPC option being used as a concept for the DUNE near detector. A detailed Monte Carlo simulation of the GAr-TPC option, including ECAL and outer detector, will be developed in the context of the DUNE software framework (**Christodoulou**, **Haigh**, **Martin-Albo**, **Kaboth**, **Shitov**). The simulation will be used to optimize the detector design, including the type of TPC gas that can impact event selection and reconstruction.

The optimization of the outer detector design is an essential aspect of a realistic GAr-TPC based near detector. There is a subtle balance between the desire to record the particles that exit the TPC fiducial volume with minimizing the material budget in which neutrino interactions will produce a source of particles entering. This work will be led by **Martin-Albo**, leveraging the UK experience with the T2K-designed electromagnetic calorimeter.

Deliverable D1.2 (Q2 2019): Optimized design of a GAr-TPC near detector concept for DUNE.

WP1 Milestones

M1.1 (Q1 2018): Improvement and justification of prior cross-section errors using published data.
M1.2 (Q2 2018): Optimized gas choice for GaTPC, including readout model
M1.3 (Q4 2018): Detector systematics for all detector options implemented in VALOR.
M1.4 (Q1 2019): Optimized outer detector choice for GaTPC
M1.5 (Q1 2019): Validity of VALOR analysis procedure illustrated in a series of physics scenarios.
M1.6 (Q2 2019): Development of VALOR fit variants optimised for each experiment configuration.

WP2: LAr-TPC Reconstruction Software

Work package managers: **Blake** (Lancaster)

Key deliverable: Physics-ready fully-automated reconstruction software for ProtoDUNE and the DUNE far detector.

Key people: Marshall (Cambridge), **Grant** (Warwick), **Brailsford** (Lancaster).

Strategic goals: i) Retain and exploit existing UK leadership of LAr reconstruction software for DUNE; ii) place the UK in the prime position to analyse data from ProtoDUNE; and iii) enable the UK to play the leading role in the preparation of DUNE TDR.

The UK is playing a world-leading role in the development of fully-automated reconstruction software for LAr-TPCs. LAr-TPCs detect neutrino interactions with exquisite detail, opening up a new era of precise neutrino physics. However, due to the large number of hits and complex event topologies, automated reconstruction of LAr-TPC events is a highly non-trivial problem, which to date has not been fully solved; its solution is critical for the physics exploitation of existing experiments and for establishing the full physics reach of DUNE. The UK has pioneered the world-leading multi-algorithm approach (Pandora) to LAr-TPC pattern recognition, led by **Marshall**, based on advanced particle-flow techniques. This was used as the basis for the first preliminary physics studies from the MicroBooNE collaboration, presented at Neutrino 2016. For example, Figure 7 illustrates the current reconstruction performance for simulated neutrino interactions in the MicroBooNE detector geometry. WP2 aims to retain and exploit the existing UK leadership with the aim of developing "physics-quality" automated reconstruction for the analysis of ProtoDUNE test beam data and for the Monte Carlo studies of DUNE physics TDR, due in the first half of 2019.
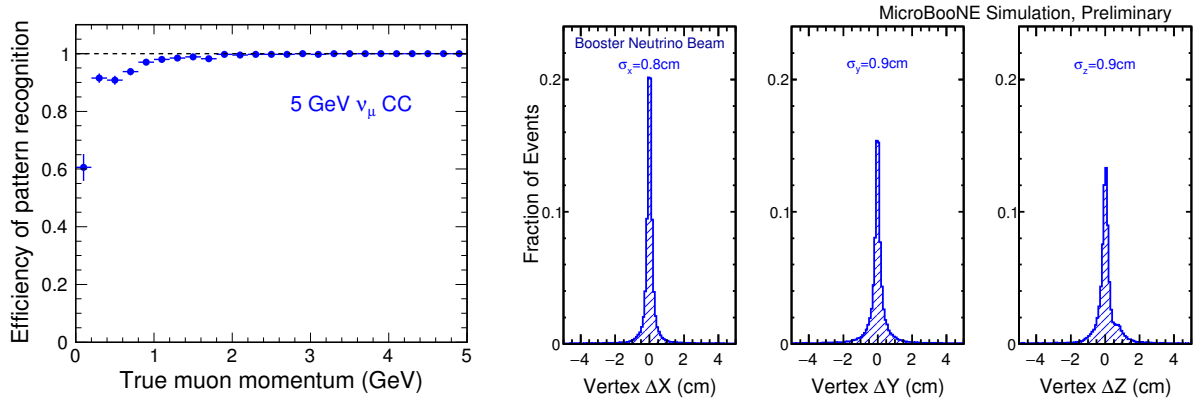
Figure 7: Performance of UK reconstruction in MicroBooNE: (left) reconstruction efficiency for muons in $5\,\mathrm{GeV}$ ν_μ CC interactions (DUNE CDR); (right) resolution of interaction vertex for neutrinos from Booster Neutrino Beam (MicroBooNE Pandora public note).

WP2: Programme of Work

This work package will enable the UK to continue its leading role in the DUNE reconstruction effort, crucial for demonstrating the scientific case for DUNE and optimising its technical design. The outputs of WP2 are essential for:

- the physics studies of WP1, which will use fully-reconstructed events to establish the full physics reach of the DUNE neutrino oscillation programme;
- the ProtoDUNE commissioning activities of WP4, where reconstructed events are required to establish the detector performance, and ultimately the physics exploitation of the ProtoDUNE data;

- the pre-construction activities of WP5, where simulation and reconstruction will form part of any design optimisation.

WP2 consists of two tasks focussing respectively on the reconstruction of ProtoDUNE test-beam data and simulated physics events in the DUNE far detector.

WP2.1: DUNE Far Detector reconstruction (Marshall)

A great deal of progress has been made in developing the UK-led reconstruction chain. By the end of the current grant a first complete version will be available for the exploitation of MicroBooNE data. The algorithmic path developed for MicroBooNE is the basis for the reconstruction of the higher-energy/more-complex neutrino event topologies at DUNE. WP2.1 will focus on development and optimisation of pattern recognition and high-level reconstruction algorithms for the DUNE far detector. The main aim is to achieve a sufficient level of sophistication that the output can be used to reliably assess the full physics reach of DUNE. The existing suite of pattern recognition algorithms first will be adapted for the full simulation of the DUNE far detector (**Blake**, **Marshall**). These algorithms will be optimised and new algorithms will be developed specifically for DUNE accelerator neutrino interactions, with a focus on the key ν_e appearance channel (**Marshall**, **Escudero**). In parallel, a pattern recognition path will be optimised for non-accelerator data samples such as atmospheric neutrinos and proton decay (**Blake**). Particle identification algorithms and energy estimators will be developed and implemented for the DUNE far detector simulation (**Grant**). The results on the performance of the UK-led DUNE LAr-TPC reconstruction will be included in the DUNE TDR (**Blake**, **Barker**). WP2.1 also includes core reconstruction software support for ProtoDUNE (**Marshall**).

Deliverable D2.1 (Q4 2018): Delivery of fully reconstructed events for DUNE physics studies.

Deliverable D2.2 (Q2 2019): Optimisation and validation of UK reconstruction for accelerator and non-accelerator events in the DUNE Far Detector.

WP2.2: ProtoDUNE reconstruction (Grant)

The UK-led Pandora reconstruction algorithms will be developed and optimised for ProtoDUNE. In the first year, the existing pattern recognition algorithms will be adapted for ProtoDUNE and new dedicated algorithms will be developed for single particles from test beam and for cosmic-ray muons (**Blake**, **Brailsford**). The UK has led the development of tools for particle identification and energy reconstruction, based on the output of the reconstruction discussed above. These tools will also be adapted and developed for the ProtoDUNE test-beam environment (**Grant**, **Ramachers**). The initial data from ProtoDUNE will be used to validate the performance of the pattern recognition algorithms (**Blake**, **Brailsford**) and to evaluate the particle identification and energy reconstruction (**Grant**, **Boyd**). The reconstruction software will also form the basis of the detector characterisation studies in WP4.

Deliverable D2.3 (Q3 2018): UK pattern recognition and high-level reconstruction ready for data-taking in the ProtoDUNE environment.

Deliverable D2.4 (Q3 2019): Characterisation of reconstruction performance using ProtoDUNE test-beam data.

WP2 Milestones

M2.1 (Q3 2018): Pattern recognition and high-level reconstruction ready for ProtoDUNE.
M2.2 (Q4 2018): Physics-quality reconstruction for events in the DUNE Far Detector.
M2.3 (Q2 2019): Results on reconstruction performance incorporated in the DUNE TDR for the CD-2/LBNC reviews.
M2.4 (Q3 2019): Characterisation of reconstruction performance using ProtoDUNE test-beam data.

WP3: DUNE Far Detector DAQ

Work package managers: **Barr** (Oxford), **Newbold** (Bristol)

Lead Engineer: **Cussans** (Bristol)

Key deliverable: A production-ready design for DAQ hardware, firmware and online computing for DUNE.

Key people: **Azfar** (Oxford), **Barr** (Oxford), **Cussans** (Bristol), **Hennessey** (Liverpool), **Newbold** (Bristol), **Watson** (Birmingham)

Strategic goals: i) Continued UK intellectual leadership of the DUNE data acquisition (DAQ) system through the development of production-ready prototypes for cost-effective high-performance DAQ readout boards; and ii) place the UK in the position to lead the consortium of institutes contributing to construction of the DUNE far detector DAQ system.

DUNE-UK has brought together a world-leading team of DAQ and electronics experts from neutrino and collider experiments. The DAQ teams at Birmingham (led by **Watson**), Bristol (led by **Newbold**) and Oxford (led by **Barr**) bring cutting-edge experience respectively from ATLAS, CMS and T2K. This is complemented by extensive electronics experience in university groups (**Abi**, **Cussans**) and RAL-PPD. The groups at Edinburgh, Liverpool, Oxford, RAL, Sussex and Warwick have experience with DAQ system design, real-time software and online algorithm development. The UK was also central to the DAQ operation of the DUNE 35-ton prototype. This experience is being taken forward with a significant UK role in ProtoDUNE, where for example the UK provides the co-leader (**Hennessy** of the ProtoDUNE DAQ team at CERN.

The DUNE-UK DAQ team has the experience and depth for the UK to be the lead nation in the DUNE far detector DAQ system.

The exquisitely detailed information provided by the LAr-TPC technology and the scale of the DUNE far detector, represent major challenges. The DAQ system is required to capture, buffer and compress the 8 Tb/s of information from each of the four 10 kton DUNE far detector modules. It also needs to be sensitive to the burst of O(10000) low-energy ν_e interactions arriving over a period of about 10 s from a galactic core-collapse supernova event, whilst maintaining reasonable data volume for beam-neutrino science.

The DAQ system will comprise a hardware (FPGA-based) front end and a software-based back end, as indicated in Figure 8. The processing tasks will be divided between these two layers, making use of the high-throughput data processing capabilities of FPGAs along with the ability to make complex trigger decisions in software, based on subtle event signatures. DUNE will rely extensively on commodity components in both layers. It is essential that the design is optimised for cost and that it provides the flexibility to upgrade the DAQ functionality over the course of the 20 year lifetime of DUNE.
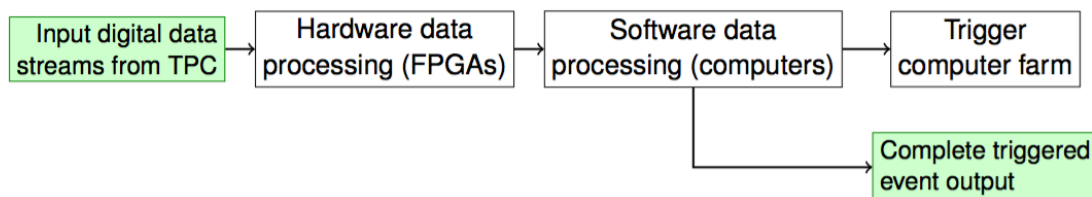

Figure 8: Hardware-level architecture of the DUNE DAQ (unshaded). The elements are interconnected with high-speed commodity networking to maximize flexibility over where the processing tasks are performed (hit finding, data compression, trigger algorithms, buffering etc.).

Although a baseline DAQ design exists, it is not optimised for cost and may be unaffordable due to the complexity of the readout boards that implement functionality not required by DUNE. In the DUNE-UK pre-construction phase, we propose to develop a cost-effective DAQ system meeting all DUNE science goals with appropriate safety margins. The long-term aim is a major UK contribution to the DUNE DAQ, with the main elements being produced in UK industry.

Programme of Work

At the end of this pre-construction grant, DUNE-UK aims to be ready for the production of the final digital processing boards and to have proven software/firmware solutions for all steps of the data transfer path. Three key technical challenges need to be addressed:

- A cost-optimised DAQ hardware platform is required for all data processing steps between the cold APA front-end electronics and the offline computing system. The proposed approach of a single FPGA stage (WP3.2) will represent a significant reduction in complexity and cost over the existing design.
- Lossless (or near lossless) data compression needs to be sustained to make triggering and event building possible. This will require use of flexible signal processing in firmware (WP3.3).
- The recent adoption by industry of very high-speed network interfaces (e.g. 40 Gb/s ethernet) with high-speed direct memory access, will allow most DAQ functions to be implemented in software. This requires a software framework and drivers capable of efficiently handling very high volume data flow (WP3.4).

The UK will conduct R&D and prototyping as part of a DUNE-wide consortium with key international partners (including SLAC) to reach a solution addressing these technical challenges. The experience with ProtoDUNE is also crucial to provide realistic expectations of detector conditions, signal characteristics and data rates (WP3.1). The successful conclusion of this project will be a complete vertical slice test of all hardware and software components and a complete architectural specification of the far detector DAQ for the DUNE TDR.

WP3.1: Commissioning and operation of ProtoDUNE-SP (Hennessy)

The DAQ design process requires a detailed understanding of the likely nature of the data (e.g. the rate and frequency spectrum of the electronic noise). ProtoDUNE provides a test of the read out of a full-scale APA with the DUNE cold electronics; the only possible test of realistic far-detector-like conditions, prior to the far detector constrution.

The UK is already contributing to the construction of the ProtoDUNE DAQ system through the STFC capital grant for ProtoDUNE. However, this capital grant does not cover UK operational support for the ProtoDUNE DAQ. Hence, as part of this pre-construction proposal, the UK will provide the necessary operational support for the ProtoDUNE DAQ system, including provision of monitoring and characterisation of the DAQ and detector performance. The operational experience gained by the UK team at CERN will be fed into the design decisions for the far detector DAQ in WP3.2, WP3.3 and WP3.4.

Deliverable D3.1 (Q1 2018): Commissioned DAQ system for ProtoDUNE.

WP3.2: FPGA processing board (hardware and firmware) (Watson)

A major component of the pre-production work is the design and prototype production of a new UK-led cost-effective FPGA processing board. The elements of this task include:

- an evaluation of current and near-future FPGA and FPGA-SoC devices and of high speed optical communication link technologies;
- identification of potential UK industrial partners for mass production of the processing board;

- design and manufacture of the FPGA processing board, allowing evaluation of hardware of the engineering choices;
- development of firmware to allow basic operation of the FPGA board. This will include system-level timing and IO functions, data interchange with cold electronics, network interface to the computing system, and a well-defined software interface. Library components will be developed in a modular fashion to allow high-level compression and hit finding algorithms to be evaluated.
- testing of the board in the vertical slice testbed (WP3.5) to evaluate the error rates on the high-speed data links.

The processing board is likely to be relatively simple, hosting a single-FPGA. For this reason the planned schedule and budget anticipates just two iterations of the board design.

Deliverable D3.2 (Q2 2018): Schematic-level design of FPGA board complete and reviewed for production.

Deliverable D3.3 (Q4 2018): FPGA board prototype delivered (first iteration).

Deliverable D3.4 (Q2 2019): FPGA board prototype delivered (second iteration).

WP3.3: Front-end data handling (Peeters)

The existing DUNE data-flow simulation framework, developed in the UK, will be used to devise optimised data compression algorithms based on the characteristics of the raw data from ProtoDUNE. These data compression algorithms will be implemented in firmware on the FPGA processing board to assess the resources required (gate counts, memory capacity, and power consumption). These studies will inform the choice of FPGA for the final design of the FPGA processing board for the DUNE far detector.

Deliverable D3.5 (Q4 2018): Documented resource requirements for data compression firmware.

Deliverable D3.6 (Q2 2019): Baseline data compression algorithms defined and implemented in software simulation.

WP3.4: DAQ online architecture (Azfar)

The FPGA processing boards provide real-time processing and distribution of the LAr-TPC data. Downstream, commodity computing and network equipment will be used to buffer, process and distribute the data. The exact division between the real-time and online functionality needs to be understood and there is scope to build in sufficient flexibility to offload some functions from the real-time FPGA processing to online software (e.g. trigger decisions). The design will need to take into account the power and cooling constraints arising from underground operation and the cost of the high-bandwidth links to the surface. In WP3.4 the software and computing tools for the back-end DAQ will be developed, based on simulations of the overall DUNE far detector DAQ data flow, and tested in an integrated vertical slice. The proposed development work includes:

- determination of the optimal division of processing between the hardware (FPGA) and software (commodity computing elements) from simulation of the DUNE FD data flow.
- development of a final design of the back-end DAQ architecture, shown to meet the requirements of the DUNE experiment, based on the DAQ simulation.

Deliverable D3.7 (Q3 2019): Final design of the software architecture for the far detector DAQ.

WP3.5: Back-end DAQ and integrated vertical slice test (Azfar)

WP3.5 will provide a demonstration of the proposed far detector DAQ architecture, including the development of the software and computing tools for the back-end DAQ. The integrated vertical slice test programme includes:

- development of demonstrators for high-speed data handling on commodity computing hardware with the aim of showing that a scalable software-based system can accommodate the needs of the DUNE far detector DAQ. This will include optimisation of hardware drivers and DAQ software, for example by minimising data movement between memory, CPU and peripherals, such that they can keep pace with modern network hardware.
- development of the existing ProtoDUNE DAQ test bed into a vertical slice test, which will bring all WP3 components together (FPGA processing board and back-end DAQ computing). This will allow the validation of all system components under realistic conditions for an extended period.
- optimisation of the interfaces between the DAQ software framework (artDAQ) and the network transfer protocols to avoid non-essential data copying. The vertical-slice testbed will provide the ideal environment for development under realistic conditions throughout the duration of this project.

Deliverable D3.8 (Q2 2018): Demonstration of key data-handling needs

Deliverable D3.9 (Q3 2019): Preliminary design of the DAQ software architecture for the DUNE TDR.

Equipment/consumables
The estimated costs of the equipment needed for WP3 are listed in Table 1.

	number	Unit cost k£	Cost k£			
			FY17	FY18	FY19	Total
FPGAs	10	3	6	9	15	30
Memory components	10	2	0	4	6	10
Ancilliary	10	0.75	1.5	2.25	3.75	7.5
PCB assembly	15	1.5	6	9	7.5	22.5
Network hardware	1	10	10	–	–	10
Teststand computing	1	10	5	5	–	10
Crate hardware	4	3	–	–	12	12
Test stand equipment	3	5	15	–	–	15
Total			44	29	44	**117**

Table 1: Consumables for WP3

WP3 Milestones
M3.1 (Q4 2017): Requirements of FPGA board captured.
M3.2 (Q4 2017): Test-bed components (except the FPGA-board) obtained.
M3.3 (Q1 2018): FPGA family (not part number) selected.
M3.4 (Q2 2018): Preliminary study of data-copy optimisation.
M3.5 (Q2 2018): ProtoDUNE data being used for compression studies.
M3.6 (Q3 2018): Preliminary survey of potential industrial partners.
M3.7 (Q1 2019): Internal collaboration design review ahead of CD2/3.
M3.8 (Q3 2019): FPGA board tested in vertical slice with compression.

WP4: DUNE LAr-TPC Prototypes

Work package manager: **Evans** (Manchester)

Key deliverable: Successful operation and characterization of the UK-built APAs for SBND and ProtoDUNE.

Key people: **Furmanski** (Manchester), **McConkey** (Sheffield), **Brailsford** (Lancaster), **Nowak** (Lancaster), **Gamez** (Manchester), **Mavrokoridis** (Liverpool), **Payne** (Liverpool)

Strategic goals: i) Demonstrate successful operation of UK-built components of SBND and Proto-DUNE detectors, establishing the UK as a world-class provider of high-quality APAs; and ii) place the UK at the heart of preparations for DUNE CD-2 approval, with UK physicists leading the ProtoDUNE and SBND detector characterization studies that will define the final DUNE far detector design.

As part of the DUNE-UK preparatory phase and supplemental ProtoDUNE grants, the UK made commitments to construct half of the APAs for both the SBND detector at Fermilab and the Pro-toDUNE detector at CERN, with the other APAs being provided by US institutes. The UK APA construction activities have enabled the UK to gain experience with all aspects of large-scale wire planes for single-phase LAr-TPC read out; it is worth noting that the APA designs (double-sided versus single-sided) and operational conditions (charged-particle test beam and neutrino beam) are very different for ProtoDUNE and SBND. The successful commissioning and operation of these detectors will demonstrate the UK capability to deliver a significant number of APAs as part of a longer-term DUNE-UK construction project. Furthermore the lessons learned from the construction and operation of these APAs will feed into the preliminary engineering design for the DUNE far detector APAs, required for the DUNE TDR. It will also inform the plans for the industrialisation of the APA production process in WP5.

The existing DUNE-UK grants cover construction and delivery of the SBND and ProtoDUNE APAs respectively to Fermilab and CERN. In order to exploit the existing UK investment in SBND and ProtoDUNE, it is essential that UK scientists play a central role in the installation, commissioning and operation of the UK detector elements. Continued involvement, beyond delivery, is also essential for the UK to continue to be viewed as a strong and reliable partner in this area.

Programme of Work

This work package focusses on a strong UK involvement in the installation, commissioning and characterisation of the UK APAs in the SBND and ProtoDUNE detectors. It will enable DUNE-UK to fulfil its responsibilities as a partner in these detectors. The outcome will be a team of UK scientists with deep hardware experience with all aspects of construction, installation and commissioning of APAs. This knowledge will be essential for the successful execution of the DUNE-UK plans for far detector construction. A total of five years of LTA support (split between CERN and Fermilab) is requested.

Although not described here, the data samples provided by ProtoDUNE (test beam) and SBND (neutrino beam) will provide rich opportunities for PhD students to work in the cutting-edge LAr-TPC technology, with many potential exciting PhD thesis topics.

WP4.1: ProtoDUNE Installation and Commissioning (Szelc)

We propose to send a team of young scientists to CERN for the installation and commissioning of the ProtoDUNE APAs (**Brailsford**, **Furmanski**, **McConkey**, **Szelc**). All have been involved in the existing DUNE-UK APA activities. Support for the integration activities will be provided by **Payne** and **Wright**.

During the first six months of this grant, the UK team will take overall responsibility for integrating the APAs into ProtoDUNE and ensuring full operational readiness of the TPC; within the DUNE

collaboration the UK is responsible for the ProtoDUNE APA installation/integration task (**Szelc**). The commissioning of the APAs will take place in Q2 2018 with the UK taking a major role on the ground at CERN (**Furmanski**, **Szelc**).. Strong support is particularly important during the three month beam data run (Q3 2018), where high up-time will be vital and DUNE-UK will provide on-call experts (**Brailsford**, **McConkey**).

In addition, **Manetti** will be leading the commissioning and operation of the ProtoDUNE purity monitors. It should be noted that DUNE-UK is also playing an important role in the ProtoDUNE DAQ system, where the UK is providing the overall ProtoDUNE DAQ coordinator (**Hennessy**). However, no new resources are requested beyond LTA support.

Deliverable D4.1 (Q1 2018): UK-built ProtoDUNE APAs operational and ready for commissioning.

Deliverable D4.2 (Q2 2018): The ProtoDUNE detector ready to begin taking physics-quality data.

WP4.2: SBND Installation and Commissioning (Gamez)
The first year of this project will see the installation and commissioning of the SBND detector. The UK will contribute to the APA installation and commissioning (**Evans**, **Gamez**, **Mavrokoridis**) at Fermilab, where **Gamez** will be the lead on-site physicist overseeing the installation and commissioning of UK-built APAs. During the data-taking phase, starting in Q4 2018, the UK will provide on-call experts.

Deliverable D4.3 (Q2 2018): UK-built SBND APAs operational and ready for commissioning.

Deliverable D4.4 (Q3 2018): The SBND detector ready to begin taking physics-quality data.

WP4.3: Detector Characterisation (Nowak)
ProtoDUNE is an engineering prototype for the DUNE far detector, constructed from the full-sized far detector elements (including the $6 \times 2.3\,\mathrm{m}^2$ APAs). The characterisation of the detector performance (**Brailsford**, **Furmanski**, **McConkey**, **Sheffield RA 2**) and validation of the engineering design will be a critical component in the TDR review process. The UK will be in a strong position to make leading contributions to the ProtoDUNE test-beam data analysis with UK leadership in the development ProtoDUNE reconstruction software (WP2). Furthermore, **Nowak** is the overall convener of the ProtoDUNE measurements working group. Publications describing the argon purity, noise levels in the TPC, and TPC response to the various charged particles ($\mu^{\pm}$, $\pi^{\pm}$, p, $\overline{\mathrm{p}}$, $\mathrm{e}^{\pm}$) will follow.

Deliverable D4.5 (Q3 2019): Publications of ProtoDUNE detector-characterisation analyses.

In parallel with the work on ProtoDUNE data, the UK will contribute to the analysis of SBND data (**Evans**, **Gamez**, **Mavrokoridis**). This will give an opportunity to test the UK-led reconstruction algorithms (WP2) in a physics environment, and to use the ProtoDUNE measurements of charged-particle response to tune the detector simulation in the context of neutrino interactions. Additionally, since the SBND APAs use single-sided readout rather than the two-sided APAs for ProtoDUNE and the comparison of the two designs is important because the DUNE FD could use single-sided APAs at the detector edges to reduce cost.

Deliverable D4.6 (Q3 2019): Publications of SBND detector-characterisation analyses.

WP4 Milestones
M4.1 (Q1 2018): Complete installation of ProtoDUNE detector.
M4.2 (Q2 2018): Complete installation of SBND detector.
M4.3 (Q2 2018): Complete commissioning of ProtoDUNE detector.
M4.4 (Q3 2018): Complete beam data-taking run with ProtoDUNE.
M4.5 (Q3 2018): Complete commissioning of SBND detector.
M4.6 (Q3 2019): Publish ProtoDUNE and SBND detector-validation analyses.

WP5: DUNE APA Pre-Construction

Work Package Manager: **Söldner-Rembold** (Manchester)

Lead Engineer: **Grant** (Daresbury Laboratory)

Key deliverable: Production of an APA prototype constructed using a prototype process (equipment and test procedures) for UK production of far detector APAs.

Key people: **Freestone** (Manchester), **Gamble** (Sheffield), **Gamez** (Manchester), **Grant** (Daresbury), **Jones** (Liverpool), **McConkey** (Sheffield), **Mercer** (Lancaster), **Sutcliffe** (Liverpool), **Wright** (Sheffield).

Strategic goals: i) Place the UK in a position to make a major contribution to the DUNE far detector construction, through production of between 75–150 APAs starting in 2020; and ii) secure UK intellectual leadership of the design of the production process for the DUNE far detector APAs.

DUNE-UK has a long-term aspirations for a major UK contribution to the DUNE far detector through the provision of far detector APAs and the far detector DAQ system. These potential contributions are strongly supported by the DUNE Collaboration and would buy the UK a major stake in the construction of the largest (by far) LAr TPC ever built. The UK investment in the far detector APA production could be at the level of £20M, sufficient for the UK to provide approximately 50% of the 300 APAs for the first two 10 kt far detector modules.

DUNE-UK took the decision to centralise the APA construction at Daresbury Laboratory, which has made available laboratory space and has a strong engineering team. The long-term plan is for Daresbury Laboratory, working in partnership with a cluster of local universities (Lancaster, Liverpool, Manchester, Sheffield) and local industry, to be the UK production centre for the far detector APAs. It is foreseen that there will also be production lines in the US and possibly Italy. Through the production of the SBND and ProtoDUNE APAs, UK engineers have developed strong working relationships with the engineering teams at the Physical Sciences Laboratory (PSL) Madison and at Syracuse/Yale – two of the potential sites for the US production lines.

The extensive experience being gained in the construction of the APAs for SBND and ProtoDUNE has enabled the UK to build a strong technical base for our long-term aims. However, the existing wiring procedures involve significant manual intervention and are not suited to a large-scale production for the DUNE far detector at the required rate. Further development is required to achieve a steady-state production rate of one APA every one to two weeks.

Programme of Work

WP5 aims to develop the industrial-scale production process at Daresbury Laboratory, which includes: the establishment of a construction facility at Daresbury Laboratory; the design and construction of a wire-winding machine to allow a fully automated APA build; the development of robust QA/QC procedures; and the development of process planning procedures. As part of this work DUNE-UK intends to further strengthen the collaboration with our UK industrial partners in design and fabrication of APA frame and ancillary PCB components. The requested resources are focused on the activities that need to be put in place in order for start of mass production in 2020. We also request some capital resources to support the development of an innovative light-readout system.

WP5.1: APA Wire Winding Machine and Frames (Pater)
The design of the final wire-winding machine for DUNE will be based on the ProtoDUNE and SBND experience. The ProtoDUNE wire winding machine (shown in Figure 9) is only partially automated and currently can only wire half a wire plane in a single operation. Working with PSL, the UK engineering design staff (**Grant**, **Muir**, **Freestone**) will advance the design such that it is fully automated,

allowing for full production readiness. The task also includes the design and assembly of the process cart (**Bitadze**) and the development and manufacture of custom tooling, as well as the control software. Based on the actual costs of the existing design as produced by PSL, the cost of the more complex fully-automated wiring machine is estimated to be £145k.

Figure 9: The ProtoDUNE wire-winding machine at PSL with the 6×2.3 m^2 APA frame mounted.

The APA frames for SBND have been successfully constructed in the UK using a welding technology, while a bolted-frame technology is used for ProtoDUNE. The required flatness and rigidity tolerances of the 6×2.3 m^2 APA frame represent significant engineering challenges for both approaches. The cost of a single "bare" frame, which meets the required tolerances, is currently expected to be about £50k. Further design studies will be pursued to determine the optimal process for mass production (**McConkey**, **Wright**), including comparisons between the welded and bolted approaches.

A number of distinct types of PCB boards are mounted on the bare APA frames. These include edge boards for positioning the wires, wire readout boards at one end of the APA, and CCR boards for the isolation of the APA HV from the readout. The boards for the UK far detector APAs would be produced in UK industry. As part of this pre-construction phase proposal, potential UK vendors will be identified (**McConkey**, **Wright**). Sufficient boards will be purchased to enable a single APA to be produced with the fully-automating wire-winding process.

The full APA construction will be tested by producing a single APA with the new wire-winding process (**Grant**, **Muir**, **Freestone**). This essential step will demonstrate the complete process in time for the LBNC and DOE CD-2 reviews of the DUNE TDR in 2019. By prototyping the process in 2019, it will be possible to move to final engineering design and a production readiness review in early 2020. Wire winding will take the place in the second half of the grant, requiring a team of two: an engineer who is familiar with the wiring machine and a technician.

Deliverable D5.1 (Q4 2017): Design of APA frames.

Deliverable D5.2 (Q2 2018): Delivery of a prototype APA frame.

Deliverable D5.3 (Q1 2019): Fully-automated wire winding machine ready for APA construction.

Deliverable D5.4 (Q3 2019): Assembled prototype APA.

WP5.2: Site Preparation and Process Definition (Grant)
The "Inner Hall" on the Daresbury site has been identified as an area that is sufficiently large to be used as the production area for APA construction. It has good access and crane coverage throughout but is currently being used as a stores building. Daresbury Laboratory management have agreed that the area is available but it would need investment to establish a safe working environment. This task focuses on performing the early preparation work for the construction area (**Grant**, **Muir**) required for production to start in 2020. The infrastructure investment is needed for:

- clearing the area of existing equipment;
- installation of ventilation, heating and sufficient power distribution for the purposes of APA construction;
- installation of a large clean-tent.

The work will be completed in time for the production of the prototype APA. The total cost for the early infrastructure preparation is estimated to be £200k. This will allow the Inner Hall to be used for the production of the prototype APA. This experience will help identify any site specific issues for the mass production. Additional infrastructure work will be required ahead of mass production and this would be requested in the production proposal.

Deliverable D5.5 (Q2 2018): Early preparation of the production area and clean room installation.

WP5.3: Quality Assurance/Quality Control (Nowak)

The elements of the DUNE far detector TPC will operate within a liquid argon volume for two decades and once the cryostat is closed they are effectively inaccessible. For these reasons detailed quality assurance and quality control procedures are a critical part of the production process. A number of testing procedures need to be established to ensure that the APAs fulfil the quality criteria required for reliable long-term operation within the liquid argon volume. Particular concerns are the flatness of the APA frames and PCBs, the tensioning and stability of the wires, electrical continuity, and the behaviour under cool-down conditions.

Cold testing is an essential part of QA/QC process for APA production. It requires a dedicated cryogenic vessel where APAs can be cooled down to liquid argon temperatures in order to establish mechanical and electrical integrity. A cryo vessel will be designed (**Chapman**, **Mercer**) and manufactured for this purpose, based on the ProtoDUNE and SBND experience. Ideally, the APA would be suspended in the vertical position to ensure the mechanical stresses are the same as will be experienced in the DUNE detector. The cryo vessel, with the APA inserted, will be cooled with gaseous nitrogen under controlled conditions. The thermo-mechanical measurements will include: a survey of the bending and distortion of the APA frame structure and comparison with FEA calculations (**Gamble**) as well as tests to verify the electrical integrity. The cryo vessel and metrology equipment that will be built during this project will be useable for the mass production of the APAs.

Wire breakage presents a major technical risk to the DUNE far detector project. A number of mitigation measures are already in place. For example, the wires will be both soldered *and* glued on the mounting boards. However, ensuring uniform wire tension within the specified tolerance is a critical part of the QA/QC process. A number of systems for the measurement of the tensions of large numbers of wires have been considered and small-scale tests have been performed (**Gamez**). At this time, two systems are being considered, both based on measuring the oscillation frequencies of the wires, either using laser measurements or by measuring the capacitance between two adjacent wires. A reliable and easy-to-use system for mass production will be developed (**Gamez**).

Deformations of the large APA steel frames need to be controlled to the sub-mm level before and after the cool-down test. A two-stage process is planned. Initial metrology tests will be developed with the APA frame manufacturer (**Gamble**, **Wright**). In addition a sophisticated geometrical quality control system will be developed (**Jones**, **Sutcliffe**), based on a laser tracker system with non-contact metrology. This has been successfully deployed for metrology tests of the ATLAS detector systems at Liverpool. The system will enable the APA to be continuously monitored at all stages of the production cycle, before and after the cold tests.

Deliverable D5.6 (Q3 2018): Wire tensioning system.

Deliverable D5.7 (Q4 2018): Cryo vessel built ready for testing of the APA prototype.

WP5.4: Photon Readout System (Szelc)

Liquid argon is an excellent scintillator and collection of the scintillation light can complement the read out of the ionisation signals in the LAr TPC. Efficient light collection can be used to improve energy reconstruction, timing resolution and to determine the position of the event in the TPC, allowing for intelligent triggering. The light collection system in DUNE is still under development and the current design does not provide the necessary uniformity of light collection.

UK scientists (**Gamez**, **Szelc**) have provided a demonstration that it is possible improve light collection yield and uniformity by installing wavelength-shifter covered reflector foils on the cathode planes of a LAr TPC. This has been shown to work at smaller scales in the LArIAT detector (**Gamez, Szelc**). Here it is proposed to develop and build a dedicated test-stand to test the efficiency of different wavelength-shifter (WLS) compounds and the behaviour of the evaporated foils at high voltage with a resistive cathode as well as for the foils. The aim is to develop an industrial-scale method of preparing the foils for DUNE, including assuring the long term stability of the foils. This work will be undertaken in the Manchester liquid-argon laboratory. Resources are requested for a test chamber and consumables to produce different substrate foils and wavelength-shifter compound combinations.

Deliverable D5.8 (Q1 2018): Selection of optimal WLS compound/substrate foil combination.

Deliverable D5.9 (Q3 2018): Demonstrated technology to produce large scale areas of WLS foils.

WP5 Milestones

M5.1 (Q4 2017): Design review for prototype APA.
M5.2 (Q2 2018): APA frame complete and delivered.
M5.3 (Q2 2018): Beneficial occupancy of the production area and clean room.
M5.5 (Q2 2018): Design of the wire tension measurement complete.
M5.6 (Q2 2018): Select WLS compound/foil/coating
M5.6 (Q3 2018): QA/QC database system designed.
M5.4 (Q4 2018): Cryo vessel built and available for testing.
M5.7 (Q4 2018): Demonstration of foil technology with DUNE electric field conditions
M5.8 (Q1 2019): Review of winding machine production readiness.
M5.9 (Q2 2019): Technology to produce foils stable on long time scales.
M5.10 (Q3 2019): APA prototype built and tested.

Task	Item	cost in k£		
		FY17	FY18	FY19
5.1	APA Steel Frame		50	
5.1	Geometry Boards	20	30	
5.1	Wiring Machine	145		
5.2	Daresbury Infrastructure	100	80	20
5.3	Cryovessel		20	5
5.3	Wire tension system		5	
5.3	Metrology System	25	25	
5.4	TBP-coated Foils/Test Chamber	10	38	0
	Total	245	278	50

Table 2: WP5 equipment costs.

7. Descoping Scenarios

In the last year of the DUNE preparatory-phase grant the total new cost to STFC was £0.9M. In addition, the supplemental grant for ProtoDUNE construction is £0.45M per annum over two years. Hence to maintain the current volume of activities, the total new cost to STFC would be £2.7M over the two years of the proposed pre-construction grant. The total new cost of the programme outlined in this proposal is £4.0M. The increased annual spend reflects: i) the status of the international project, where we are now confident that construction of the far detector components will commence in 2020 and ii) the growth in DUNE-UK (Birmingham, Bristol, Edinburgh and STFC-DL). Descope options are presented between the baseline request (£4.0M) and a continuation at the current level of funding (£2.7M).

7.1 Baseline request: 100%, total new cost £4.0M

The breakdown of staff and new costs by work package is summarised in Table 3. In addition to the numbers shown, £400k is requested for travel and subsistence, and £200k is the estimated level of working allowance. The request for project-funded staff is dominated by named existing posts (29.6 out of 35.8 FTE·years). Removal of all project-funded new (unnamed) staff would reduce the total project cost by £391k. Hence, descope options beyond 10 % inevitably will impact the ability of DUNE-UK to retain existing posts through to a construction project.

	FTE·years				New Cost (£k)			
	Project	CG	Other	Total	Staff	Equip.	LTA	Total
WP0	0.0	1.6	0.8	2.4	0	0	0	0
WP1	4.1	1.0	0.0	5.1	326	0	0	326
WP2	4.0	1.2	0.8	6.0	312	0	0	312
WP3	10.0	10.5	1.7	22.5	786	117	0	903
WP4	5.6	6.9	2.1	14.6	412	20	60	492
WP5	12.1	3.2	2.8	17.1	755	573	0	1328
Total	35.8	24.4	8.2	67.7	2593	710	60	3363

Table 3: Breakdown of FTEs and new costs by WP. The CG count includes PPD baseline staff.

The descoping scenarios presented below are intended to indicate the impact of a reduction in requested resources. This project proposal is already lean and all descoping options result in either a loss of research volume and/or increased risk of not achieving the stated goals. Two possible scenarios for a 10% descope are presented (1A and IB). Scenarios 1A and IB are combined to give a 20% descope, resulting in a very significant impact to the DUNE-UK programme. The impact of a 30% descoping scenario would be extremely damaging. Nevertheless, three possible scenarios for a 30 % descope are presented (3A, 3B, 3C) to indicate the extreme negative impact.

7.2 Scenario 1: 90%, total new cost £3.6M

Two 10% descope scenarios are considered. The first shows the impact of removing specific tasks, whereas the second indicates the likely impact of reducing resources within a number of tasks.

Scenario 1A: 90%, total new cost £3.6M

The impact of this scenario would be to delay pre-construction infrastructure work and to decrease the breadth of the UK-led scientific activities.

- Removal of WP1.2 (Near Detector Design and Optimisation): This would break the connection between the UK prototyping of the high-pressure GAr-TPC concept for a near detector tracker and the DUNE-UK scientific activities. The impacts would be: i) loss of UK scientific

leadership within DUNE; and ii) reduction in the likelihood of deploying a UK-led technology in the DUNE near detector, which could be an attractive opportunity for new UK groups to participate in DUNE in the event of a down selection to single future long-baseline neutrino oscillation experiment in the UK.

- Removal of WP5.2 (Photon Readout System) capital: resulting in loss of UK intellectual leadership in developing a new technique with potential benefits to DUNE and other experiments.
- Removal of WP5.4 (Inner Hall site preparation): a reduction in £200k (infrastructure capital). The prototype APA would be produced in Hall B, which is currently being used for SBND and ProtoDUNE APA production. This would necessitate moving the wire-winding machine from Hall B to the Inner Hall at the start of far detector APA construction. The wiring machine would need to be dis-assembled, moved in parts and then re-assembled. There are a number of impacts: i) risks associated with reassembling the wiring machine, that could incur additional costs due to damage; ii) additional costs associated with setting up the wire-winding machine for a second time. iii) loss of the opportunity to perform early site preparation; iv) additional risk of the area not being available in time to start the UK APA construction; and v) loss of opportunity to gain experience of working in the Inner Hall and establish any infrastructure issues.

Scenario 1B: 90%, total new cost £3.6M

A 10% descope also can be achieved by a 25% reduction of PDRA effort in four of the five main work packages. These are almost all named posts. The overall impact would be a significant reduction in the involvement of young UK scientists at an important time for the scientific efforts of DUNE.

- Reduction of PDRA effort in WP1.1 (Near Detector Constraints and Oscillation Sensitivity): there are two main impacts: i) increasing the risk of WP1.1 not reaching its scientific goals in time for the DUNE TDR; and ii) failure to retain a highly-skilled member of the DUNE-UK team through to the start of construction.
- Reduction of PDRA effort in WP2.2 (ProtoDUNE reconstruction): effectively halving the effort available for UK-led ProtoDUNE-specific reconstruction development. This would reduce the influence and effectiveness of the UK in the exploitation of the ProtoDUNE data – a failure to exploit the existing UK investment.
- Loss of half a PDRA post in WP3: this would leave one of the five main contributing institutes without PDRA support for the DAQ development, significantly increasing the risk that the institutional commitments will not be met, damaging the overall UK DAQ effort.
- Removal of all PDRA effort in WP4.2 (SBND Installation and Commissioning) and reduction in effort in WP4.1 (ProtoDUNE Installation and Commissioning) with two main impacts: i) there would be no PDRA effort devoted to SBND commissioning, resulting in reputational damage from DUNE-UK delivering hardware to Fermilab without playing a major role in its commissioning; and ii) the UK would no longer commission and operate the ProtoDUNE purity monitors, which is an area of UK leadership within the ProtoDUNE organisation.

7.3 Scenario 2: 80%, total new cost £3.2M

Scenario 2 is the combination of scenarios 1A and IB, combining the negative impacts of both.

7.4 Scenario 3: ~70%, total new cost ~£2.8M

There are currently over 120 UK members of the DUNE collaboration. This group has the scientific and technical resources to continue to play a leading role in DUNE. Combining support for the scientific effort of a collaboration this large with two major UK prototyping efforts is unlikely to be possible at a total funding level of £2.8M or below. The options presented below are intended to indicate the major impact of a 30% reduction in funding. In practice, at this level of resource a new

more restricted programme of work would need to be constructed from scratch, but there would be an inevitable loss UK would world-class leadership.

Scenario 3A: ~70%, total new cost £2.8M

Removal of WP1 (Physics), WP2 (Reconstruction) and WP4 (Prototype detectors) and a corresponding reduction in travel. This would have a devasting effect on DUNE-UK. In each case the UK would have failed to exploit and build on previous investment. World-leading scientific leadership (physics and reconstruction) would be lost and the UK would have a very limited contribution to the installation, commissioning and operation and of UK hardware for SBND and ProtoDUNE.

Scenario 3B: ~70%, total new cost £2.8M

Removal of WP3 (DAQ) and WP5.4 (Inner Hall site preparation) and a corresponding reduction in travel resource. As a result, the UK would almost certainly lose the leadership of the DUNE DAQ. Only low-level DAQ development would be possible through the deployment of consolidated grant effort and it would not be possible to prototype the FPGA-based processing board or overall DAQ architecture. This would significantly damage the strategic aim of the UK taking the leading role in the far detector DAQ. The impact of losing WP5.4 was discussed in Scenario 1A.

Scenario 3C: ~66%, total new cost £2.6M

Removal of WP5 (APA pre-construction). This would most likely eliminate the possibility of the UK contributing a significant fraction of the APAs for the first far detector module. This would not only have a very negative effect on DUNE-UK, but could also delay the far detector construction. A significant UK contribution to the second far detector module would still be possible, but the UK would effectively be building to specification, without major intellectual and engineering input to the final design.

7. Summary

LBNF/DUNE is now an approved project in the US and the US DOE has legal authority to commit the $300M for construction of the underground far detector facility in South Dakota. DUNE represents a major scientific opportunity for the UK and for the global particle physics community. The UK particle physics community has responded to this opportunity, with DUNE-UK now numbering over 120 scientists and engineers; forty UK academics are signatories to this proposal. The UK has significant leadership within DUNE and is pursuing a clear plan for long-term UK contributions. The resources requested in this proposal will allow the UK to retain major scientific and technical leadership in DUNE and will enable DUNE-UK to perform the pre-construction work required to take a major role in the construction of the far detector DAQ and APAs, commencing in 2020. DUNE-UK has the strength and depth to undertake such a major long-term construction project.

The international commitments for the construction of the first two far detector modules will need to be defined at the time of the DUNE TDR for the DOE CD-2/3 review 2019. With the resources requested in this proposal, the UK will be in the position to make a commitment to the DUNE detector construction based on technical strength and well-understood costs.

The proposed investment will pave the way for a leading UK contribution to the construction of the largest international project ever hosted by the US, with the UK at the heart of the cutting-edge liquid argon detector technology.

Appendix: Financial Tables

	2017/18	2018/19	2019/20	Total
RESOURCE				
New Staff costs (including estates and indirects)	494	1144	568	2206
Total group costs	**494**	**1144**	**568**	**2206**
Laboratory costs				
Staff PPD staff costs (including overheads)	16	32	16	64
Staff TD staff costs (including overheads)	57	178	89	323
Travel and subsistence	125	235	100	460
Consumables/equipment under £10k	5	10	5	20
Working allowance	25	100	75	200
Total laboratory costs	**228**	**555**	**285**	**1067**
CAPITAL				
Equipment	289	307	94	690
Total equipment	**289**	**307**	**94**	**690**
EXISTING PROJECT COSTS				
Consolidated grant effort	274	538	264	1076
RAL PPD baseline staff	42	116	66	225
Total existing costs	**317**	**654**	**330**	**1301**
GRAND TOTAL				
Total new cost to STFC	1010	2006	947	3963
Overall project cost	1327	2660	1277	5264

Table 4: Summary of Total Costs

Appendix: Staff Tables

Staff type	2017/18	2018/19	2019/20	Total
New staff				
RA	4.43	10.75	5.23	20.40
Technicians	2.53	5.75	2.93	11.20
RAL PPD	0.25	0.50	0.25	1.00
RAL TD	0.60	1.70	0.85	3.15
Existing staff				
CG academic	3.51	6.85	3.83	14.18
CG core post	0.00	0.00	0.00	0.00
CG RA	1.98	3.65	1.58	7.20
CG technicians	0.77	1.55	0.82	3.14
RAL PPD baseline	0.35	0.95	0.55	1.85
Total new posts	**7.80**	**18.70**	**9.25**	**35.75**

Table 5: Staff Effort Summary

Staff type	2017/18	2018/19	2019/20	Total
Existing staff				
CG academic	0.40	0.80	0.40	1.60
RAL PPD baseline	0.30	0.60	0.35	1.25
Total new posts	**0.00**	**0.00**	**0.00**	**0.00**

Table 6: WP 0 Summary

Staff type	2017/18	2018/19	2019/20	Total
New staff				
RA	0.80	2.00	1.30	4.10
Existing staff				
CG academic	0.13	0.15	0.13	0.40
CG RA	0.30	0.20	0.10	0.60
RAL PPD baseline	0.05	0.15	0.10	0.30
Total new posts	**0.80**	**2.00**	**1.30**	**4.10**

Table 7: WP1 Summary

Staff type	2017/18	2018/19	2019/20	Total
New staff				
RA	1.00	2.00	1.00	4.100
Existing staff				
CG academic	0.30	0.60	0.30	1.20
Total new posts	**1.00**	**2.00**	**1.00**	**4.00**

Table 8: WP2 Summary

Staff type	2017/18	2018/19	2019/20	Total
New staff				
RA	1.50	3.00	1.50	6.00
Technicians	0.75	1.50	0.75	3.00
RAL PPD	0.25	0.50	0.25	1.00
Existing staff				
CG academic	1.48	2.85	1.42	5.75
CG RA	0.96	1.93	0.86	3.75
CG technicians	0.55	1.10	0.60	2.25
RAL PPD baseline	0.00	0.20	0.10	0.30
Total new posts	**2.50**	**5.00**	**2.50**	**10.00**

Table 9: WP3 Summary

Staff type	2017/18	2018/19	2019/20	Total
New staff				
RA	1.30	3.00	1.30	5.60
Existing staff				
CG academic	0.96	1.95	1.32	4.23
CG RA	0.61	0.83	0.31	1.75
CG technicians	0.22	0.45	0.22	0.89
Total new posts	**1.30**	**3.00**	**1.30**	**5.50**

Table 10: WP4 Summary

Staff type	2017/18	2018/19	2019/20	Total
New staff				
RA	0.33	1.75	0.63	2.70
Technicians	1.28	3.25	0.63	6.20
DL TD	0.60	1.70	0.85	3.15
Existing staff				
CG academic	0.25	0.50	0.25	1.00
CG RA	0.10	0.70	0.30	1.10
CG technicians	0.00	0.00	0.00	0.00
Total new posts	**2.20**	**6.70**	**3.15**	**12.05**

Table 11: WP5 Summary