LBNF Beamline Instrumentation and Alignment

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Accelerators Capabilities Enhancement Workshop

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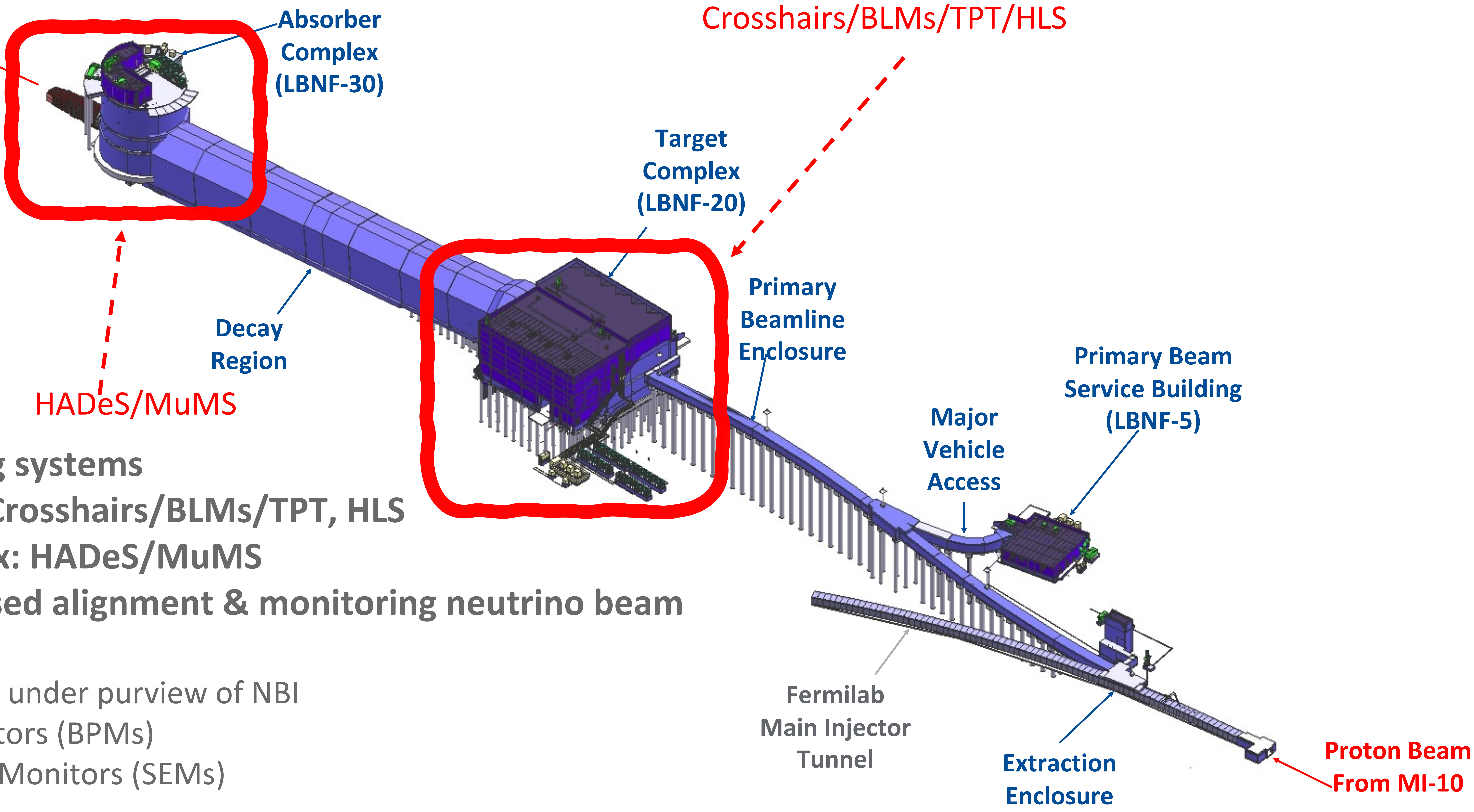
Overview

- Neutrino Beam Instrumentation (NBI) and where it sits in LBNF
- Requirements & alignment tolerances
- Required instrumentation
- Tolerance upgrade needs for 2.0+ MW operation
- Instrumentation upgrade needs for 2.0+ MW operation
- Considerations for option 0
- Schedule
- Summary – planning table

LBNF Beamline & Locations of NBI



Consists of following systems

- **Target complex: Crosshairs/BLMs/TPT, HLS**
- **Absorber complex: HADeS/MuMS**

- **Used for beam-based alignment & monitoring neutrino beam**

Upstream of target, not under purview of NBI

- Beam Position Monitors (BPMs)
- Secondary Emission Monitors (SEMs)

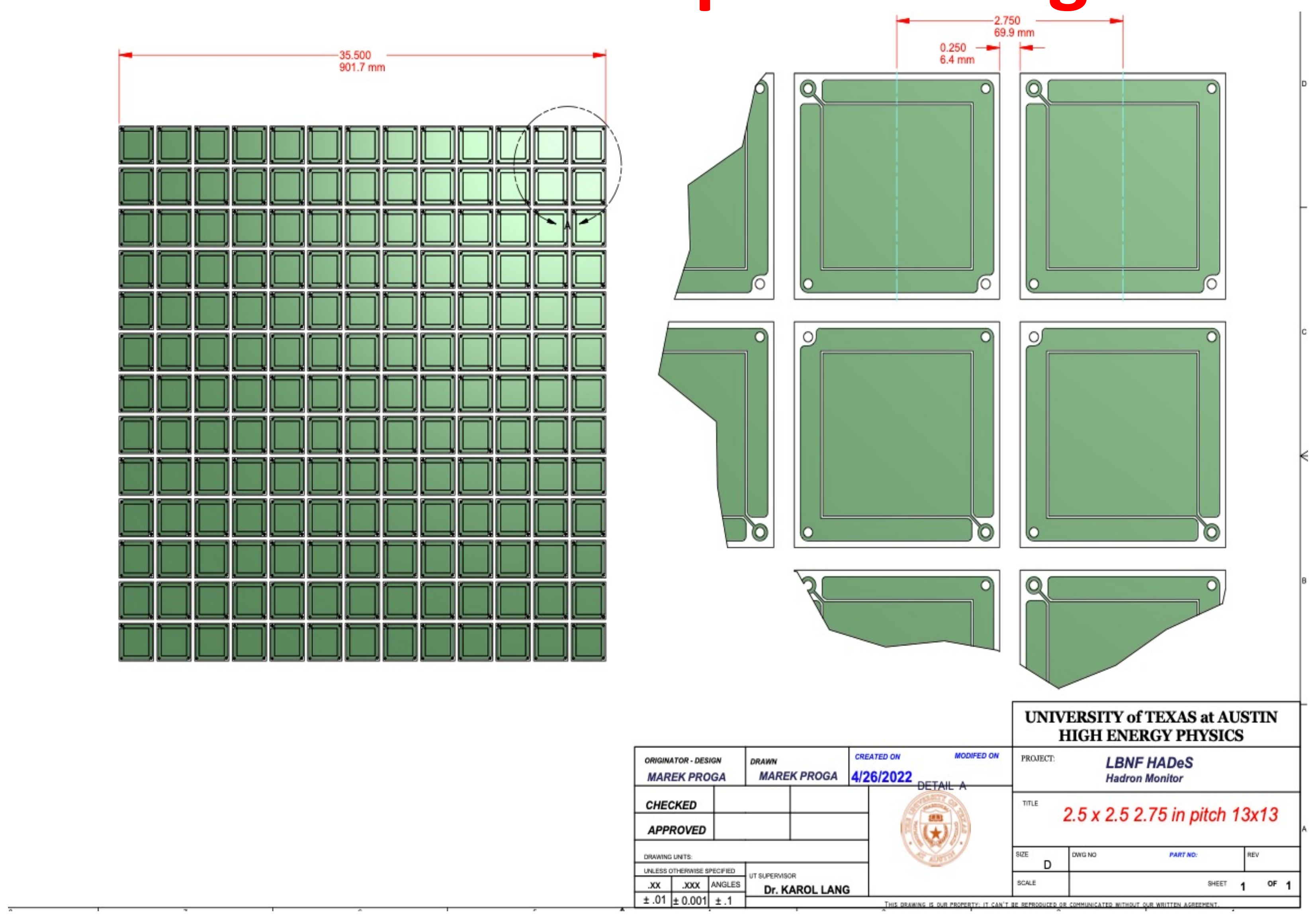
Requirements & Tolerances

- Require well controlled neutrino beam with minimal systematic errors
- Some requirements come from radiation considerations
- All instruments designed for 1.2 MW operation & should work at 2.4 MW, easily upgradable
- Tolerances:
  - ➢ Proton beam angle: 70 μrad
  - ➢ Proton beam position: 0.5 mm, profile: 10%
  - ➢ Baffle beam scraping: 1%
  - ➢ Target and Horn A/B/C displacement (transverse/tilt): 0.5 mm

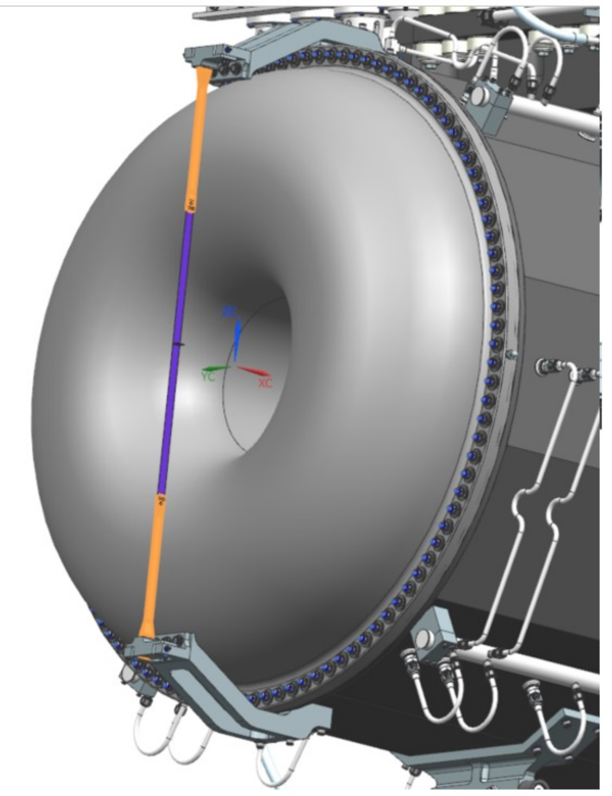
Required Instrumentation: HADeS, Cross-Hair, BLM

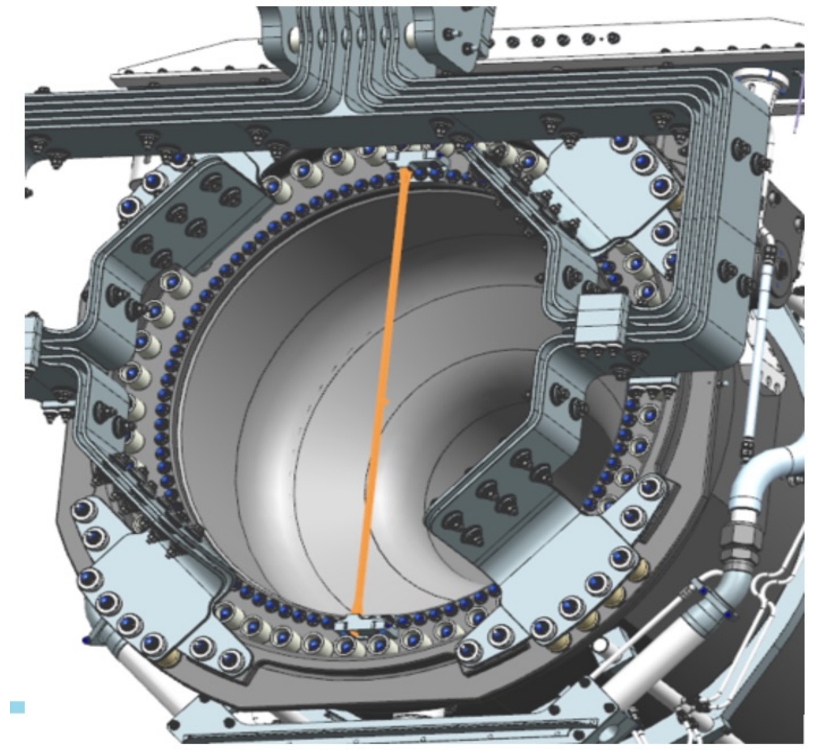
- Systems designed to meet requirements
- Align beamline elements within tolerance with low intensity beam, 1mm RMS spot size
- Needed for Beam-Based Alignment:
    - Beam Position Monitors (BPMs, upstream of target, not under purview of NBI)
    - Hadron Alignment Detector System (HADeS), in front of absorber, at end of decay pipe)
    - Horn cross-hairs and beam-loss monitors (BLMs)
    - Heavily rely on abundant experience with NuMI

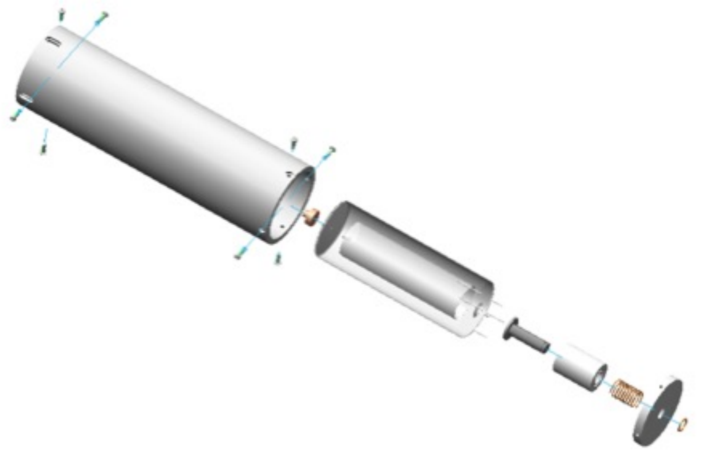
HADeS Conceptual Design



Cross-Hair & BLM Conceptual Design



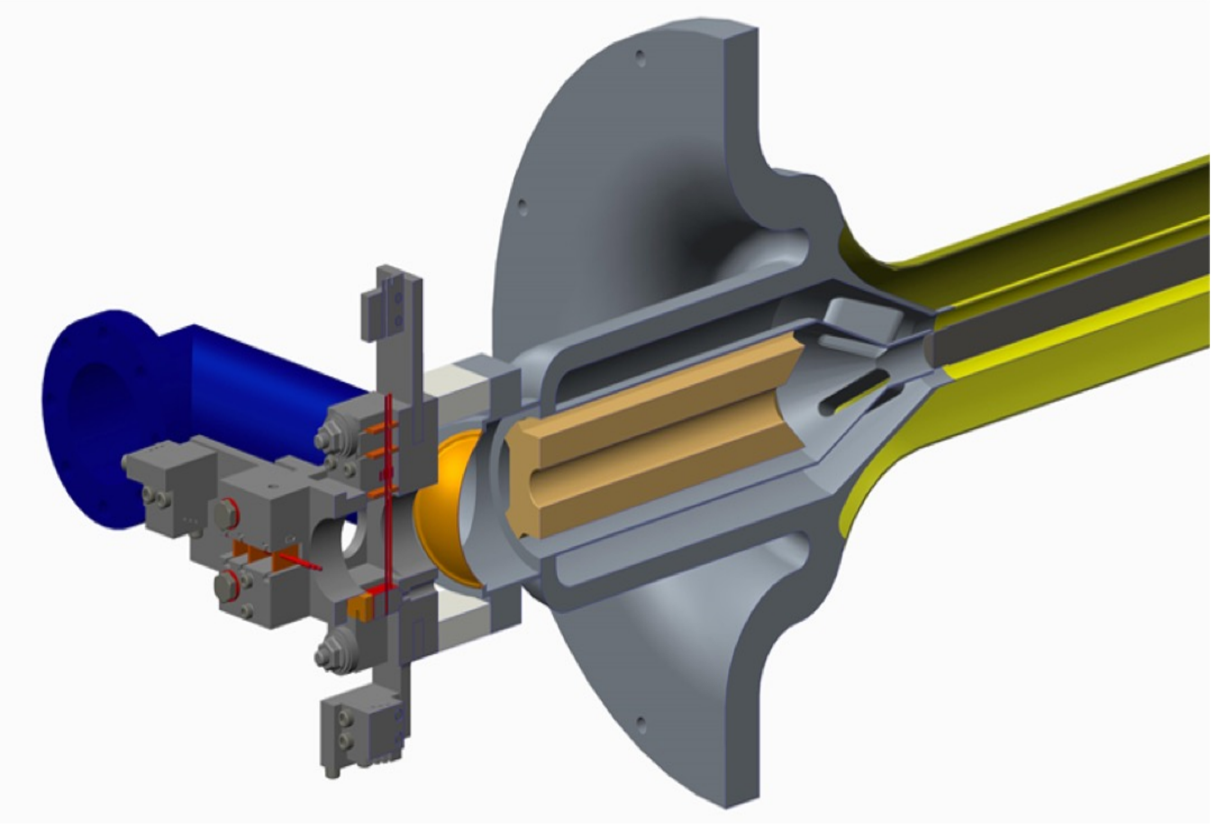




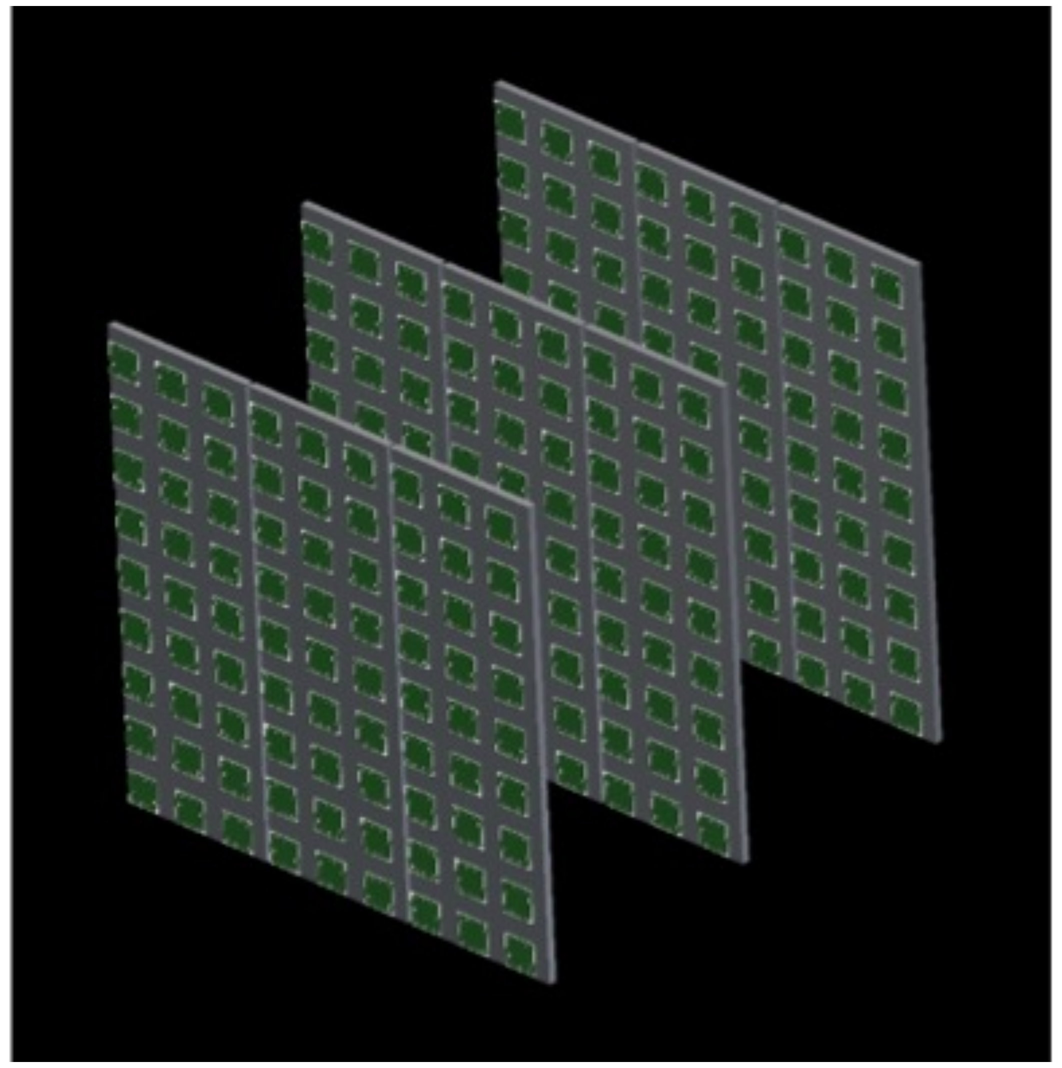
Required Instrumentation: TPT, MuMS, HLS

- TPT, MuMS, HLS used during high intensity run
- Systems designed to meet requirements
- Needed for Monitoring of neutrino beam intensity and direction during operation:
    - Target position thermometer (TPT): if position of beam on target changes w/ no corresponding change in position on BPMs, could be an indication that target itself moved
    - Muon monitor system (MuMS): tracks intensity, beam center and width of the tertiary muon beam on a spill-by-spill basis
    - Horn-leveling system (HLS): independent measurement of positions of focusing horns

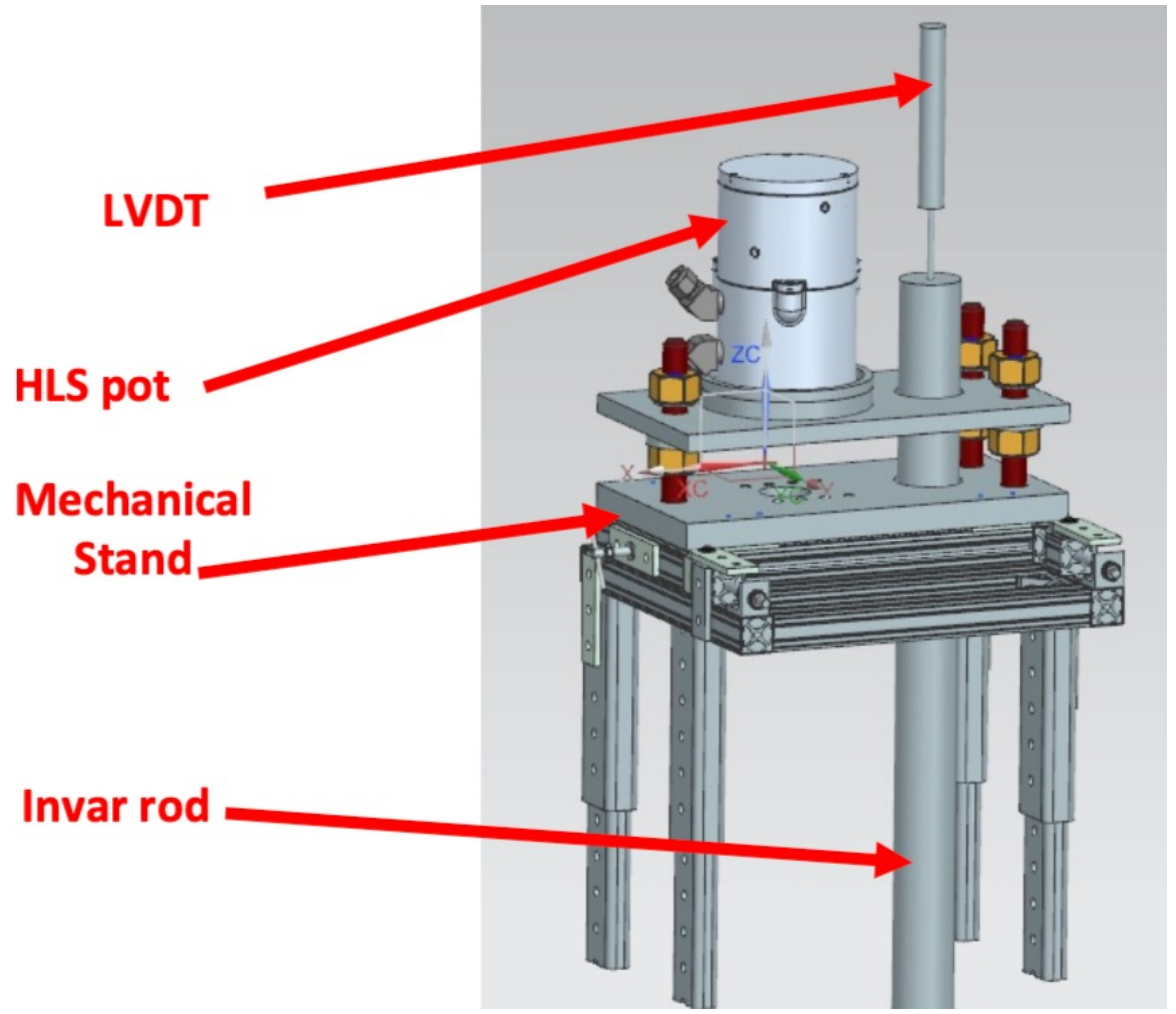
TPT design based on NuMI experience



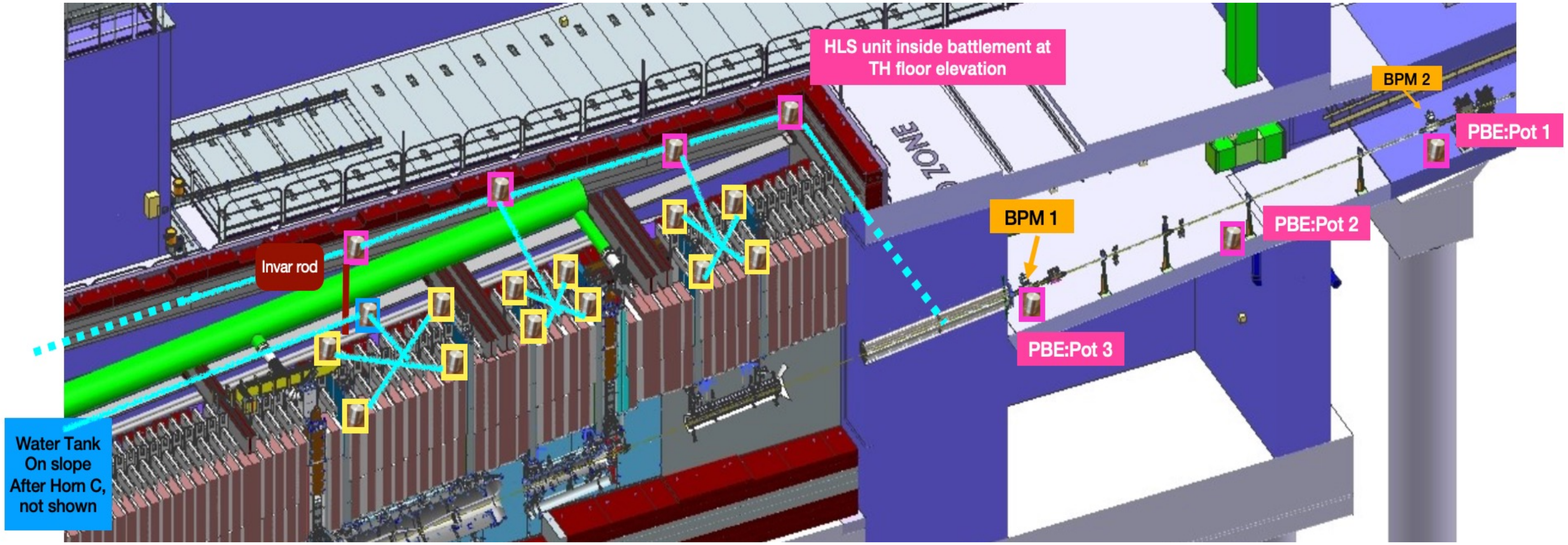
MuMS conceptual design: NuMI approach



HLS conceptual design: inspired by similar CERN system



Instrumentation in Upstream to Downstream Order



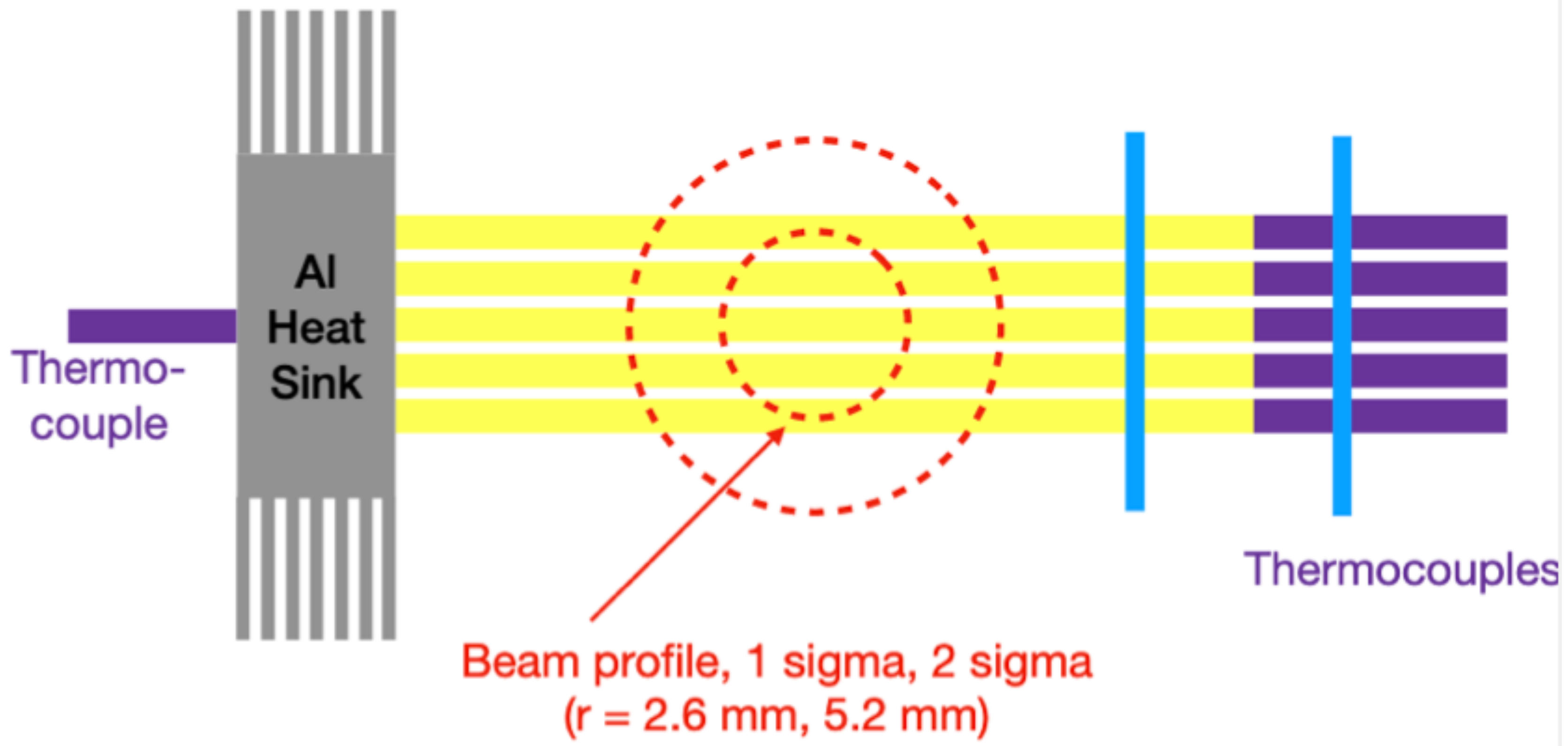
- **HLS** monitors vertical shifts of beamline components (pre-target BPMs, Baffle, Horns)
  - ➢ Uses water level to transfer height between sensors, system based on Frequency Scanning interferometry (FSI)
  - ➢ Simultaneously compares multiple interferometers to same reference
  - ➢ Can sustain radiation on top of LBNF module (5 – 50 kilo-rad/year)
- **BPM**s steer beam on target
- Beam-based alignment finds target & other elements within BPM coordinates

Instrumentation in Upstream to Downstream Order

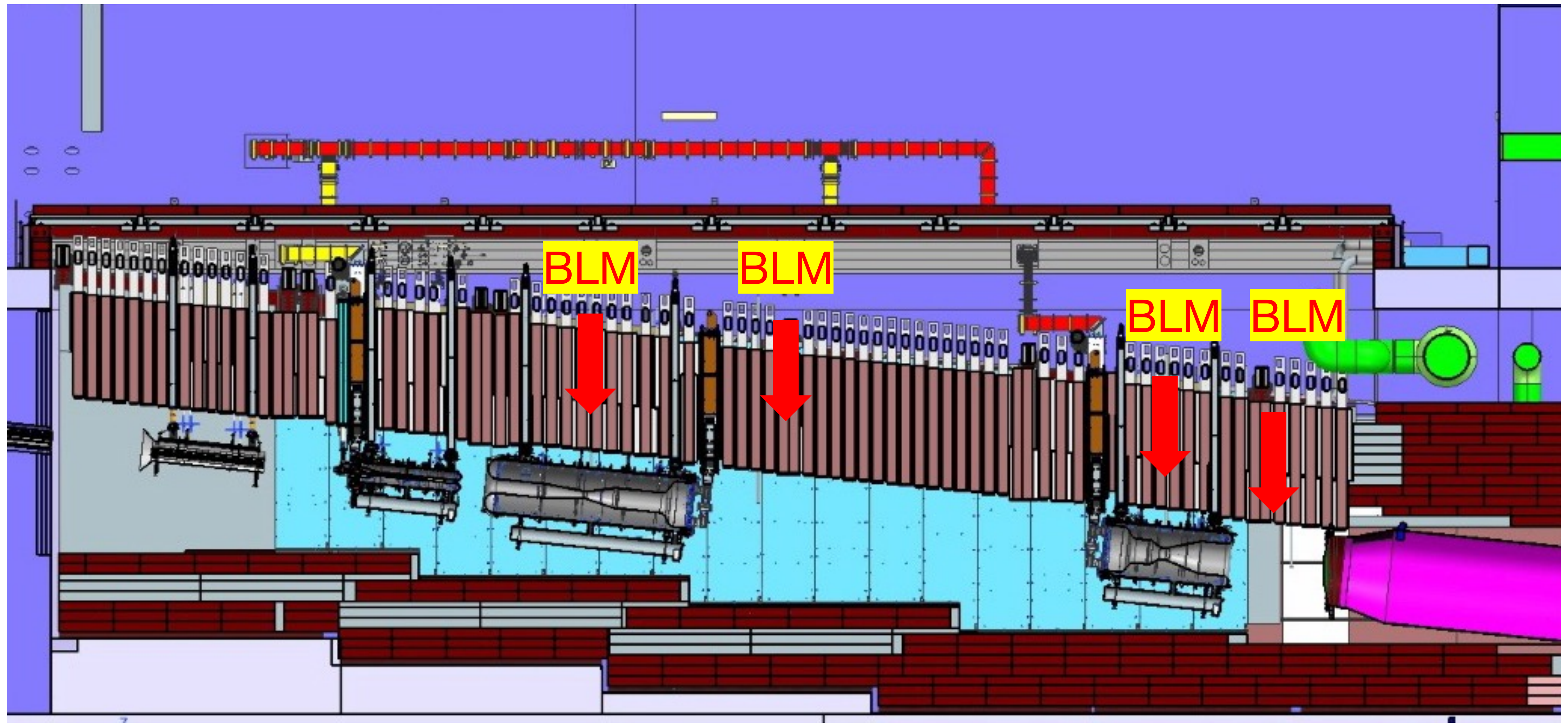
- **TPT** measures beam on target with full intensity
  - **LBNF modifications on TPT:**

    For 1.2 MW beam – 7.5 X 10^{13} ppp, 2.7 mm RMS beam

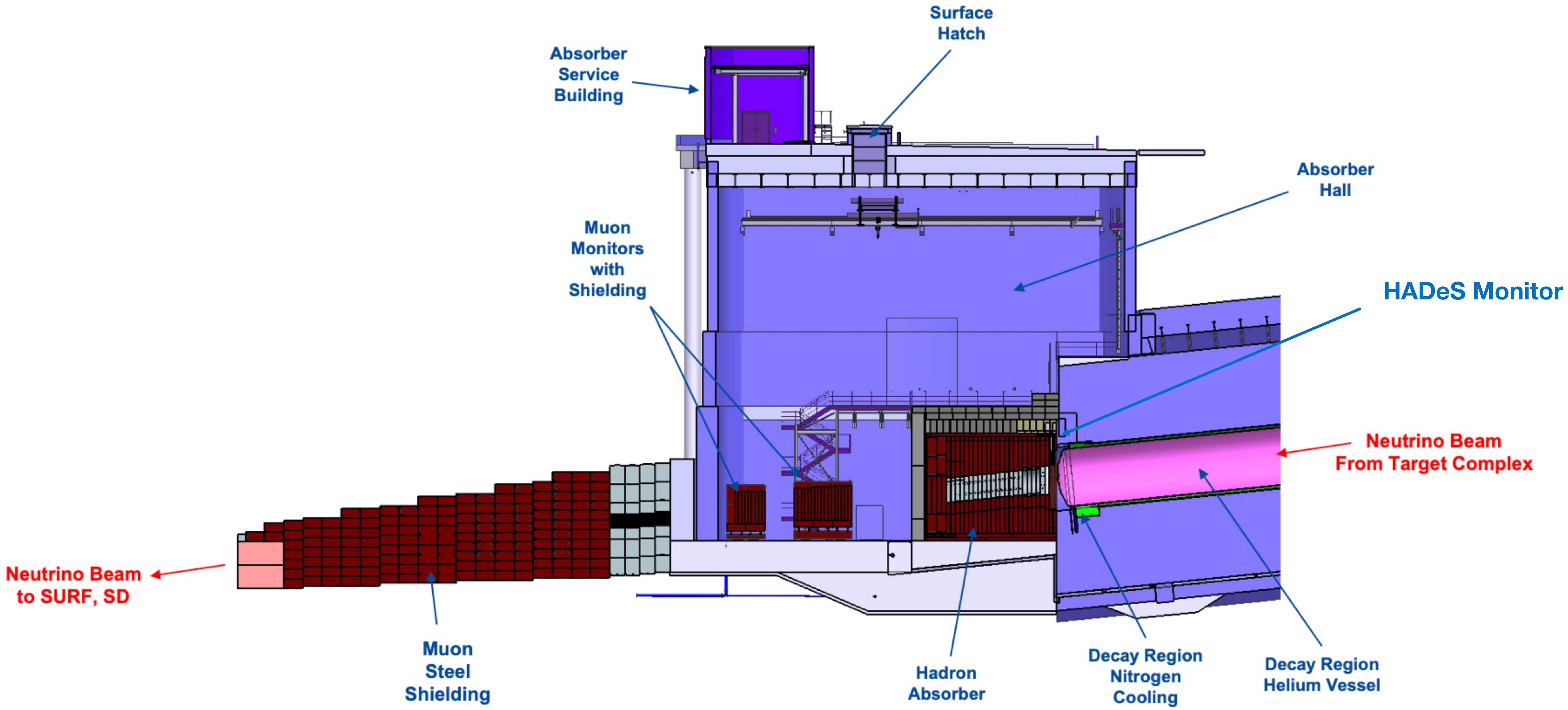
    - ➢ Change from 3 to 5 strips
    - ➢ Heat sink with cooling fins



- **Cross Hairs/ BLMs**
  - ➢ Horn B & C aligned as part of BBA
  - ➢ Scan beam across known physical features to locate each element
  - ➢ Use Cross Hairs at upstream & downstream ends of Horns B & C
  - ➢ Beam loss monitors to detect beam scatter from Cross Hairs



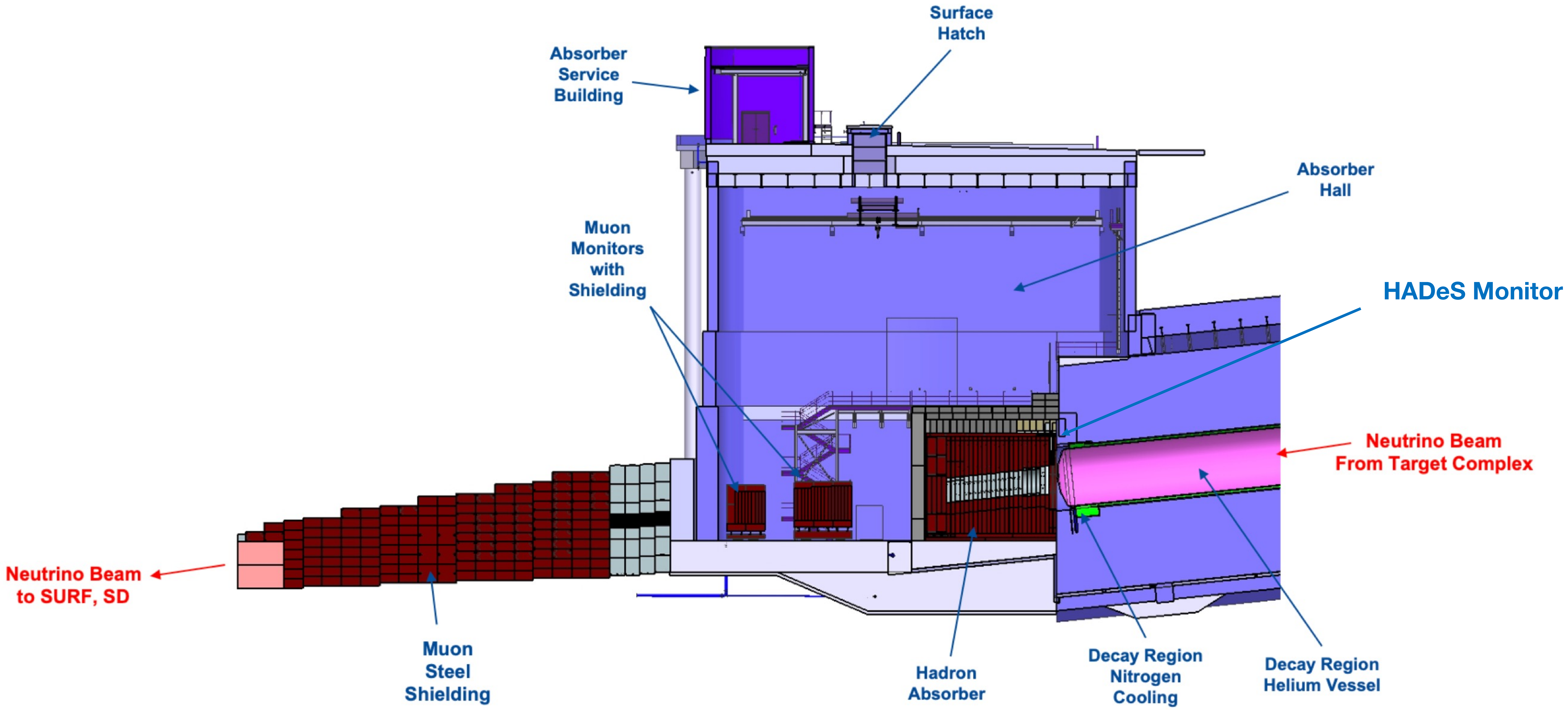
Instrumentation in Upstream to Downstream Order



- **HADeS** – array of ionization chambers
  - ➢ Measure centroid position, integrated intensity, RMS change
  - ➢ Inserted only for alignment, retracted during normal operation

- **LBNF modifications on HADeS:**
  - o Optimize pixel size, # of channels

Instrumentation in Upstream to Downstream Order



- **MuMS**
  - ➢ Sensitive to beam focusing problems, measure beam centroid
  - ➢ Same technology as HADeS
  - ➢ 3 Stations with muon thresholds at 5, 11, and 15 GeV

- **LBNF modifications on MuMS:**
  - o Improved gas system to maintain 1% spill-to-spill integrated flux normalization

Tolerance Upgrade Needs for 2.0+ MW Operation

- BIWG specific question (tolerance studies were all done with full DUNE exposure)
- **Tolerances likely to not change**

> ➢ Proton beam angle: 70 μrad
> ➢ Proton beam position: 0.5 mm, profile: 10%
> ➢ Baffle beam scraping: 1%
> ➢ Target and Horn A/B/C displacement (transverse/tilt): 0.5 mm

- **Radiation on top of LBNF module for 2.4 MW operation with 2.4 m target expected to be 500 – 5000 kilo-rad/year**
  - HLS can stand up to 10,000 kilo-rad/year

Parameter	Protons per cycle	Cycle Time (sec)	Beam Power (MW)
≤ 1.2 MW Operation - Current Maximum Value for LBNF			
Proton Beam Energy (GeV):			
60	7.5E+13	0.7	1.03
80	7.5E+13	0.9	1.07
120	7.5E+13	1.2	1.20
≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase			
Proton Beam Energy (GeV):			
60	1.5E+14	0.7	2.06
80	1.5E+14	0.9	2.14
120	1.5E+14	1.2	2.40

$(1.1 - 1.9)\times10^{21}$ POT/yr

$(2.2 - 3.8)\times10^{21}$ POT/yr

- **Higher Average Power impacts**
  - ➢ Shielding
  - ➢ Cooling
- **Higher Beam Pulse Intensity impacts**
  - ➢ Thermal Shock
  - ➢ Radiation Damage

Likelihood and Impact of Changes to Alignment Scheme

- Horn B&C alignment with cross-hairs and BLM, Hades should be fine for any target horns upgrade
- Baffle alignment steps are also likely to remain unchanged in future upgrades
- Beam spot size at target is tunable: 1-4 mm
- Target & horn A alignment depends on actual target & Bafflette geometry, which is driven by spot size and intensity - could be problematic in an upgrade if spot size and target diameter are significantly increased
- TPT provides some redundancy to the bafflette measurement, giving target angle, but not in same scan
- An additional BLM for Baffle can provide redundancy & cross-checks – recommended by Jim Hylen

Instrumentation Upgrade Needs for 2.0+ MW Operation

HADeS, Cross-Hair, BLM

- HADeS, BLMs : being designed to be used for low intensity beam during beam-based alignment - will be retracted during normal operation **- No design change required**

- Impact of higher radiation on BLM:
  - ➢ Holes on BLMS need to be plugged adequately
  - ➢ Carrier tube for BLMs needs to have adequate shielding on top to allow technicians to come and connect/disconnect

- Cross Hairs and support brackets currently designed for 1.2 MW
  – engineering studies will have to be redone for 2.0+ MW operation
  (similar to: https://docs.dunescience.org/cgi-bin/sso/ShowDocument?docid=23108)

Instrumentation Upgrade Needs for 2.0+ MW Operation

TPT, MuMS, HLS

- If beam spot size needs to be adjusted, TPT spacing may need adjusting
- Studies for TPT heat sink design required for 2.0+ MW operation
- No impact on HLS design expected
- With increased intensity per spill, need to make sure MuMS system is not saturated
- MuMS in beam permit system by evaluating muons/POT (to protect absorber/beam intercepting devices)
  - Requires readjustment depending on how linear the response is
  - Scan over beam intensity and check the MuMS response (tune ionization gap etc.)
  - Identify a threshold where muons/pot can be ruled out as simply statistical fluctuations

Changes to Beam Accident Conditions to Development of 2.4 MW components/systems

- Document (Anomaly-conditions-NBI) available with known sources of anomaly conditions, i.e., horn displacements/tilts etc.
- Anomaly events also include potential accident conditions, i.e., delivering full beam power directly onto absorber
- Will be combined into a single document
- If beam spot size change is needed for 2.4 MW target operation, **will require reexamination of accident conditions/anomaly events** because of possible changes in Baffle and Bafflette due to possible beam spot size change

Consideration for Option 0

Option 0: Achieve 2.4 MW beam power

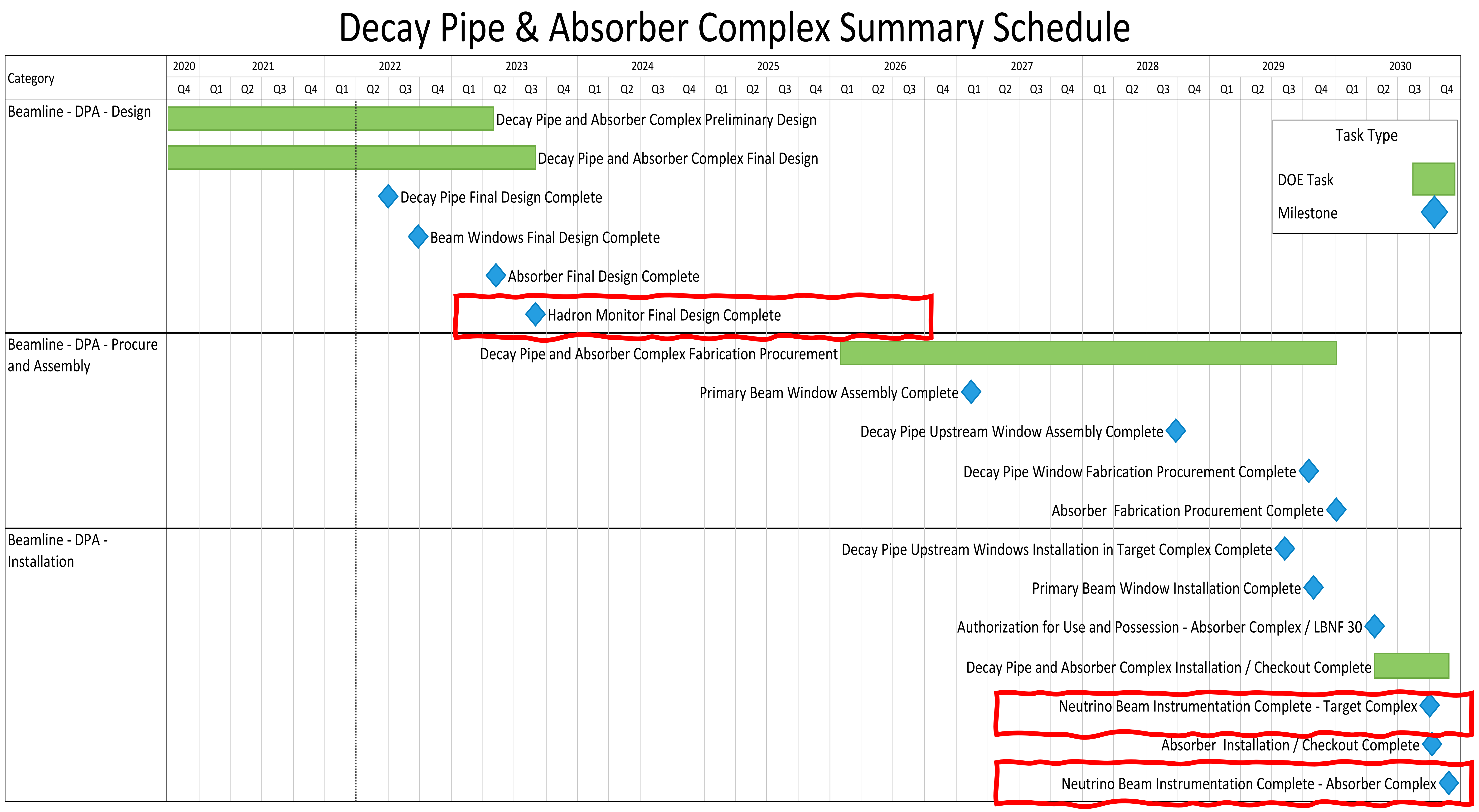
- Utilizing Fermilab Accelerator Complex with PIP-II but without major replacements
- Shortening MI cycle would allow increasing LBNF proton flux without raising MI intensity

- Accident conditions/anomaly events definition remains unchanged with **Higher rep rate rather than increased intensity per spill may help**

- MuMS/Toroid beam-permit system **more obviously works for increasing rep rate rather than per pulse intensity increase** – needs front ends to work faster

- Main impact of higher repetition rate is on target and horn heating – need feedback from horn and target engineering groups
  - TPT : if the same power is being deposited, no change expected from power
    : lower instantaneous stress & heat on all items

Schedule



- On track to have NBI installed and commissioned by 2031, in line with rest of the project
- Upgrades to 2.0+ MW operation are doable

Critical Path runs through Absorber installation – Funding availability for NSCF

Summary

- Tolerance, Alignment: Likely to not change
- Instrumentation upgrade needs:
  - BLM – Engineering study, MARS simulation
  - Cross Hairs & Support Brackets – Engineering study, simulation
  - TPT design, heat sink – Reoptimizing heat sink design, heat transfer study, simulation
  - MuMS – Beam intensity scan, impact on MuMS response
- Option-0 possibly helpful for accident condition definition, MuMS in beam permit system
- All upgrades should be achievable between late 2024 and 2025

System	Limits	R&D Description Level/Risk Time	External Dependencies	Start/Duration To achieve 2032 To achieve 2035 Independent	R&D Labor	R&D M&S Cost	Component Delivery	Duration Estimate Total Estimate	Estimate Start Ready Date	Cost M&S	Labor FTE total	Overall risk of delivery
BLM	**Radiation: 500-5000 kilo-rad/year**	• Engineering studies • MARS simulations	N/A	Later half of 2024-2025	1 month	10k	• Engineering study result • MARS simulation result	2 months	Later half of 2024-2025	$18000	200 hours	Low
Cross Hairs, Support Brackets	**Increased Fatigue, Temperature, Radiation: 500-5000 kilo-rad/year**	• New engineering studies for 2.4 MW operations needed • Simulations	Horn design	Later half of 2024-2025	1 month	10k	• Engineering study result • Simulation result	2 months	Later half of 2024-2025	$18000	200 hours	Low
TPT	**Increased Beam Power, temperature**	• Heat transfer study • Reoptimize heat sink design for 2.4 MW operation • Simulations	Target design	Later half of 2024-2025	1 month	10k	• Result of Heat transfer study, • Engineering study • Simulation study	2 months	Later half of 2024-2025	$18000	200 hours	Low
MuMS **a. Validating as part of machine protection** **b. Do it as a NuMI study**	**Increased intensity per spill: 1.5E14**	• Beam intensity scan and check MuMS responses • Validation study	N/A	N/A	N/A	N/A	Test result	N/A	N/A	N/A	N/A	Low

Based on 50% of current schedule & assuming beam spot size remains the same

Backup

Quantity	1-sigma Shift	Notes	In TDR
Horn A Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	Y
Horn A Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn B Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	Y
Horn B Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn C Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	N
Horn C Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Target Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	N
Target Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N

Monitored by HLS, TPT, MuMS

Alignment using HADeS, XHairs

Horn A Longitudinal Displacement	2 mm		N
Horn B Longitudinal Displacement	3 mm		N
Horn C Longitudinal Displacement	3 mm		N
Proton Beam Transverse Position	0.5 mm	X and Y shifted separately; added in quadrature	Y
Proton Beam Radius	10%	Updated from 0.1 mm for NuMI	Y
Proton angle on target	70μ rad	X and Y shifted separately; added in quadrature	Y
Decay Pipe Radius	0.1 m		Y
Horn Currents	1%	Changed in all three horns simultaneously	Y
Baffle Scraping	0.25%	To Be Updated	N
Bafflet Scraping	0.25%	To Be Updated	N
Target Density	2%		Y
Horn Water Layer Thickness	0.5 mm	Changed in all three horns simultaneously	Y
Upstream Target Degradation			N
# Protons on Target	2%		Y
Near Detector Position			N
Far Detector Position			N
Field in Horn Necks			N
Decay Pipe Position	20 mm		N

Table 1: Sources of alignment and focusing uncertainties in the neutrino fluxes at DUNE. Sources that were considered in physics studies in the TDR are marked with a 'Y' in the 'In TDR' column.

Monitored by MuMS, HLS (If longitudinal displacement is coupled to transverse displacement)

Monitored by TPT, MuMS

Aligned with HADeS

Aligned with XHairs

Monitored by MuMS