Forward Physics Facility @ LHC: experiment design and impact on infrastructure

Jamie Boyd (CERN)
On behalf of the FPF working group

PBC annual workshop, CERN
25/3/24

Ackowledgments:
Anastasiya Magazinik (EN-ACE),
Kincso Balazs / John Osborne/ Tamara Bud (SCE-SAM-FS),
Akitaka Ariga / Tomoko Ariga (FASERv2),
Hidetoshi Otono / Josh McFayden / Olivier Salin / Alan Barr (FASER2),
Matthew Citron / Juan Vargas (FORMOSA),
Milind Diwan / Steven Linden / Steven Trabocchi / Larry Bartoszek (FLArE)

FPF 7th workshop

- FPF7 workshop held at CERN Feb 29 – Mar 1:
  - https://indico.cern.ch/event/1358966/timetable/?view=standard
  - 135 people registered, ~50 in person at CERN
- Broad programme covering facility, experiments, physics, and funding/collaboration topics
- Lots of progress in many areas shown
- This talk is a summary of the technical progress shown in the workshop, covering:
  - Civil engineering, integration and the experiment deisgn (including infrastructure requirements)

Reminder: site investigation (single core sample drilled) done: March/April 2023

Forward Physics Facility

Site Investigation Works

➢ Drilling machine in place

➢ Works started

➢ Core samples

Site Investigation Works

Results and Recommendations

Results

- Ground found mostly competent for tunnelling purposes
- Signs of hydrocarbons were found in the soft sandstone at depths between 84m and 90m
- Foundations of the surface buildings will sit within competent moraine
- No water table has been identified. Overall the ground is not very permeable.
- Vertical swelling test carried out showed a high swelling potential.
- Slight exceedance shown of fluoride levels in the existing backfill material.

Recommendations

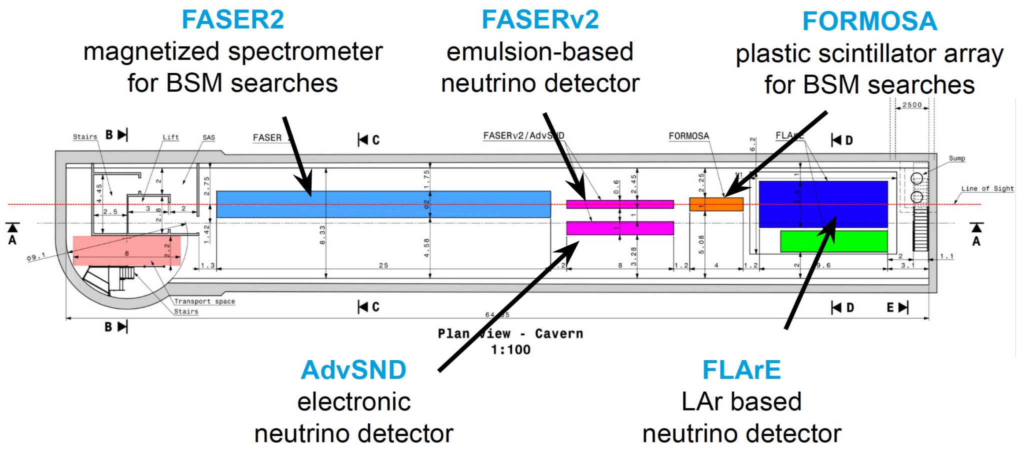
- Excavation material contaminated with liquid hydrocarbons will require specific spoil management
- Underground tunnels and works in contact with soils contaminated with hydrocarbons will require specialised waterproofing membrane
- Swelling pressures to be considered during the design of the final lining
- Existing backfill material will need to be disposed of at appropriate facilities

Summary: Ground conditions are favourable, with some attention needed to hydrocarbons, fluoride and swelling

Based on site investigation findings, and other factors (inflation) an updated cost estimate for the facility was produced, and validated by an external experts. This led to the estimated cost of 30MCHF for the CE works (was 25MCHF).

Evolution of facility

- Original facility layout based on rough sketches of the proposed experiments. Allocated space mostly for fiducial volume for physics.

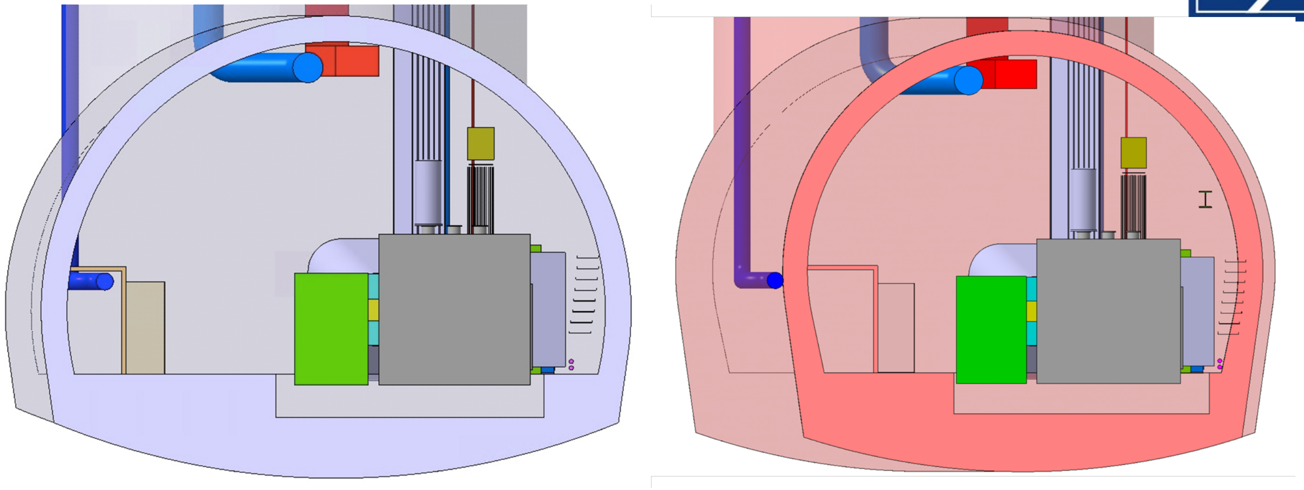


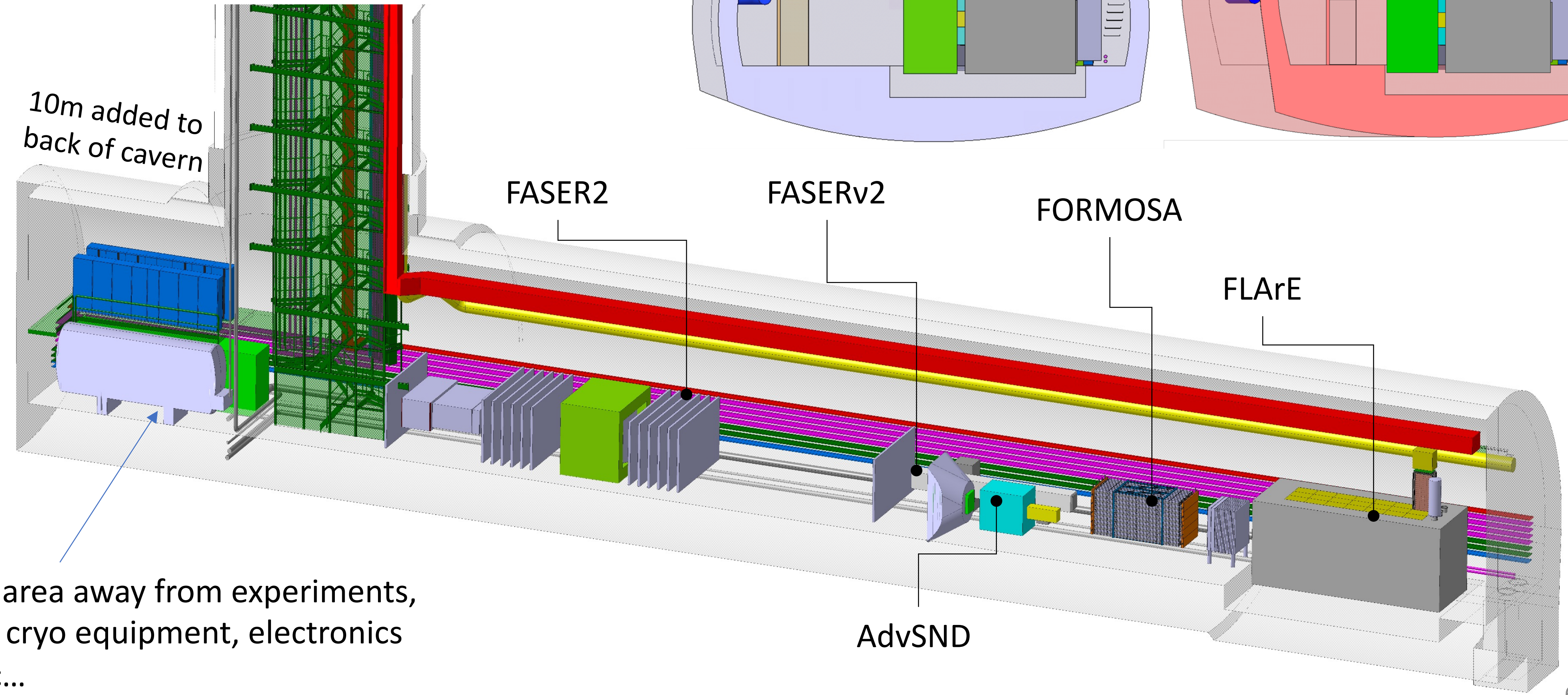
- Over the last 9 months started a more rigourous integration effort, including:
  - CAD models of detectors, including support structures etc..
  - Include main infrastructure (cryogenics, electronics racks, cable trays, piping)
- Quickly became clear that this will not all fit in original cavern layout
- Discussed with civil engineering experts the most affordable options for creating more space
- Based on this have come up with a new baseline:
  - 10m longer, 1m increase in radius
  - CE estimate that this is ~10% more expensive

Evolution of facility

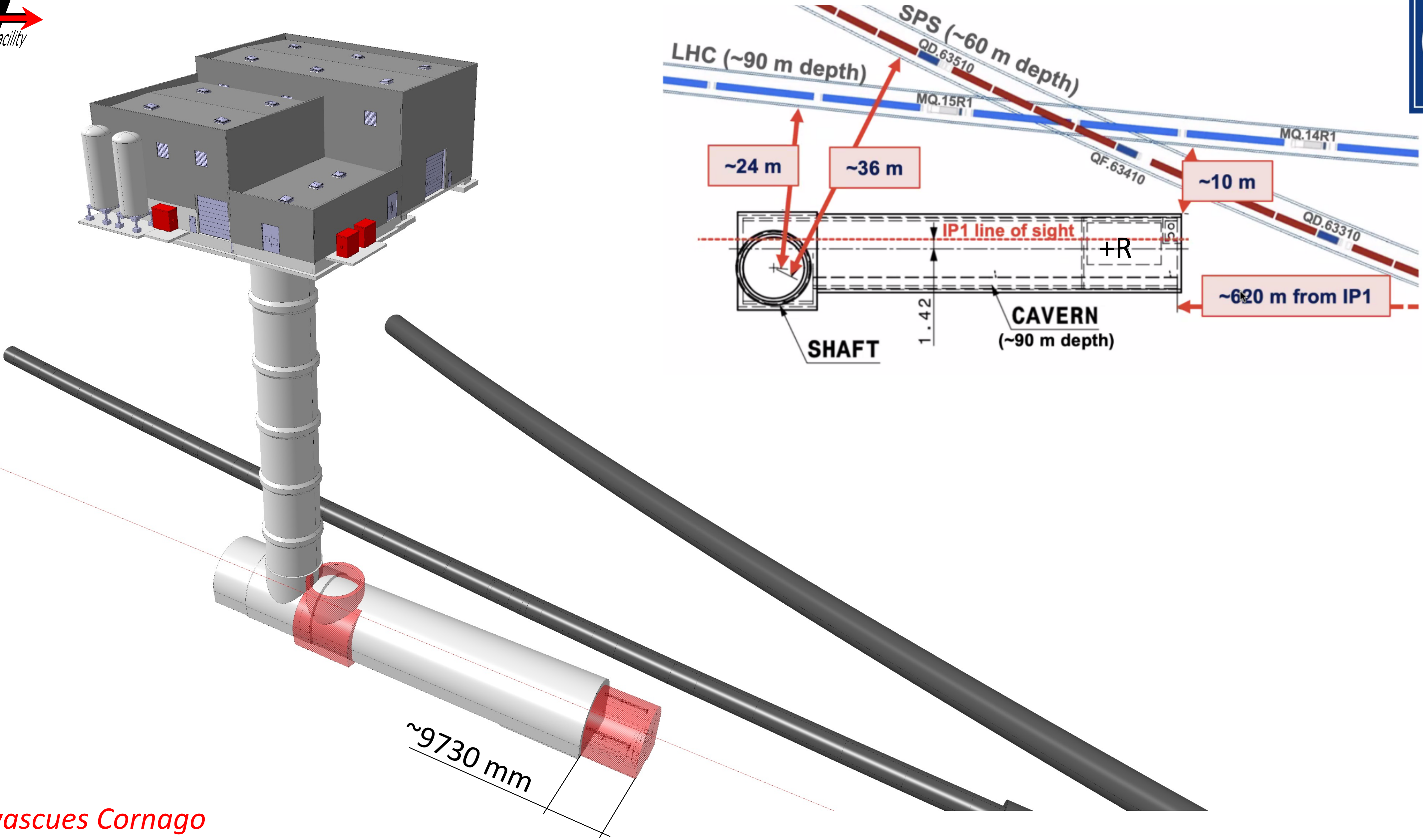
Added 10m in length, and increased transverse radius by 1m

Transverse view



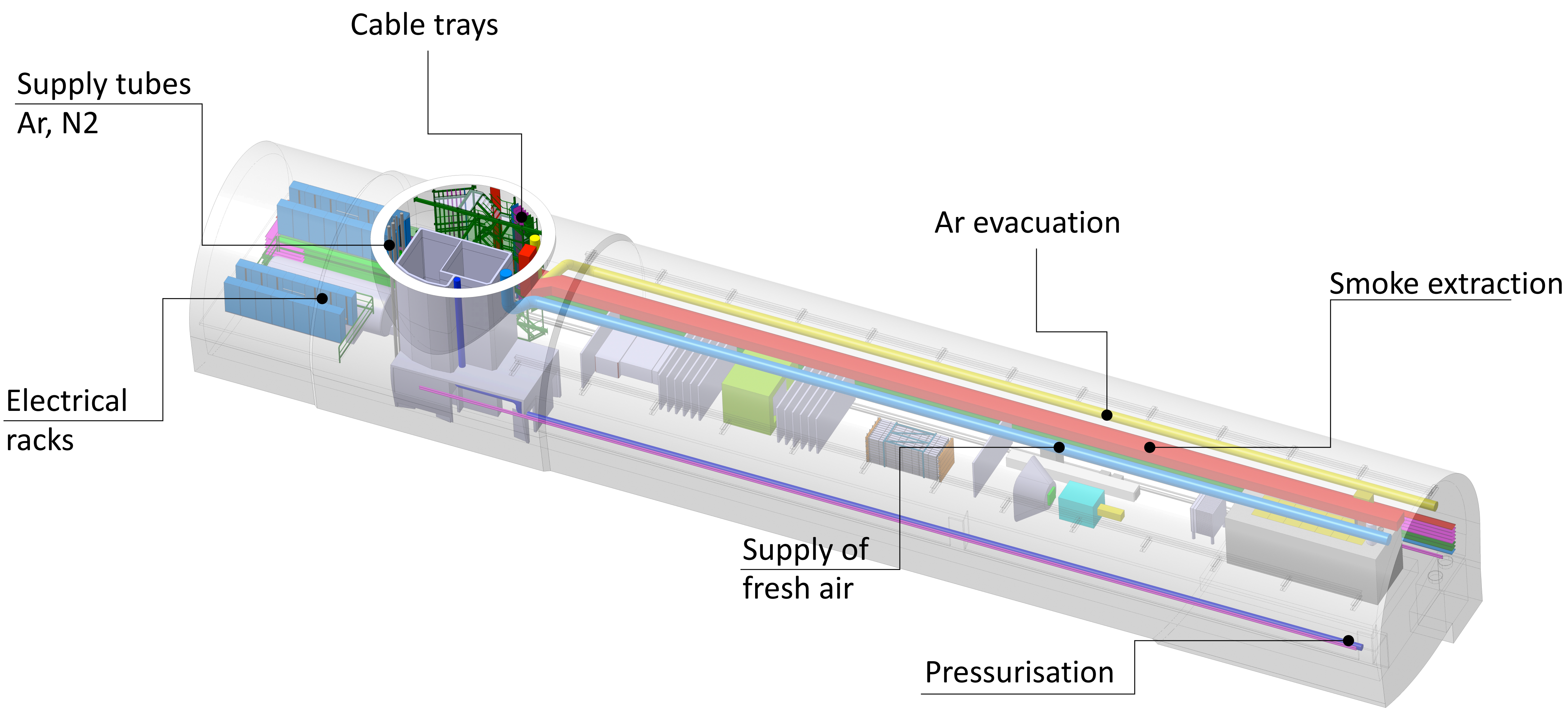


Services area away from experiments, contains cryo equipment, electronics racks etc…



Angel Navascues Cornago

Integration – adding services



Technical Progress During 2023

Study	Status	Conclusion
Excavation works during beam operation?	Sudy by CERN beam physics group. **Complete**	Vibrations / tunnel-movement not expected to be an issue [1]
Access to cavern during beam operation?	Study by CERN Radioprotection group. **Complete**	Can access cavern for people classified as radiation workers. [2]
Muons background flux	Simulation study by CERN FLUKA team. Complete	Expected muon flux O(1Hz/cm^2) within 1m or LOS. Generally OK for experiments. [2]
Geological conditions	Site investigation works carried out by CERN civil engineering group (with contractor GADZ SA). **Complete**.	Geological conditions look good for proposed works. [3]
Is one access point to facility OK for safety?	Study by CERN safety team. **Complete**.	Addition of over pressure safety corridor along the facility length allows only 1 access point. [2]
Preliminary facility CE costing	First CE works costing updated based on site investigation and checked by external conractor (ARUP). **Complete**.	CE costs for baseline facility 30MCHF. (Class 4 costing)

[1] – "Impact of vibration to HL-LHC performance during FPF facility construction", https://doi.org/10.18429/JACoW-IPAC2023-THPA039

[2] – "Update on the FPF Facility technical studies", https://cds.cern.ch/record/2851822/

[3] – "Forward Physics Facility: Geotechnical Report", GADZ SA, https://edms.cern.ch/document/2910442/1

Technical Progress During 2023

Study	Status	Conclusion
Excavation works during beam operation?	Sudy by CERN beam physics group. **Complete**	Vibrations / tunnel-movement not expected to be an issue [1]
Access to cavern during beam operation	Study by CERN Radioprotection group. **Complete**	Can access cavern for people classified as
Muons backgro		$/cm^2$) within 1m or riments. [2]
Geological cond	Complete.	good for proposed
Is one access point to facility OK for safety?	Study by CERN safety team. **Complete**.	Addition of over pressure safety corridor along the facility length allows only 1 access point. [2]
Preliminary facility CE costing	First CE works costing updated based on site investigation and checked by external conractor (ARUP). **Complete**.	CE costs for baseline facility 30MCHF. (Class 4 costing)

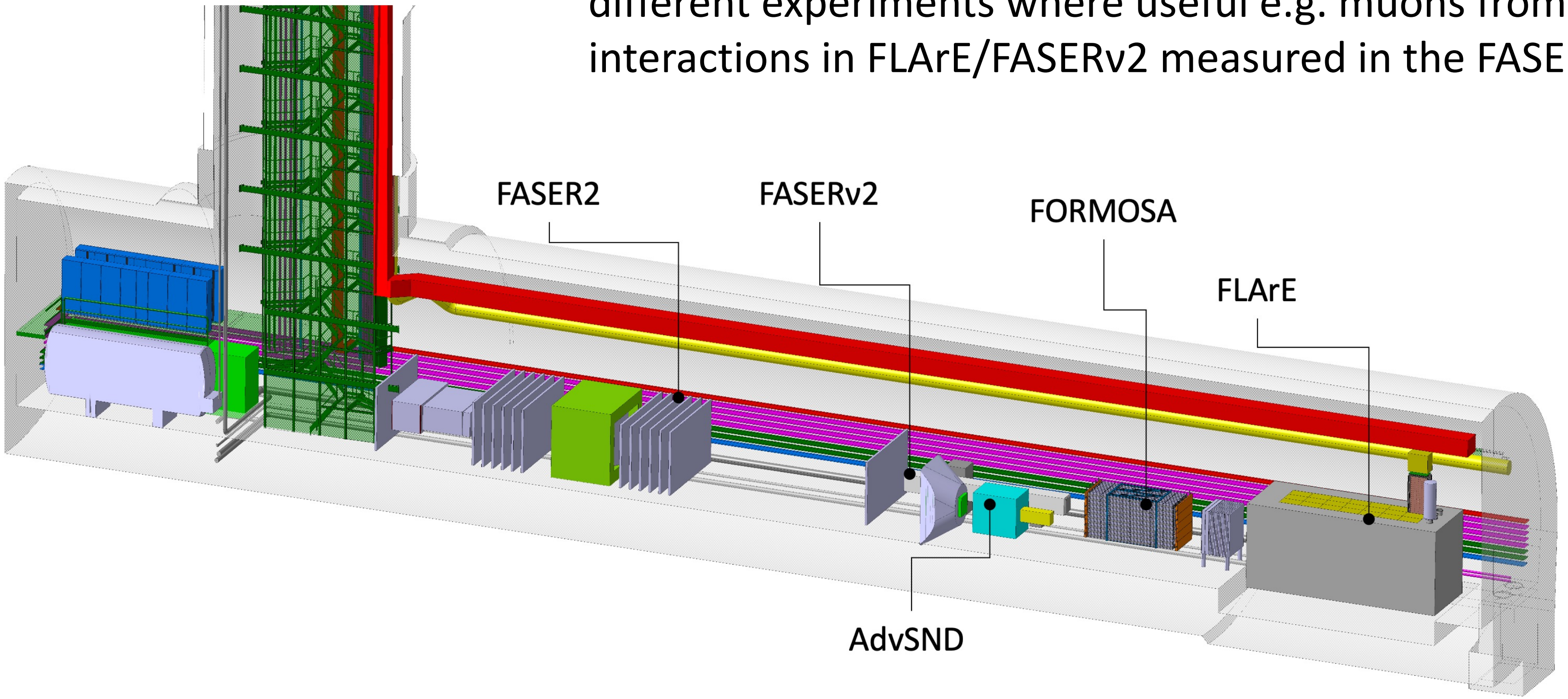
Planning to release a PBC note on the timescale of June, summarizing the technical progress in the facility design and integration.
Hope to include transport study on transporting and installing the largest/most-complex pieces into the cavern.

[1] – "Impact of vibration to HL-LHC performance during FPF facility construction", https://doi.org/10.18429/JACoW-IPAC2023-THPA039
[2] – "Update on the FPF Facility technical studies", https://cds.cern.ch/record/2851822/
[3] – "Forward Physics Facility: Geotechnical Report", GADZ SA, https://edms.cern.ch/document/2910442/1

FPF Experiments

Much progress across all FPF experiments - Flash a few details of recent items in next slides

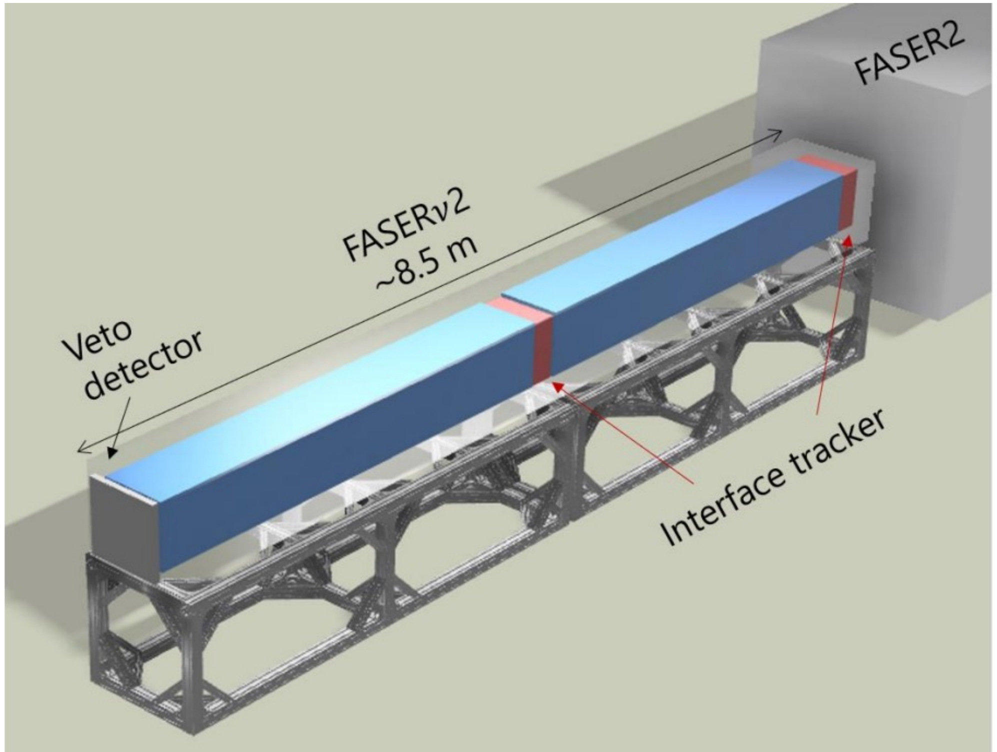
Want to optimize the physics across the facility, combining info from different experiments where useful e.g. muons from neutrino interactions in FLArE/FASERv2 measured in the FASER2 spectrometer



AdvSND are considering to be located in the existing LHC infrastructure (TI18) and not part of the FPF (see next talk from Giovanni De Lellis). Since the FPF is a dedicated facility, we can certainly make room in the facility for AdvSND if needed.

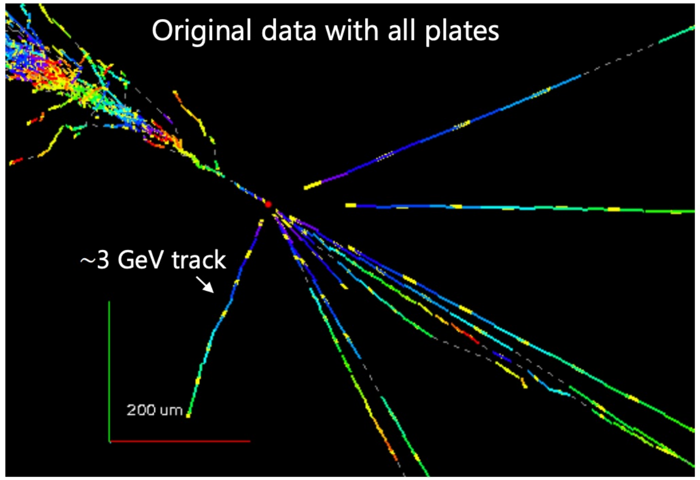
FASERν2

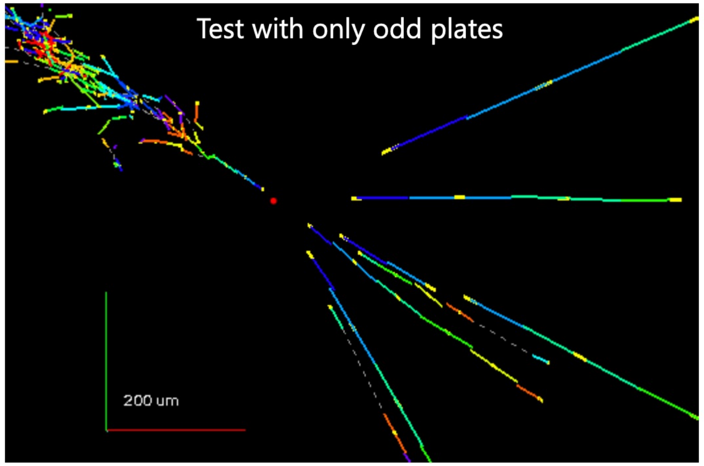
- FASERν2 is a tungsten/emulsion detector
  - 20 tonne target mass
  - 40cm x 40cm x 8.5m long
  - Detector cooled to prolong emulsion performance
  - Muons from neutrino interactions in tungsten can be reconstructed in FASER2 spectrometer
    - Requires scintillator veto system and interface trackers
- Dealing with high detector occupancy from muon background (~1Hz/cm^2) is the main challenge
  - Investigating sweeper magnet to reduce muon flux
  - Investigating improved emulsion reconstruction to cope with higher occupancy
- Several studies ongoing to optimize the setup for FASERν2 (see next slide)

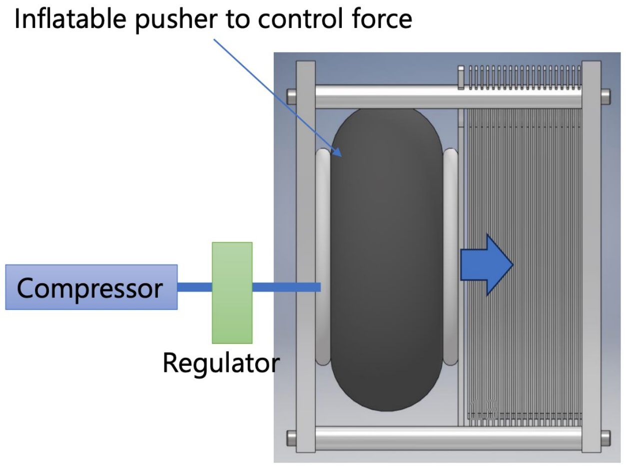


FASERν2 – ongoing work

- Long term stability test of emulsion film ongoing
  - Test noise-hit (fog) rate and track efficiency after long exposure (as would be the case in the FASERν2)
  - Test using films exposed to test beam in Aug 2023
  - Films kept in different temperatures and for different lengths of time, and then developed to study performance
- Test of using 2mm thick tungsten plates between films (cf 1mm plates in FASERν)
  - Reconstruct FASERν data skipping every other emulsion film
  - Compare neutrino candidates with default and modified reconstruction
  - Results looks encouraging
- Detector structure development
  - Design structure to allow assembly of emulsion detector (after exchange of emulsion) on site
  - Need system to apply sufficient pressure on tungsten/emulsion to ensure good alignment
  - Prototype under development for testing this







FLArE detector overview

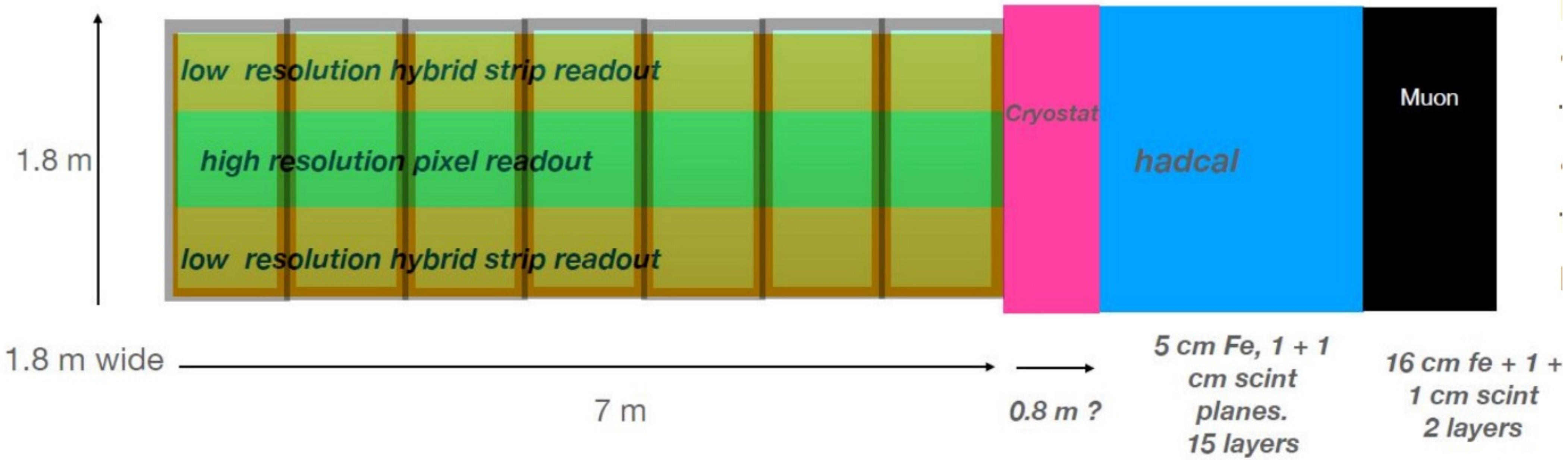
LAr TPC detector, optimized on high energy neutrino events, with aim to have good containment and high resolution reconstruction.

Baseline parameters:

- Gtt cryoststat (as used for protoDune)
- Longitudinally, 7 sets of 1m deep TPCs
- Transversely, 3 TPCs per set: middle TPC ($1x1m^2$) with better resolution, forms the fiducial volume
- Scintillator based hadronic calorimeter and muon catcher at back of cryostat
- Total mass of LAr 30tn (Fiducial mass 10tn)

Options and open questions for TPC:

- Possibility to use optical readout (ADRIANNE concept)
- Number of pixel for central section (many channels increases heatload)

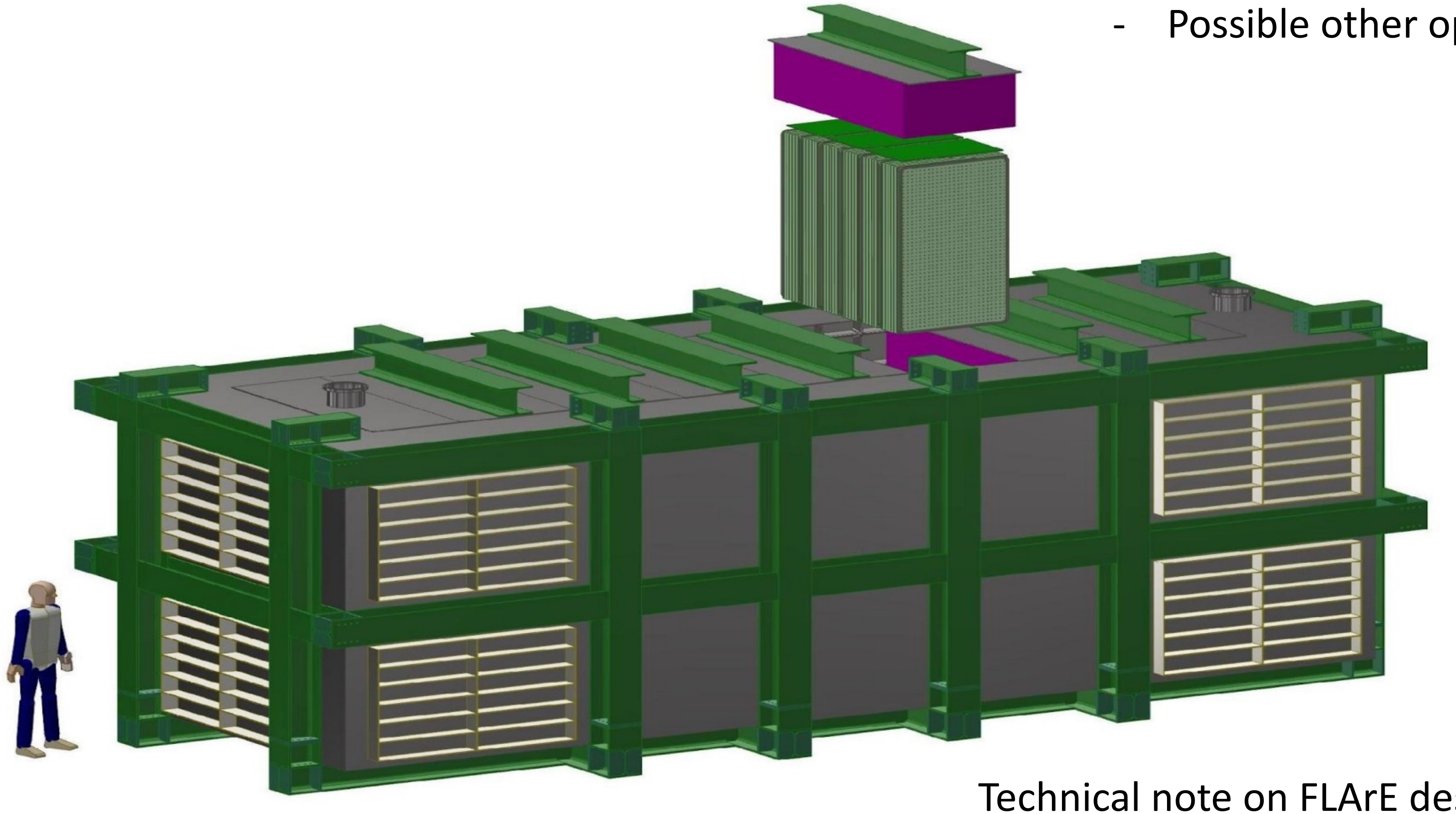


FLArE detector design/integration

Conceptual design of the detector integrated into cavern.
Transport study of largest/most complex pieces to be launched.
Question of how to access to repair TPC underdiscussion

- Baseline TPC installed from the top as shown
- Possible other option of installing through side

One detector module (3 TPCs) hung above the cryostat



Technical note on FLArE design in preparation

FLArE - cryogenics

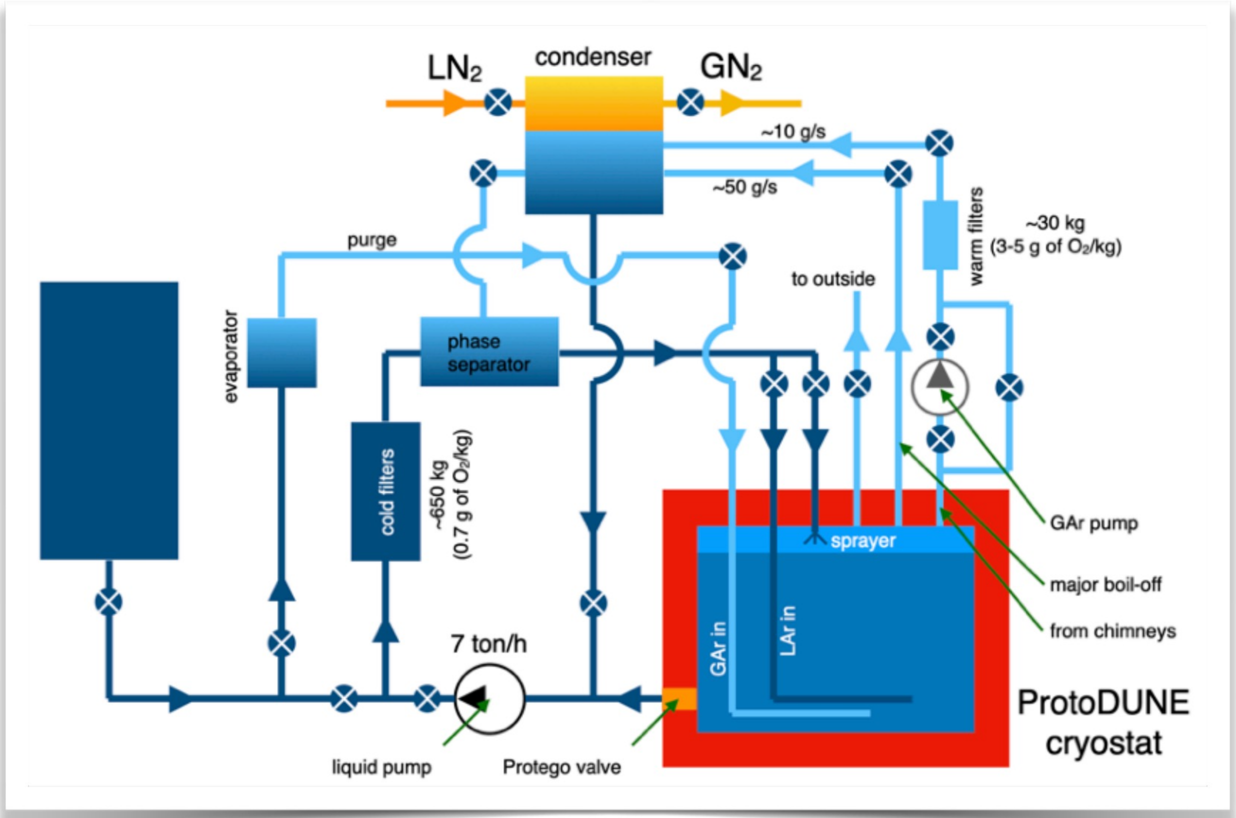
Conceptual design of FLArE cryogenics discussed with J. Bremer (TE-CRY) and F. Resnati (EP-NU, protoDune).

Concept similar to that of protoDune

- Boil off Ar is re-condensed using liquid nitrogen;
- The nitrogen is re-liquified using a Turbo-Brayton system with 10kW cooling capacity (not used for protoDune);
  - 100kW electrical power needed
- System allows for storing Ar in cavern if needed.

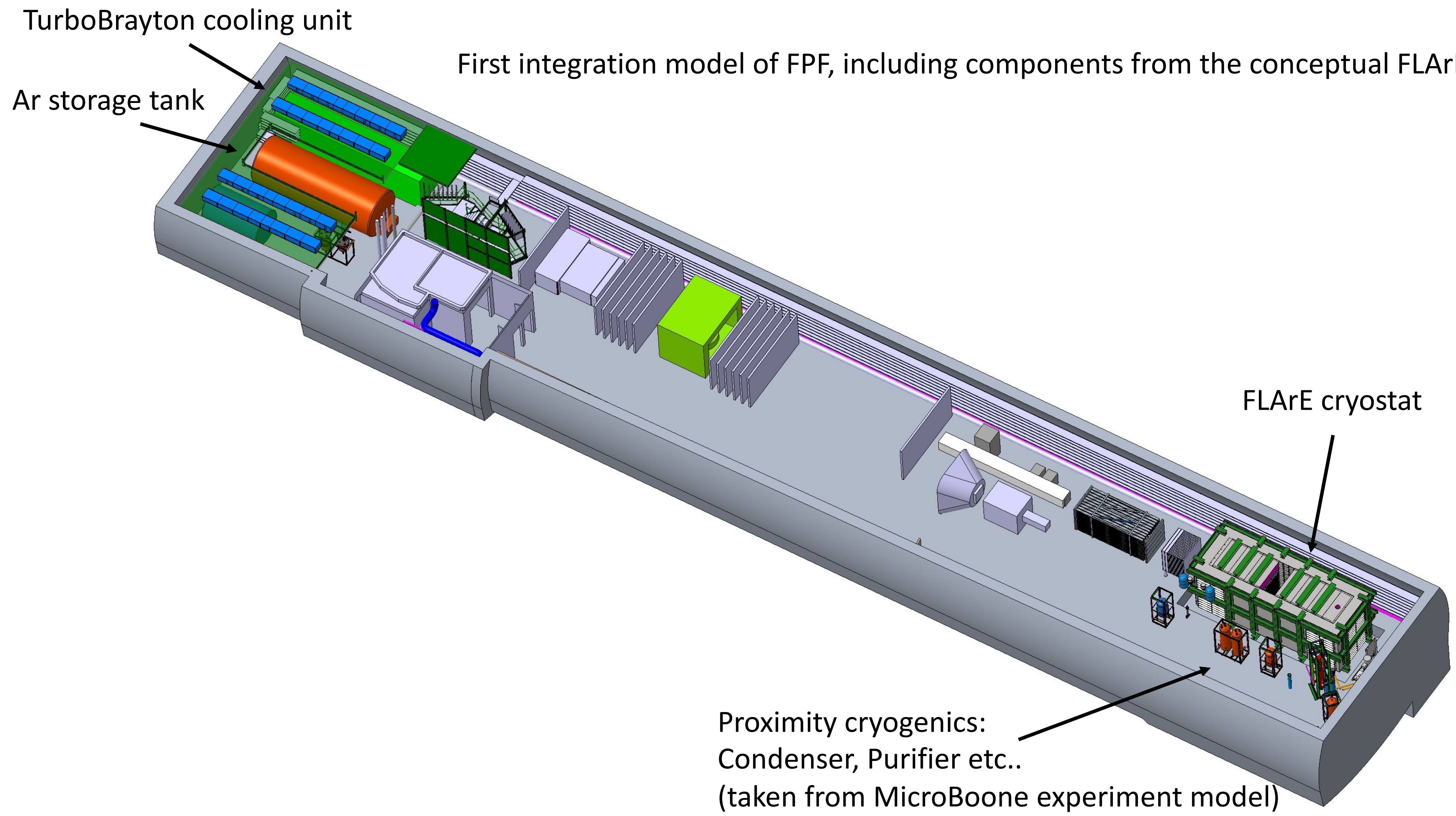
Important next steps:

- Safety considerations (ODH from Ar leak)
- Transport considerations for cryo equipment



FLArE - cryogenics

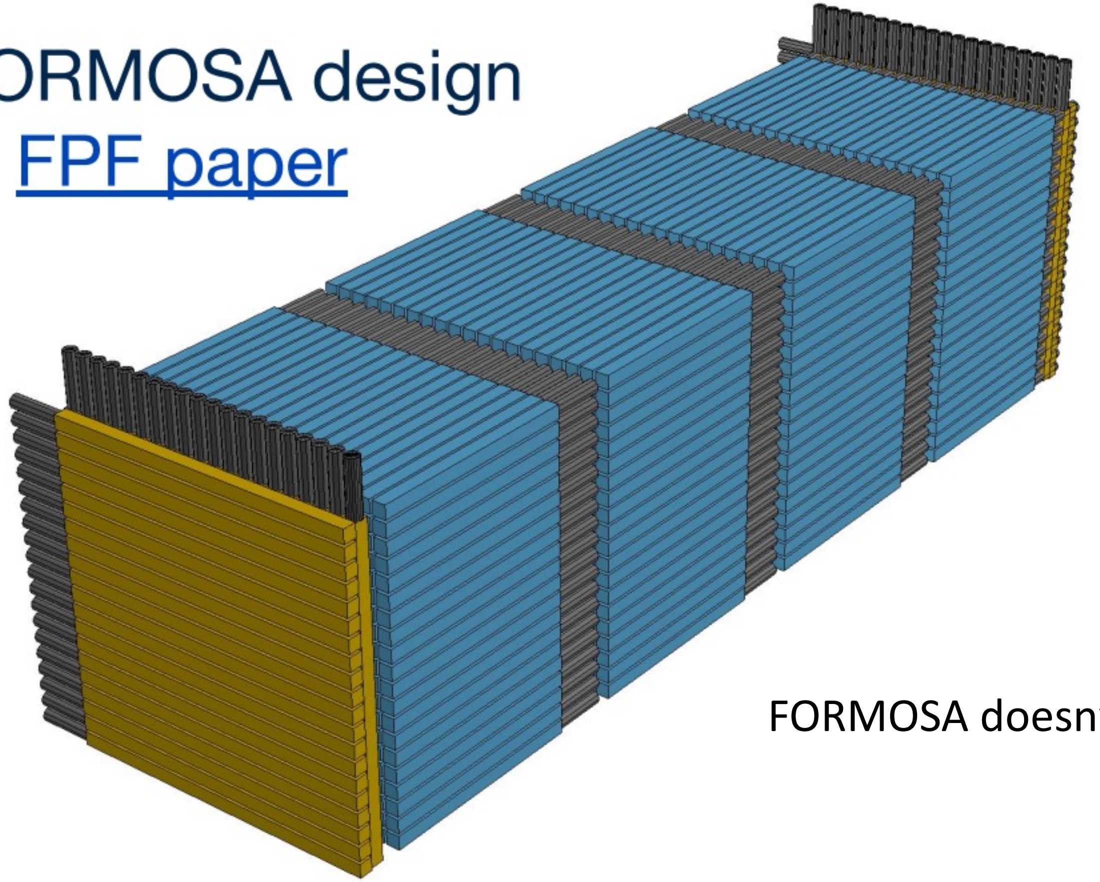
First integration model of FPF, including components from the conceptual FLArE cryogenics.



FORMOSA

FORMOSA is a scintillator-based detector for searching for millicharged particles.
Detector design well advanced, based on experience with miliQan experiment.

FORMOSA design
in [FPF paper]

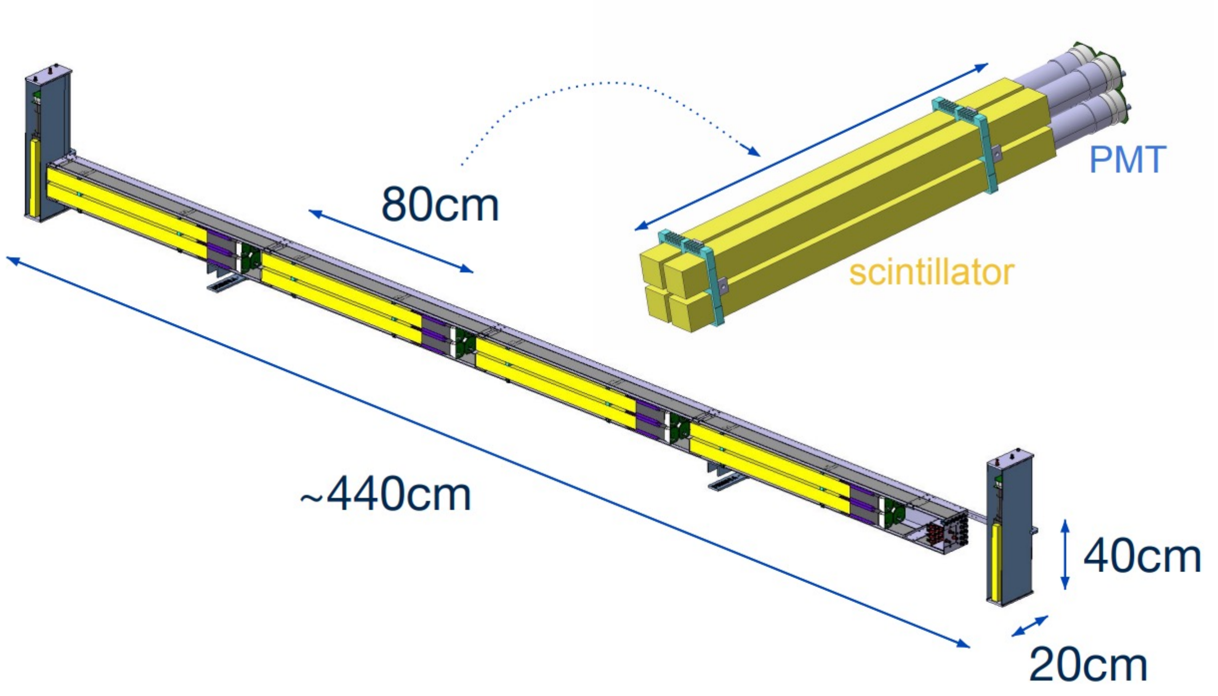


20rows x 20cols x 4layers of bars for detection
Main background: beam muons → veto panels

FORMOSA doesn't present big challenges for infrastructure in the FPF

FORMOSA

FORMOSA is a scintillator-based detector for searching for millicharged particles.
Detector design well advanced, based on experience with miliQan experiment.
Question on how to deal with higher rate of through going muons than at miliQan.
To study this, a small demonstrator detector was installed behind FASER in the UJ12 cavern during the YETS.

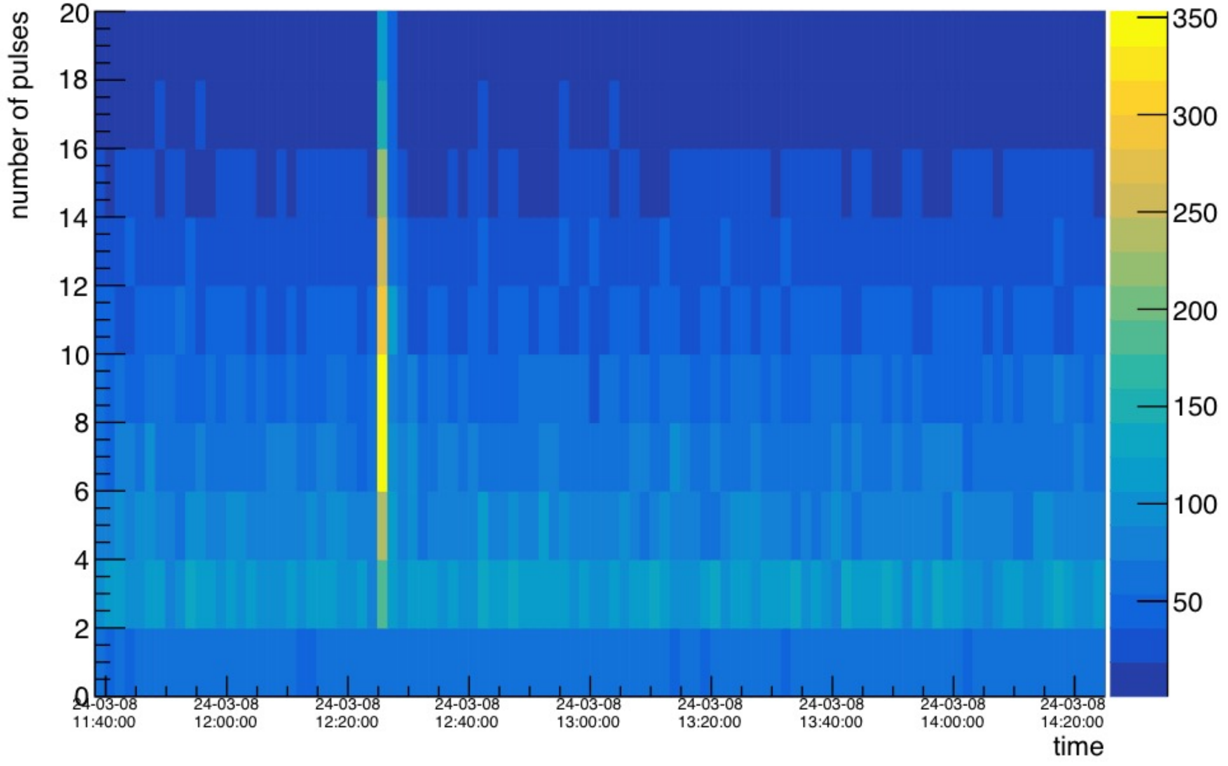


Detector consists of 4 layers of 4x4 scintillator bars, with front/back veto slab scintillators (18 channels total)

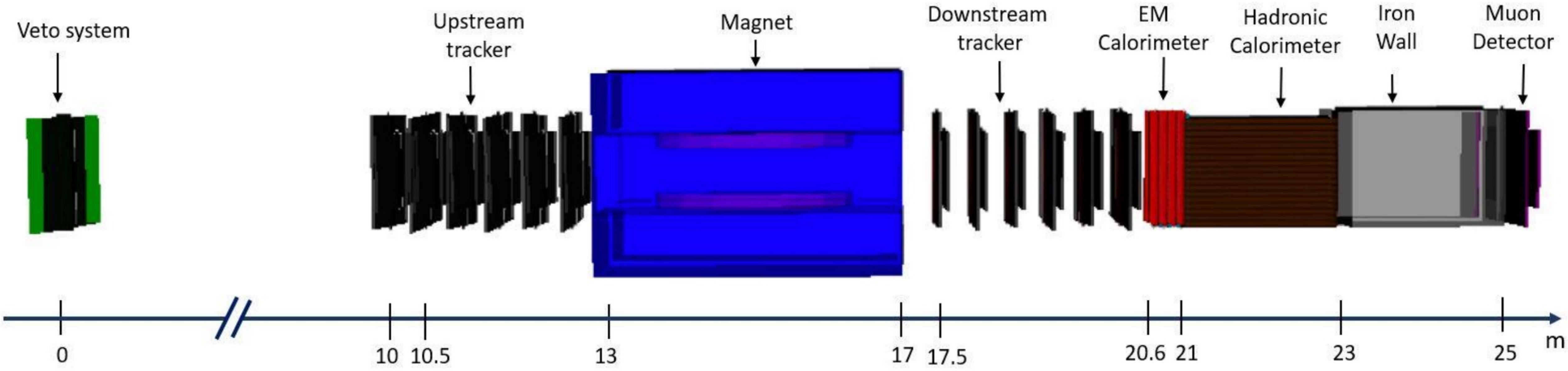
FORMOSA

FORMOSA is a scintillator-based detector for searching for millicharged particles.
Detector design well advanced, based on experience with miliQan experiment.
Question on how to deal with higher rate of through going muons than at miliQan.
To study this, a small demonstrator detector was installed behind FASER in the UJ12 cavern during the YETS.

First beam related activity in FORMOSA demonstrator during splash events (March 8th). Commissioning ongoing.



FASER2



Tracking spectrometer, for LLP decays, and for measuring muons from neutrino interactions seen in upstream detectors (FLArE and FASERnu2).

Baseline tracker technology ScFi tracker (like LHCb). If installed in LS3, could re-use current LHCb SciFi modules (significant money saving).

Simulations studies used to detail spectrometer requirements:

- transverse size, magnet bending power, tracker hit resolution, alignment tolerances, material budget, number of tracking layers…

A note describing this in preparation.

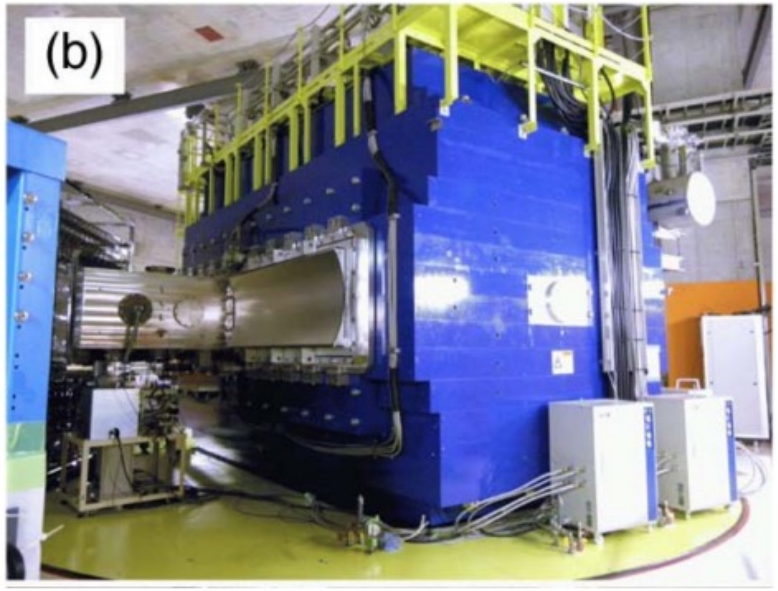
FASER2 magnet - baseline

FASER2 spectrometer has a large apperture magnet. Options discussed with Toshiba, Japan and TESLA, UK.
Baseline design is a superconducting dipole magnet based on the SAMURAI magnet (manufactured by Toshiba).

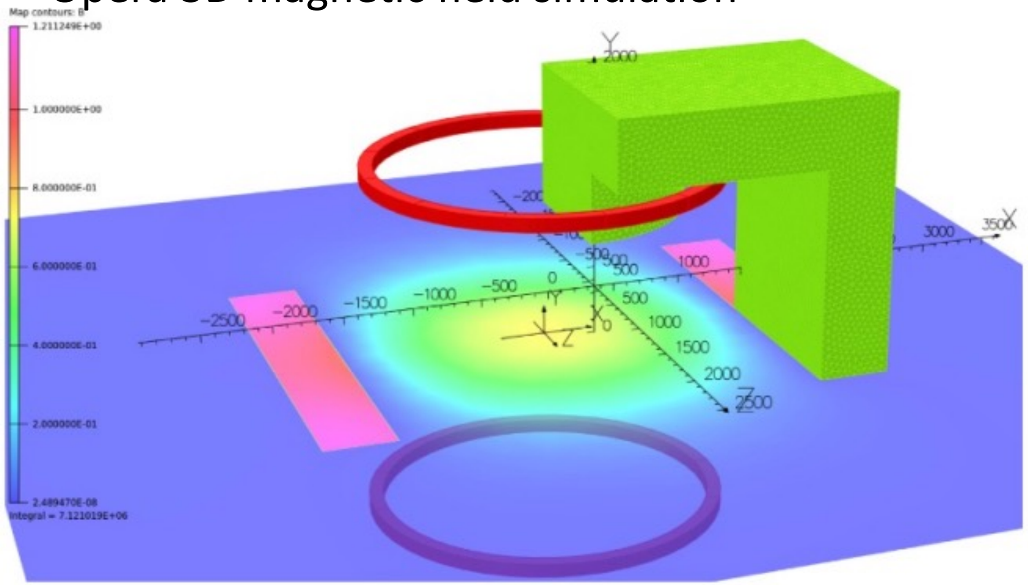
- 2Tm bending power
- 3m x 1m (gap) apperture (now studying a square apperture 1.7m x 1.7m)
- 4m wide x 3m high outer dimensions
- Peripheral equipment:
    - Cryogenics based on 4 cryo coolers
    - Other equipment (Vacuum pump unit, Water cooled compressor, Power source)
    - 36kW maximum power usage

Rough costing from Toshiba of 4.3MCHF (without transportation), and 3-4 year lead time.
Study of transporting super conducting coils into cavern being started.

SAMURAI magnet at Riken in Japan



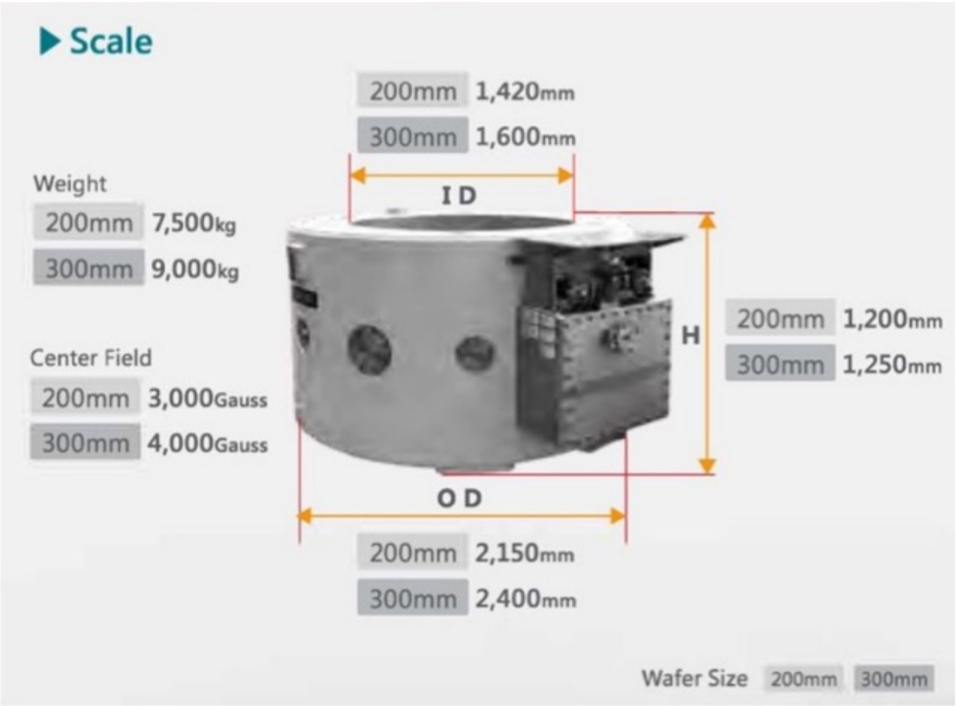
Opera 3D magnetic field simulation

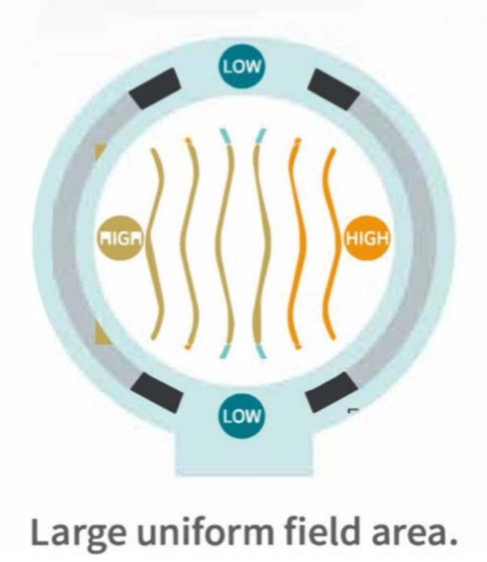


FASER2 magnet - alternative

FASER2 spectrometer has a large apperture magnet. Options discussed with Toshiba, Japan and TESLA, UK.
A possibility is to use an off-the-shelf 'crystal-puller' magnet available from both companies.
Specifications:

- Central field 0.4 – 0.5T
  - Can be chained together to provide more bending power e.g. 3 magnets can give 1.8 Tm
- Aperture 1.6m diameter (possibly up to 2m diameter)
- Advantages: Off the shelf, no R&D needed (shorter lead time, less risk), cryo system integrated into unit, cheaper
- Units would need to be rotated, checking with companies about possible modifications needed for that

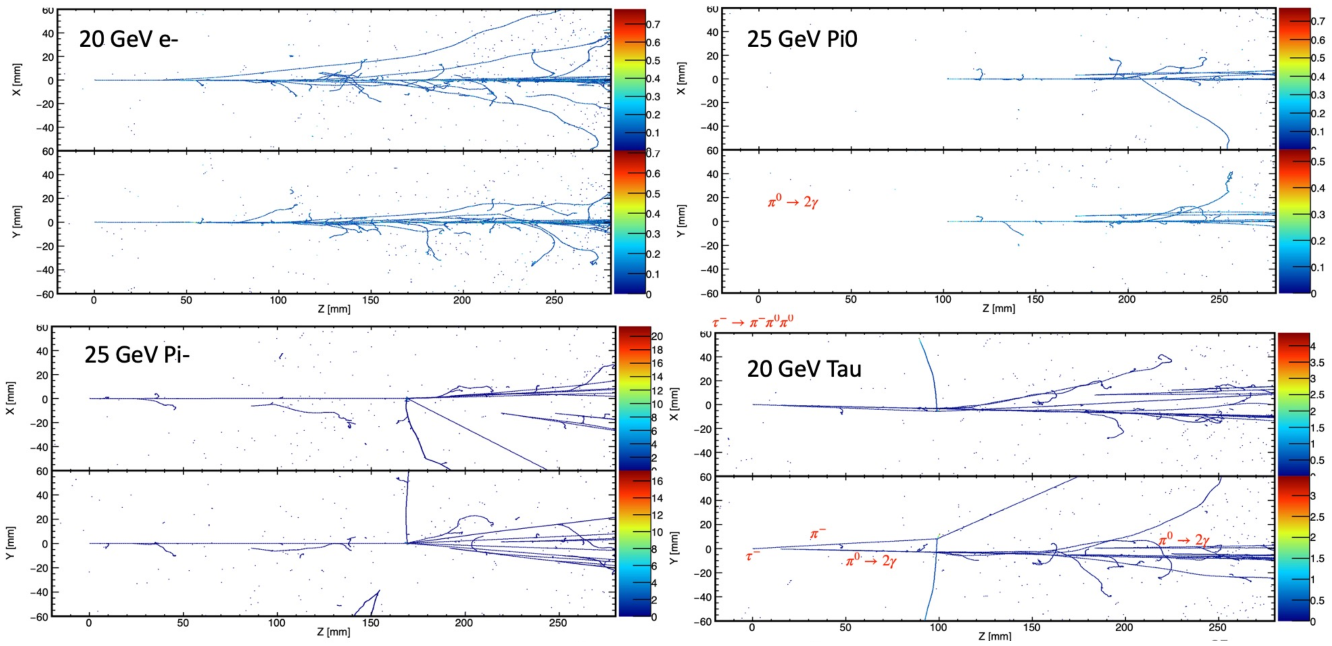




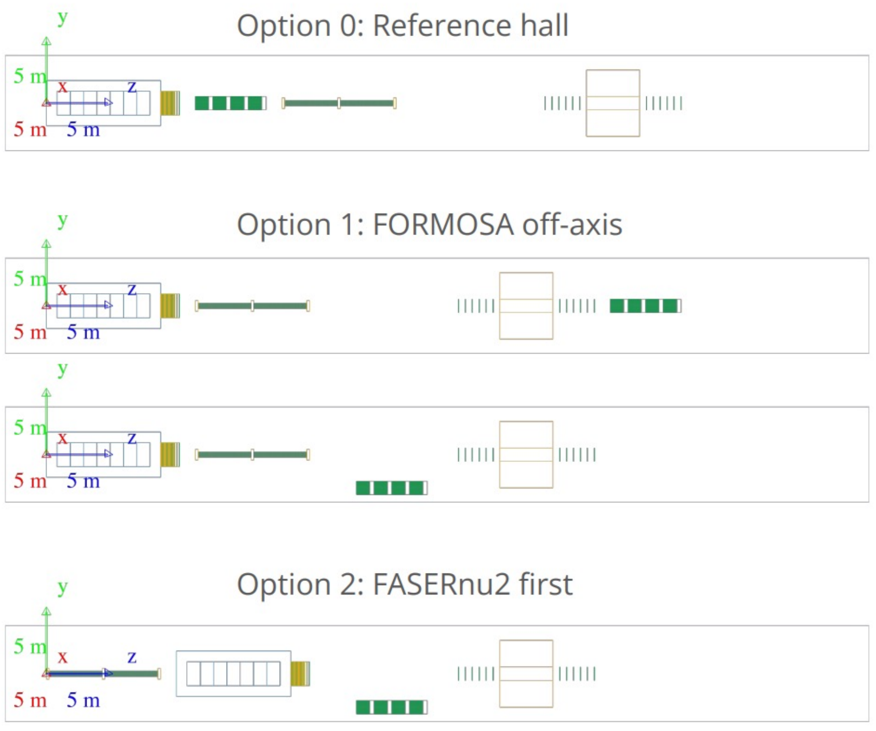
Study of transporting this unit into cavern being started.

Example Simulation Studies

Single particle response in FLArE

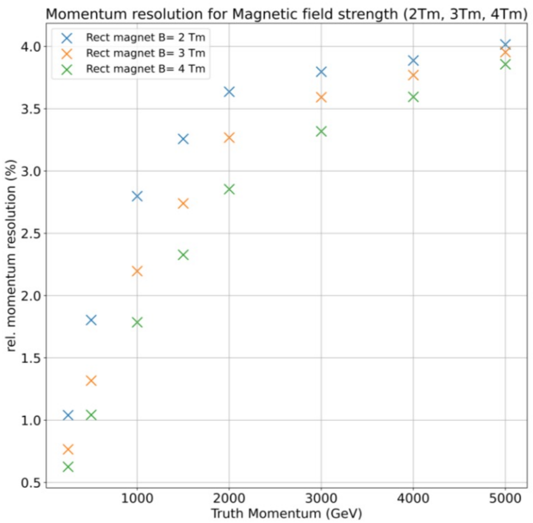


FASER2 muon acceptance for different cavern layouts

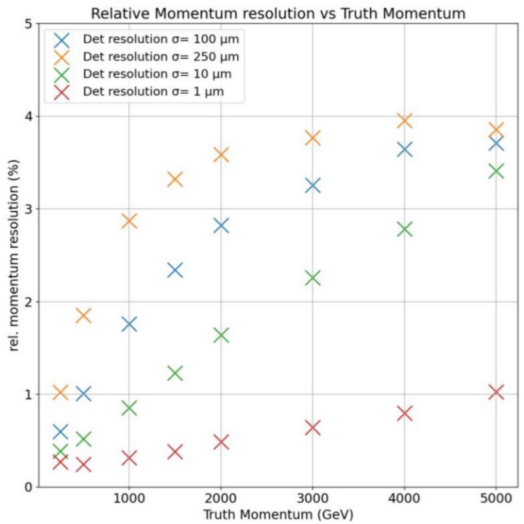


Effect of FASER2 design on muon momentum resoluton in simulated muon neutrino interactions in FLArE

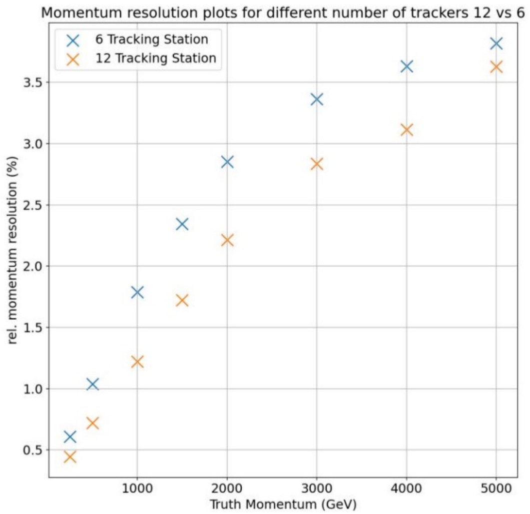
Field strength



Tracker resolution



Number of tracking station



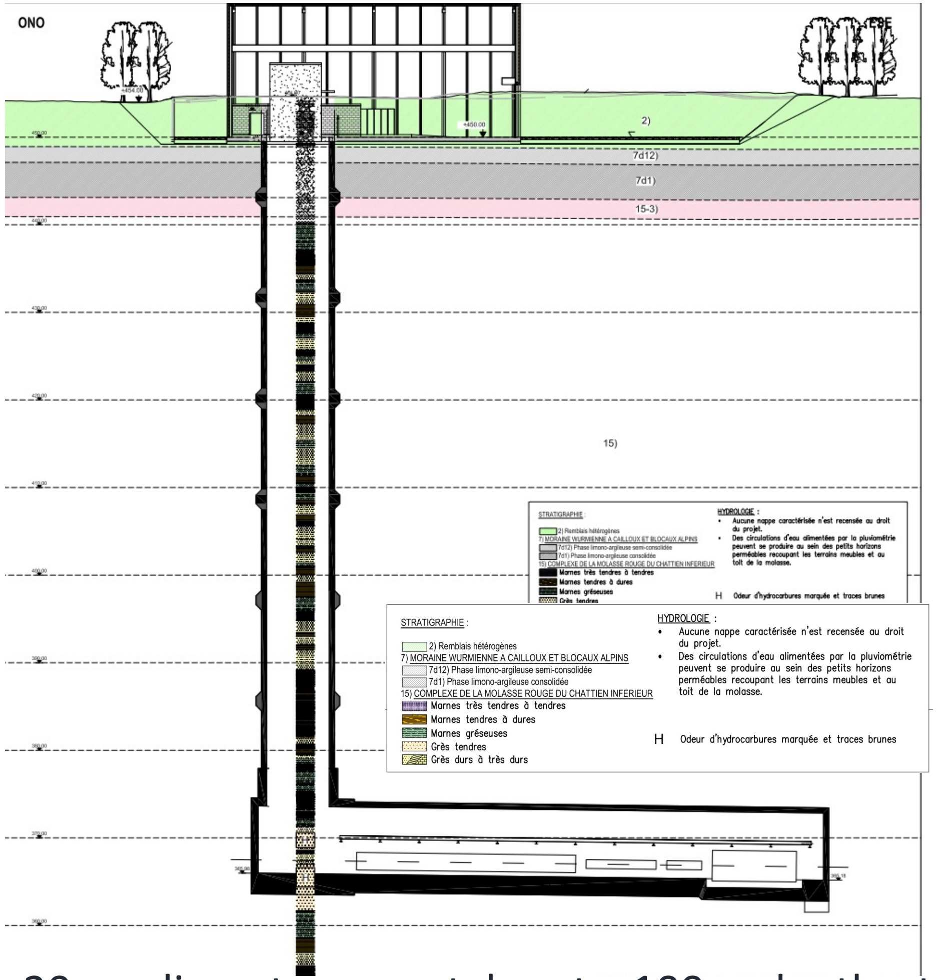
Summary

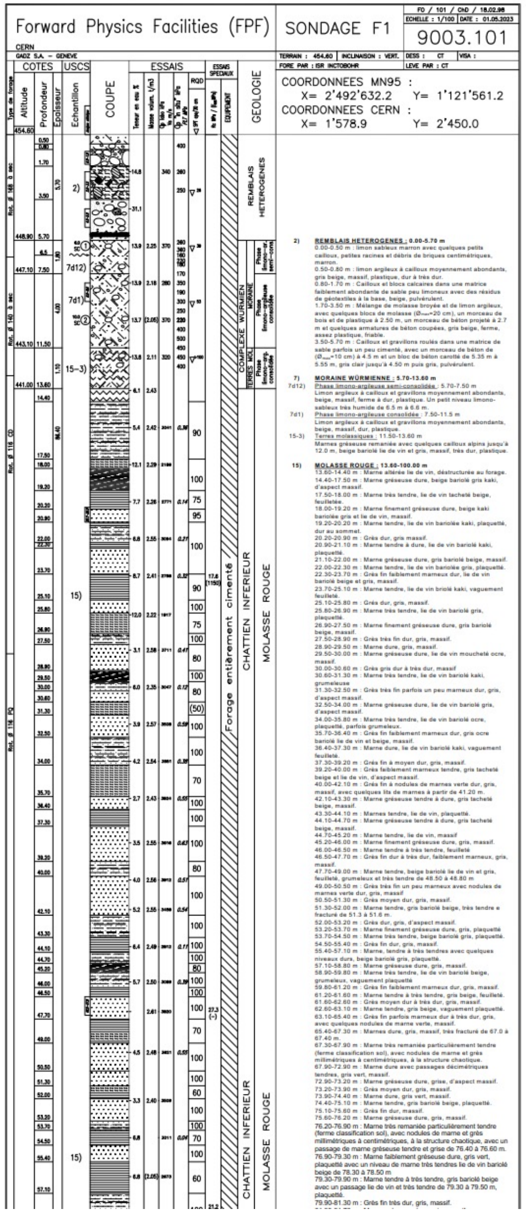
- Experiments:
  - Lots of progress in experiment design, integration and infrastructure requirements
    - FORMOSA demonstrator installed in LHC to study through-going muon background
    - Several tests ongoing to validate FASERv2 concepts
    - Simulation studies to optimize designs, starting to include global optimization combining information across expts
  - Key areas that influence global facility design:
    - FASER2 magnet – 2 reasonable cost options under consideration
    - FLArE cryogenics – conceptual design of cryo system advancing
- Facility:
  - Updated costing of facility considering site investigation findings & inflation
    - Reviewed by external experts
  - Integration of experiments, including associated infrastructure showed bigger facility needed
  - New facility baseline longer and wider to accommodate this (~10% more expensive)
- Next steps:
  - Plan to submit a PBC note on the updated facility design, costing and integration on the timescale of June
  - Planning to submit LOI to LHCC in Jan 2025

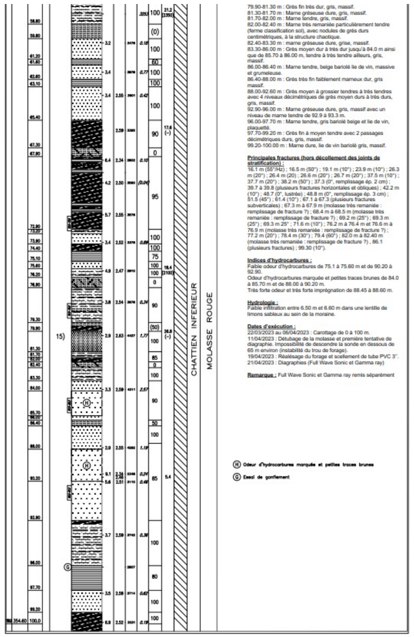
Many thanks for the PBC support of FPF studies

BACKUP…

FPF Site Investigation Works

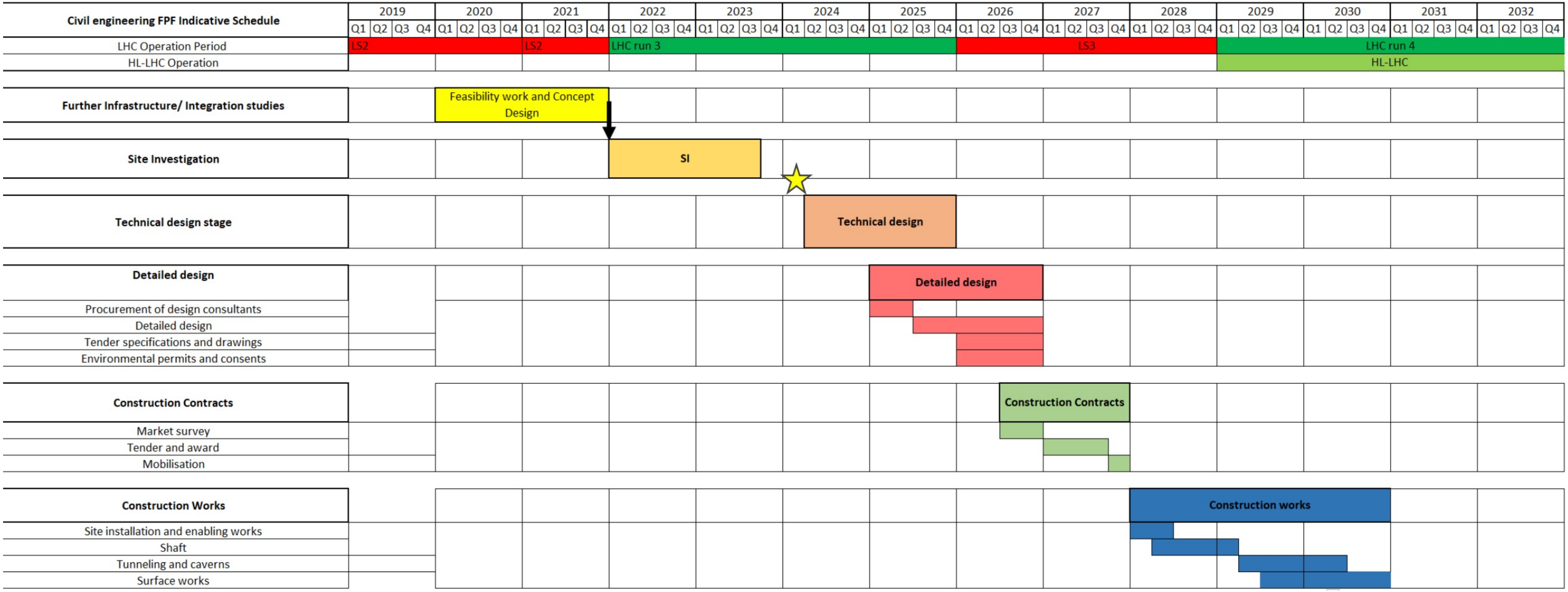






- 20cm diameter core taken to 100m depth at proposed FPF location
- Detailed Geological study of core carried out
    - No showstoppers identified
    - Area looks good for excavation

Proposed Civil Engineering Schedule



NB Very early stage estimate for schedule

☆ **Design must be frozen before technical design can begin**

CE Cost Update

Please find enclosed the first draft of the updated cost based on the results of the site investigations and the cost review done by ARUP. The estimated cost of the facility based on the existing design is 30.1MCHF, the estimate being a Class 4 (accuracy ranges being -15% to -30% on the low side, and +20% to +50% on the high side).

Ref.	Work Package	Cost [CHF]
1.	Underground Works	10,000,000.00
1.1	Preliminary activities	1,600,000.00
1.2	Access shaft	3,900,000.00
1.3	Experimental Cavern	4,500,000.00
2.	Surface Works	6,120,000.00
2.1	General items	640,000.00
2.2	Topsoil and earthworks	660,000.00
2.3	Roads and network	730,000.00
2.4	Buildings	4,090,000.00
2.4.1	Access building	2,000,000.00
2.4.2	Cooling and ventilation building	1,400,000.00
2.4.3	Electrical Building	490,000.00
2.4.5	External platforms	200,000.00
3.	General items	10,000,000.00
4.	Miscellaneous	4,000,000.00
	TOTAL CE WORKS	30,120,000.00

Assumptions

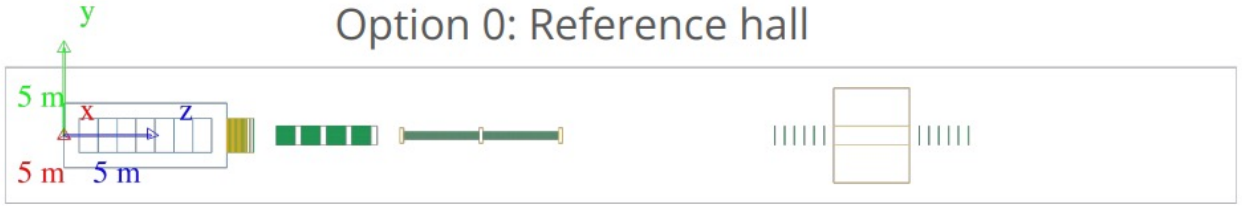
1. Services not included
2. Technical galleries not included
3. Cranes not included
4. Access building as a conventional steel portal frame structure with cladding, only one floor
5. CV Building as a reinforced concrete building, only one floor
6. Finished floor level at 450m ASL
7. Sectional doors not included

Very preliminary estimate of cost increase to make cavern larger (to accommodate additional infrastructure etc..):

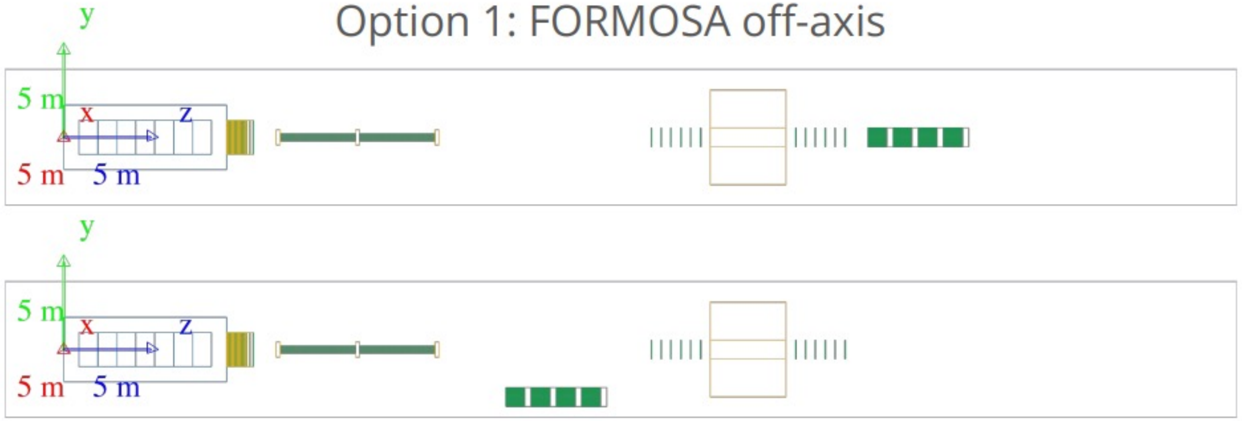
	Additional cost
5m longer cavern	700,000 CHF- 1,000,000.00 CHF
10m longer cavern	1,400,000 CHF - 2,000,000.00 CHF
Increase of the radius of the cavern by 1m	700,000 CHF- 1,000,000.00 CHF

Alternative hall options

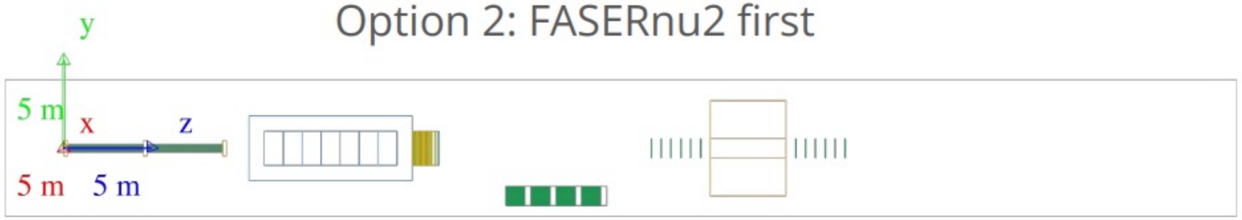
Option 0: Reference hall



Option 1: FORMOSA off-axis



Option 2: FASERnu2 first



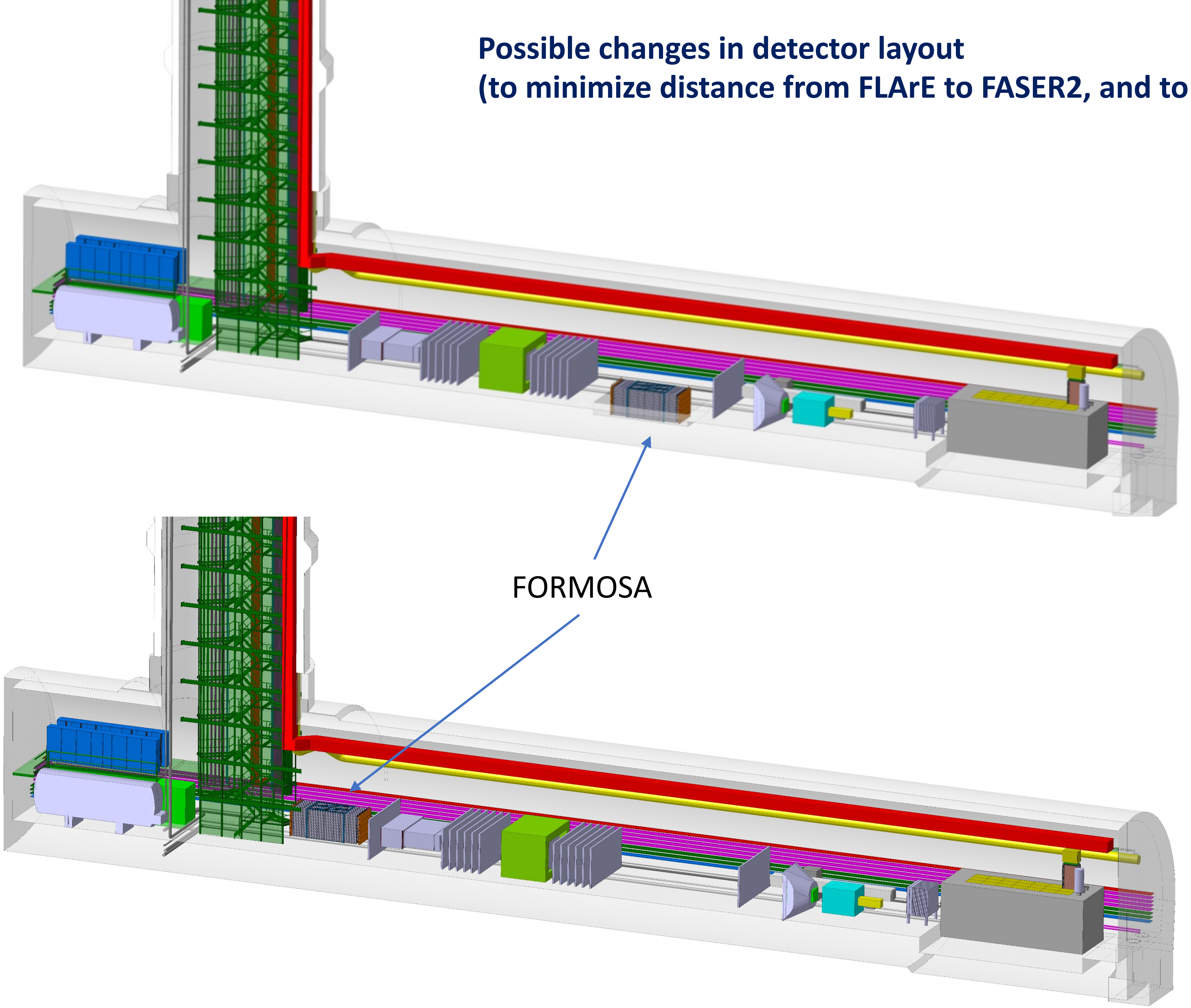
Detector	Total length [m]
FLArE	10.2
FORMOSA	5.3
FASERν2	8.6
FASER2 (SAMURAI-like)	10.2
FASER2 (Crystal-pulling)	6.3

Several alternative FPF configurations have been proposed. Each option can accommodate both FASER2 magnet designs.

FPF hall configurations					
Name	Comment	FLArE (y,z) [m]	FORMOSA (y,z) [m]	FASERν2 (y,z) [m]	FASER2 (y,z) [m]
Option 0	Reference hall	$(0, 4.3)$	$(0, 13.9)$	$(0, 22.0)$	$(0, 42.6)$
	...with CrystalPulling magnets	$(0, 4.3)$	$(0, 13.9)$	$(0, 22.0)$	$(0, 40.7)$
Option 1a	FORMOSA behind FASER2	$(0, 4.3)$	$(0, 45.1)$	$(0, 15.5)$	$(0, 36.1)$
	...with CrystalPulling magnets	$(0, 4.3)$	$(0, 41.1)$	$(0, 15.5)$	$(0, 34.1)$
Option 1b	FORMOSA below decay volume	$(0, 4.3)$	$(-2.5, 26.0)$	$(0, 15.5)$	$(0, 36.1)$
	...with CrystalPulling magnets	$(0, 4.3)$	$(-2.5, 26.0)$	$(0, 15.5)$	$(0, 34.1)$
Option 2	FASERν2 before FLArE	$(0, 14.1)$	$(-2.5, 26.0)$	$(0, 4.3)$	$(0, 36.1)$
	...with CrystalPulling magnets	$(0, 14.1)$	$(-2.5, 26.0)$	$(0, 4.3)$	$(0, 34.1)$

Table 1: Summary of the FPF configurations. The (y, z) positions of the on-axis detector centers are reported. A 1.2 m buffer between each experiment is assumed. The center of the coordinate system always corresponds to the front of the first detector, 3.1 m from the cavern wall. The z-axis represents the line of sight, while y is the vertical direction. The full length of the cavern is 65 m.

Possible changes in detector layout
(to minimize distance from FLArE to FASER2, and to save space)



Considerations on cryogenics

Total heat load of ~8 kW (4 kW cryostat, 1 kW GAr circuit, 1 kW LAr purification, 1 kW electronics, 1 kW other inefficiencies)

Analogous approach as for ProtoDUNEs:
- Pressurised LN_2 for re-condensing the argon vapour
- Forced LAr circulation at a rate of 1 volume in 5 days => 600-700 kg/h
- Proximity cryogenics order of 1 MCHF

Main cooling (instead of exhausting evaporated N2):
- Turbo-Brayton (~8 m x 1.6 m x 2.7 m) TBF-80 unit (~10 kW cooling) in the cavern
- 100 kW electrical power (max), 5 kg/s water (max)
- Order of 3 MCHF

LAr and LN_2 lines down shaft:
- GAr/GN_2 out 30 cm diameter
- GAr in 10 cm (vacuum jacket included)
- LN_2 20 cm (vacuum jacket included)
- LAr 20 cm (vacuum jacket included)

Dewars on surface:
- 50 m^3 LAr
- 10 m^3 LN_2

Cost and Timeline

Work	Months	Comments
Designing	9	
Procurement	12	could be started before designing
Winding wire	6	could be done while designing
Assembly	12	
Test	3	
Dismantlement, Delivery	2	
	44 (3.6 years)	could be 35 (2.9 years)

3-4 years expected before commissioing

	JPY [MJPY]	CHF [MCHF]
Material	**384**	**2.2**
Superconducting wire	6.3	0.04
Yoke material	88	0.51
Yoke manufacturing	106	0.62
Vacuum chamber, shield, etc	130	0.76
Coil winding jig, assembly jig	51	0.30
Testing instruments	2.7	0.02
Commercial product (cryogenics, power supply, etc)	**73**	**0.43**
Manufacturing and assembly	**102**	**0.60**
Others (Designing, testing, etc)	**174**	**1.02**
	733	**4.29**

Transportation fee is not included

Magnet parameters

In addition, 3 m x 2 m aperture (wider gap) with 2 Tm is also tried

- 50 cm thick return yoke still work; total width is kept at 4 m, while total height increases to 4 m
- Stored energy still below 10 MJ, no need to use Liquid He bath cooling

	SAMURAI	2 Tm gap 1 m	2 Tm gap 2 m
Coil diameter [m]	2.6	2.6	2.6
Coil cross section [mm^2]	180 × 160	100 × 100	100 × 100
Current density [A/mm^2]	66.74	37	86
Coil current for Φ1.2 mm cable [A]	563	48	112
Total width [m]	6.7	4	4
Total height [m]	4.64	3	4
Iron yoke thickness [m]	1.65	0.5	0.5
Iron weight [t]	566	167	190
Gap [m]	0.88	1	2
Coil center field [T]	3.08	0.89	0.75
Max field in coil [T]	5.4	1.5	2.9
Integral magnetic field at center [Tm]	7.05	2.20	1.92
Stored energy [MJ]	27.4	2.2	8.2

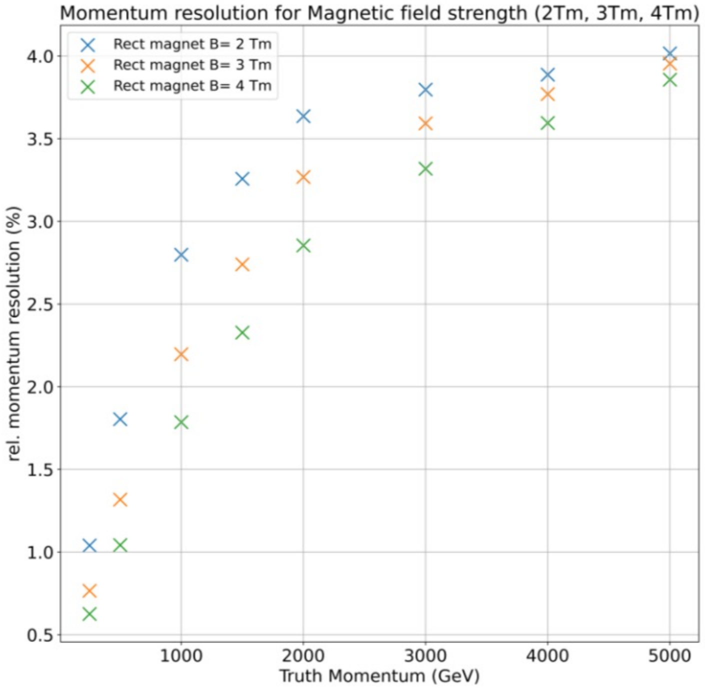
4.3 MCHF + ~1 MCHF [TBC]

1.7 m x 1.7 m aperture will be tried in the next iteration

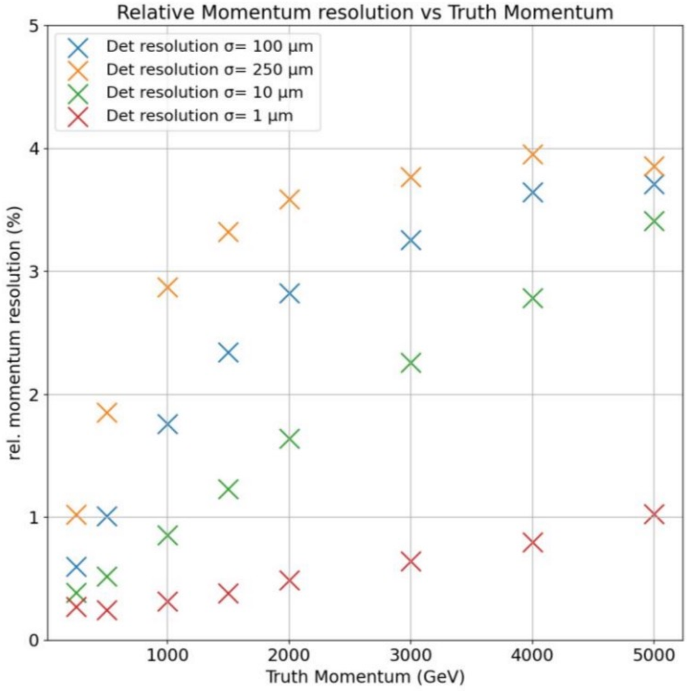
FASER2 Software: Performances

- ACTS performance plots for different FASER2 detector configurations/parameters

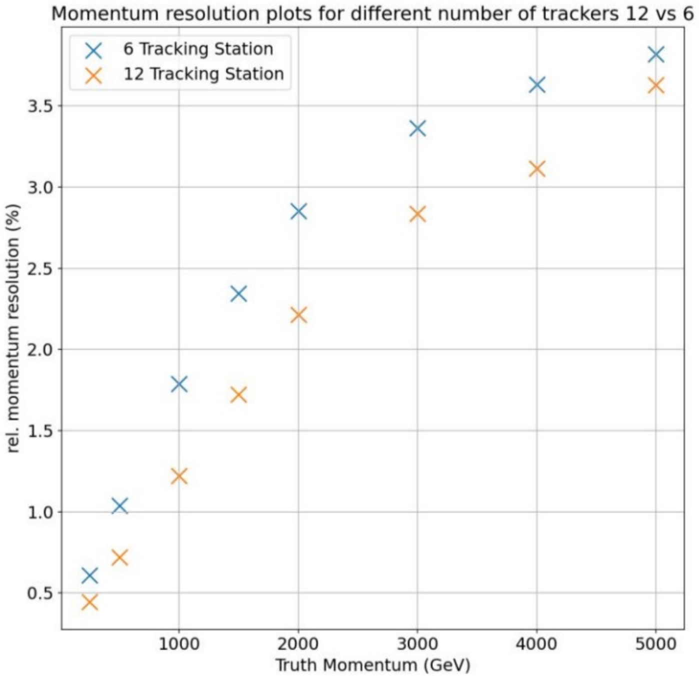
Field strength



Tracker resolution



Number of tracking station

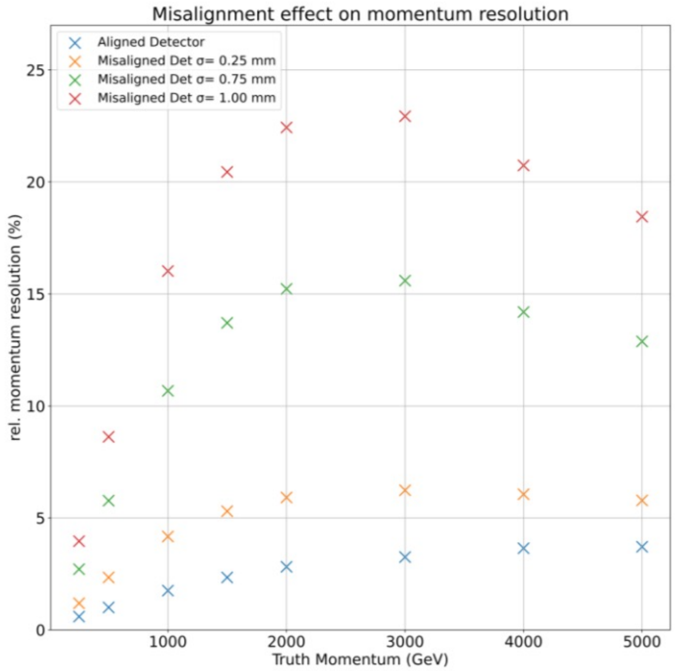


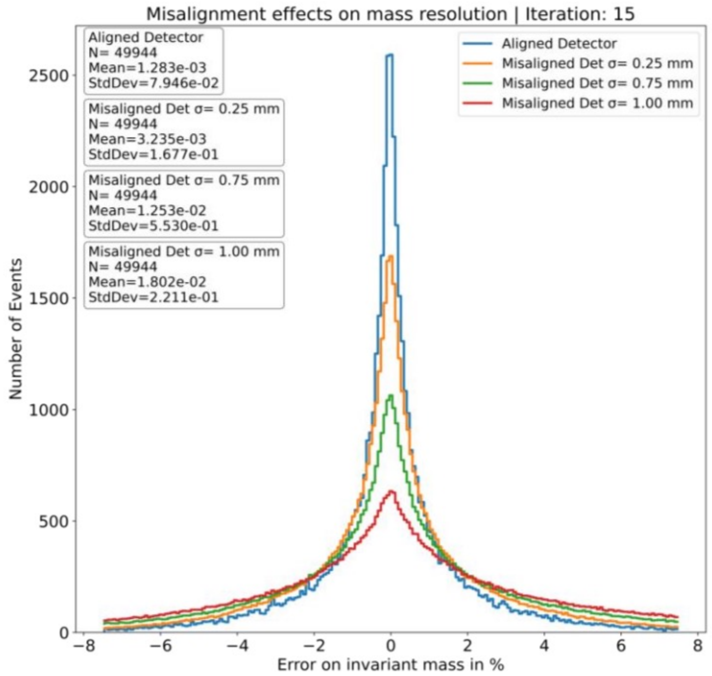
- Momentum resolution remains good while reducing magnetic field to 2 Tm
- Effect of tracker resolution on the momentum resolution
- Good performances with 6 tracking layers configuration

FASER2 studies:

FASER2 Software: Alignment

- ACTS performance plots for detector toy misalignment of FASER2
- Study identifies the tracker alignment is a key performance driver





- Misalignment of tracking station > 250 μm starts to have significant impact on momentum resolution
- Expected mechanical precision should have alignment precision of 250 μm
  - ➢ Achieving 250μm alignment precision across large detectors (~10m appart) is challenging
- On-going studies to use the muon background for track alignment (Luke Kennedy)

Single particle simulation studies in FLArE: