FLArE Technical Design

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FLArE: Forward Liquid Argon Experiment

Broad range of physics topics:

Neutrino physics: high-statistics samples of all flavors, cross-section measurements, neutrino tridents

QCD physics: accessed both in production and in DIS at the FPF; can study small-x proton structure, BFKL dynamics, intrinsic charm, nuclear structure functions



BSM physics: light dark matter scattering (produced by decay of mesons in forward direction) complementary with missing transverse energy collider searches and with direct detection of relic DM

FLArE: Forward Liquid Argon Experiment

Lots of progress since FPF7!

- Simulations (see Matteo's talk)
- TPC design
- Installation plan
- Cryogenics & heat load
- Electronics

We have prepared a detailed technical note on the design, which we plan to make available in draft form this week.

Scientific Requirements

Label	Description
OG-1	Measure the neutrino flux for all flavors
OG-2	Measure the neutrino cross-section for all flavors
OG-3	Search for neutrino-philic new physics
OG-4	Charm and QCD measurements
OG-5	Detection of direct light dark matter scattering
OG-6	Operation in high-rate environment

Table 2: Summary of the overarching physics goals for FLArE.

We start from a set of overarching physics goals, from which we derive eleven measurement requirements.

From the measurement requirements, we then derive a set of specific capability requirements (see next slide)

Label	Description	Event rate	Rationale	Threshold	$\Delta E/E$	Supports
MR-1	Measure CC ν_{μ} events.	203k – 268k	FLArE must be able to identify and recon- struct ν_{μ} -Ar events.	10 GeV	30%	OG-1 OG-2 OG-3
MR-2	Measure CC ν_e events.	36k – 113k	FLArE must be able to identify and reconstruct ν_e -Ar events.	10 GeV	30%	OG-1 OG-2 OG-3 OG-4
MR-3	Measure CC ν_{τ} events.	1.5k – 4k	FLArE must be able to identify and reconstruct ν_{τ} -Ar events.	10 GeV	30%	OG-1 OG-2 OG-3 OG-4
MR-4	Measure $\nu - e$ elastic scatter- ing.	110	Flux can be extracted exploiting the well- known cross-section for $\nu - e$ elastic scattering.	1 GeV	10%	OG-1 OG-2 OG-4
MR-5	Measure inverse muon decay (IMD).	440	Flux can be extracted by exploiting the ν_{μ} + e process with well- known cross-section.	11 GeV	20%	OG-1 OG-2 OG-4
MR-6	Measure low- ν events.	1% of CC rates	Flux can be extracted by exploiting the flat energy dependence of low recoil events.	-	10%	OG-1 OG-2 OG-4
MR-7	Measure neu- trino tridents	25	FLArE must be able to search for neutrino tridents.	100 GeV	30%	OG-3
MR-8	Measure sterile neutrino oscilla- tion	1.5k – 4k	FLARE must be able to search for ster- ile neutrino oscilla- tions with tau neutri- nos.	10 GeV	10-20%	OG-3
MR-9	Measure low- energy electron recoils	BSM	FLARE must be able to search for DM scat- tering on electrons.	< 1 GeV	10%	OG-5
MR-10	Measure low- energy nuclear recoils	BSM	FLArE must be able to search for DM scat- tering on nucleons	< 1 GeV	10%	OG-5
MR-11	Assess muon- induced back- ground.		FLArE must be able to monitor the muon- induced background.	2	-	OG-6

Table 3: Summary of the measurement requirements for FLArE. Event rates are per 3000 fb^{-1} (total expected luminosity) and 10 ton of liquid argon (FLArE fiducial mass). Please note that 1 fb⁻¹ corresponds to roughly one day of HL-LHC operations.

Scientific Requirements

Label	Description	Specification	Rationale	Subsystem
CR-1	Fiducial mass	$m \sim 10$ ton	FLArE fiducial mass must be enough to collect sufficient statistics for potential new physics signatures as well as neutrinos of all flavors.	TPC
CR-2	Muon ID	$ \begin{array}{c} \text{Efficiency} \\ \gtrsim 50\%, \text{purity} \\ \gtrsim 80\% \end{array} $	FLArE must be able to tag muons using combined informa- tion from all subsystems.	TPC, HadCal, External Spec- trometer
CR-3	Electron ID	Efficiency $\gtrsim 50\%$, purity $\gtrsim 80\%$	FLARE must be able to tag elec- tron showers in the TPC.	TPC
CR-4	Tau ID	Efficiency $\gtrsim 20\%$, purity $\gtrsim 60\%$	FLArE must be able to tag tau leptons in the liquid argon vol- ume via their decays.	TPC
CR-5	Muon momentum	$\delta_p < 5\%$	FLARE must be able to recon- struct the muon momentum us- ing combined information from all subsystems.	HadCal, Exter- nal Spectrome- ter
CR-6	Event containment	$\gtrsim 80\%$	FLARE must be be able to con- tain fiducial events within its ac- tive volume to collect all the available visible energy.	TPC, HadCal
CR-7	Phase space coverage	$\gtrsim 80\%$ coverage	FLARE must be able to cover most of the phase space limit- ing event topologies or kinemat- ics where the hadron shower is not contained.	TPC, HadCal
CR-8	Lepton kinematics	Efficiency ≥ 50%	FLArE must be able to recon- struct the lepton kinematics with good efficiency.	TPC, HadCal, External Spec- trometer
CR-9	Vertex kinematics	$ \begin{split} \delta_x &\sim \mathcal{O}(1 \text{ mm}), \\ \delta_\theta &\sim \mathcal{O}(1^\circ) \end{split} $	FLArE must be able to recon- struct vertex kinematics resolv- ing track angle and momentum for the outgoing particles with sufficient resolution.	TPC
CR-10	Scintillation timing	$\delta_t \sim O($ ns $)$	FLArE must be able to achieve a ns-level scintillation timing reso- lution to separate the pile-up of interactions per bunch crossing.	TPC

These capability requirements are meant to justify the design choices we make in the rest of the document.

Table 4: Summary of the capability requirements for FLArE. An initial set of specifications has been derived based on feasibility estimates of the current design. These are conservative, and driven mostly by neutrino physics.

TPC Design

Our baseline design includes 21 TPC modules, arranged in 3 rows of 7.

1.8 m

Also considering alternative optical readout design (see Kostas's talk yesterday).

Each module contains 2 drift volumes.

Anode readout is pixellized, with 5 mm. spacing.



7 m

Parameter	Value	comment
TPC liquid fill	LAr	radiation length 14 cm
Modules	3 (Wide) x 7 (Length)	21 modules
Module dimension	60 cm (W)x 100 cm (L) x 180 cm (H)	approximate
Gap length	30 cm	Cathode in center
Drift field	500 V/cm	
Max voltage	15000 V	
Anode pixel size	4 mm x 4 mm	5 mm spacing
Charge channels/anode	72000	two anodes per mod
Photon system	WLS plate with TPB	
SiPM channels/anode	50	

Table 8: Preliminary parameters for the FLARE TPC.

TPC Design

The TPC design has been modified from top-installation to a side-installed "filing cabinet" design.

This avoids issues with crane height in installation from above, while the modules remain easily removable for repair.

The GTT membrane cryostat has been replaced with a foam-insulated cryostat.



TPC Design

Each unit of three modules is supported from the "door" by cantilever arms.

Mass of the three-module unit is 1088 kg.

Each module contains a cathode plane in the center and an anode on either side.



A sketch of an installation procedure has been created by our engineering contractors, Larry Bartoszek and Chris Daurer.

The side-loaded design is based on work Larry did for EXO.

A custom Installation Machine is required, as well as a TPC assembly cart.

The following slides show an outline version of the installation procedure - the full set of slides from Larry is attached to this talk on Indico.

Foam supports, bottom, and back blocks are installed.



Lowering the cryostat box down the access shaft



The welded SS box weighs 19.78 tonnes

View showing that the cryostat must be the first item in the beam line



Once the cryostat is rotated level with the floor and placed on a rolling dolly, it is clear from this picture that it cannot be rolled down the tunnel with the other beam elements in place, especially the FASER 2 tracker planes.

Cryostat placed on bottom foam



It is a judgement call about whether the back foam or the cryostat gets placed on the bottom foam first. It depends on the fixturing required to do the moves.

Placing the top block of foam above the cryostat



Removal procedure shown (installation is the same, in reverse).



Installation machine pins to attachment lugs on the face of the TPC module.



The adjustments of all of the degrees of freedom on the installation machine line up the machine to the position of the TPC module lift points. If the modules are sealed with bolts and a Jetseal metal o-ring, all bolts are removed at this point. If the modules are welded $_{16}$ into the cryostat, the weld must be ground.

The TPC Module is translated out of the Cryovessel on the Installation Machine's linear bearings on the X axis.



Close-up of roll, yaw, and Y translation mechanisms, looking US and to beam left



The rod ends on the ends of the yellow arms that attach to the TPC lift brackets can be extended or retracted to provide yaw adjustment

Y adjustment

Roll is accommodated by a turret bearing not visible behind the red plate.

This mechanism is a conceptual model adapted from the installation machine built for the EXO cryostat. It will need further engineering to ensure the stability and capacity of the mechanism.

The EXO machine was all manually operated, being smaller and manipulating a smaller mass. It remains to decide which axes are motorized. **Installation** The Installation Machine translates the TPC Module to the Assembly Cart. The Installation Machine lowers the TPC Module onto open hooks of the Assembly Cart.



The handoff takes place by adjusting the Installation Machine to transfer the load to the Assembly Cart, then the pins are removed from the attachment lugs connected to the Installation Machine.

Alternative Design: Optical Readout

 An alternative design using an ARIADNE-style optical readout is also being considered (see Kostas's talk yesterday).

- Technology already well developed and demonstrated.

- Liverpool is interested in delivering the light readout plane and the optical system for FLArE.

- This design offers ~20% cost savings.

- Challenge: Not modularized. The longer drift length means more diffusion and space charge.



Figure 27: A conceptual model of a 3D optical dual-phase TPC option for FLArE.



Figure 28: A conceptual model of a vacuum jacketed commercial cryostat with a reopen-able lid for the dual phase fast optical readout option. The cryostat lid will open with hydraulic arms instead of a crane since 20 there is not enough height clearance.

Cryogenics and Heat Load



Figure 8: The cryogenic system schematic of FLArE Cryostat.

Conceptual cryogenics design uses a commercially-available Turbo-Brayton pump for cooling. Max. cooling power 16.5 kW at 77 K.

Circulation system continually purifies argon. Uses now-standard LAr purification strategy of filters, molecular sieves, and getters.



Cryogenics and Heat Load

Preliminary heat load estimates are well within the 16.5 kW capacity of the Turbo-Brayton.

Heat load from the environment is estimated at about 2.7 kW.

Heat load from electronics depends on readout choices, but in worst case we expect to keep it < 2.4 kW.

Heat Source	Heat Load (Watt)
Leak in cryogenic piping	1000
Radiation from the top	40
Conduction thru gas	30
Wall conduction	100
Penetration components	500
Liquid through cryostat wall	832
Convection	200
Total	2702

Parameter	Value	comment
Total capacity	32000 lt	Includes inactive region
Inner dimensions	$1930 \text{ mm} \ge 2394 \text{ mm} \ge 8788 \text{ mm}$	Cryostat internal dimensions
Outer dimensions	$3645 \text{ mm} \ge 3461 \text{ mm} \ge 10,039 \text{ mm}$	
Ave. Insulation thickness	600 mm	
Material	Rigid polyurethane foam	
Maximum Design Pressure	34.5 kPa	
Weight of the Stainless Vessel	~ 20 Ton	
Estimated heat load from electronics	< 2400 Watts	
Estimated cryogenics heat load	2702 Watts	

Calorimeter





A downstream calorimeter is needed for energy containment.

Current design is based on BabyMIND, a design developed by T2K and deployed at J-PARC.

Consists of plates of magnetized iron interspersed with scintillator planes.

Magnet modules are individually magnetized by coils wound on their surface.

Scintillator bars read out by SiPMs via wavelength-shifting fibers.

Layout of BabyMIND shown at left, with scintillating strips in blue and magnetic modules in yellow. The exact configuration of these modules will be optimized for FLArE.

Electronics

Two main options for charge readout:

LArPix: Developed for DUNE near detector. Similar to conventional charge-sensitive amplifier with external reset. Digitization and readout only occur when amplitude exceeds a threshold.

Q-Pix: Developed by Q-Pix consortium. Integrates until a threshold is reached, then resets and reports the time. Essentially measures dt/dQ instead of dQ/dt.







Space Charge

Significant flux of muons makes space charge a concern.

Space charge is the underlying distribution of charge in the detector volume.



Ionizing particles produce not only electrons (which are removed from the volume relatively quickly) but also positive ions (which are removed much more slowly).

With a constant flux of ionizing particles, a persistent positive charge density builds up.

E-field near the anode is reduced, near the cathode is increased.

Space Charge: 1D Model

Palestini* presents a one-dimensional model for space charge effects.

Can be parametrized with dimensionless parameter α : $\alpha = \frac{1}{2}$

L = drift length

 E_0 = electric field in absence of space charge

 ϵ = permittivity of LAr

 μ^+ = ion mobility in LAr

 \boldsymbol{K} = charge density injection rate



Note:

- α is linear w.r.t. L and 1/E₀

- Effect on field is roughly quadratic in $\boldsymbol{\alpha}$
- Above $\alpha\approx 2,$ field at anode is zero and field at cathode increases ~linearly



*S. Palestini and F. Resnati. Space charge in liquid argon time-projection chambers: a review of analytical and numerical models, and mitigation methods. JINST, 16:P01028, 2021, 2008.10472

Space Charge: 1D Model

For FLArE:

L = 30 cm. for horizontal drift, 180 cm. for vertical drift

 E_0 is to be determined, but we've been thinking ~0.5 to 2.0 kV/cm.

 ϵ for LAr = 1.504 ϵ_0

 μ^+ for LAr has large experimental uncertainties; best fit value about 1.6E-7 m²/Vs

K is the product of:

- Flux of muons, about 0.77 hz./cm² for the right-side modules (less for others).
- Average dE/dx for muons in LAr, about 2.1 MeV/cm.
- Dimensionless recombination factor R in LAr, roughly 0.7±0.1 for E in range of 0.5 to 2 kV/cm.
- Elementary charge e
- Average ionization energy of an electron in argon, 23.6 eV

Some caveats:

- Our muon flux is not constant over the detector cross-section. This is a 1D model that ignores any effects from that variance.
- Uncertainties on μ^+ and R mean that there should actually be sizeable error bars on these numbers, but for now I'm ignoring those.

Space Charge: 1D Model

Plugging everything in, with a field of 1 kV/cm, we get $\alpha = 0.18$ for horizontal drift and $\alpha = 1.05$ for vertical drift. These correspond to a ~1% effect and a 20-30% effect on the field.

Note: This is for the "worst case" right-side modules. For the fiducial modules (0.44 hz/cm²), the numbers are $\alpha = 0.14$ for horizontal and $\alpha = 0.8$ for vertical drift.



For comparison, Palestini calculates α = 0.4 in ICARUS and 0.81 in MicroBooNE.

Cost

We include a preliminary estimate of core costs in the technical note.

Item	M&S/contracts (kCHF)	Labor (100 hrs)	Comment
Cryogenic Infrastructure	3782	TBD	
Cryostat/cryogenics	2626	TBD	To be reviewed
LAr	40	TBD	To be reviewed
Field structures	1102	23	Eng/Tech
Electronics	1638	115	Eng/Tech/Students
TPC HV	200	5	Tech
HV Feedthrus/cables	21	5	
LV Power	200	5	
Photon System	639	25	
Trigger system	200	35	
Muon System	4120	50	Baby-MIND design
Assembly	131	135	Techs/Students
DAQ	200	35	Staff/Students
Computers/Online	200	50	Staff/Students
Management		25	Technical Coordination
Prototypes	2000	TBD	R&D tech/students
Total core costs	10.65 MCHF		Excluding Cryogenics

The optical readout option is expected to be about 2 MCHF less.

Table 10: The core costs for materials, equipment and contracts is provided in column two, the estimated labor hours are in column four. The costs of cryogenic infrastructure, cryostat and liquid argon both near and far, is 6.5 MCHF. It is kept separate from the cost of the detector instrumentation.

Summary

A tremendous amount of work has been done on the FLArE design in the past year.

The design and simulation technical notes will shortly be available in draft form - it would be very helpful if we could get a few people from this group to review them.

Thanks to the team that has put these notes together, especially: Milind Diwan, Matteo Vicenzi, Wenjie Wu, Yichen Li, Connor Miraval, Larry Bartoszek, Jianming Biang, Kostas Mavrokoridis, and Aleksey Bolotnikov.