LBNE Beamline Planning and Options

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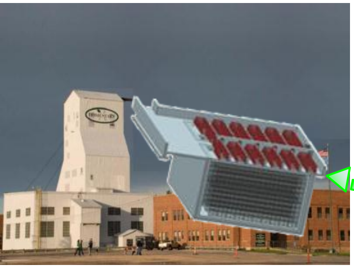


Outline
(items requested by P5)

- Beamline Scope
- Requirements and Assumptions
- Design Overview
- Considered design changes to increase the physics potential
- How we will deal with increasing beam power
- Summary

Main Points

- We know how to build neutrino beams. Following closely the design and lessons learned from NuMI (including re-using components) and many LBNE team members have the experience of NuMI.
- We have a well developed design for the LBNE Beamline for 700 kW, upgradeable to 2.3 MW. (Many Beamline, Project, Director and DOE internal and external reviews have validated this).
- The high power LBNE Beamline is the key application for the MW class facility at Fermilab. The strategy to design for a facility upgradeable to 2.3 MW will serve us well in the long run.
- We are exploring a number of improvements to the design (beyond CD-1) which could increase the number of neutrinos per proton by up to 50%.

Neutrino Program at Fermilab

A Beamline for LBNE

- “Design” started just after the 2008 P5 recommendation that we design a new, high power neutrino beamline to DUSEL(now SURF)
  - Began with a working group to document “lessons learned” from NuMI
- In 2009 we began addressing particular details to meet the requirements for this new beam
  - Team built on the experience of the NuMI scientists and engineers
- Working on this for the past ~ 5 years; ~20 FTEs now

Past and projected performance

Building on past experience

Past (FY2012)

NuMI Multi-batch slip- stacking in Main Inj.	
MI cycle time (s)	2.1
MI intensity (ppp)	$3.7x10^{13}$
NuMI beam power (kW)	340 (at 120 GeV)
PoT/year to NuMI	$3.6x10^{20}$

Projected

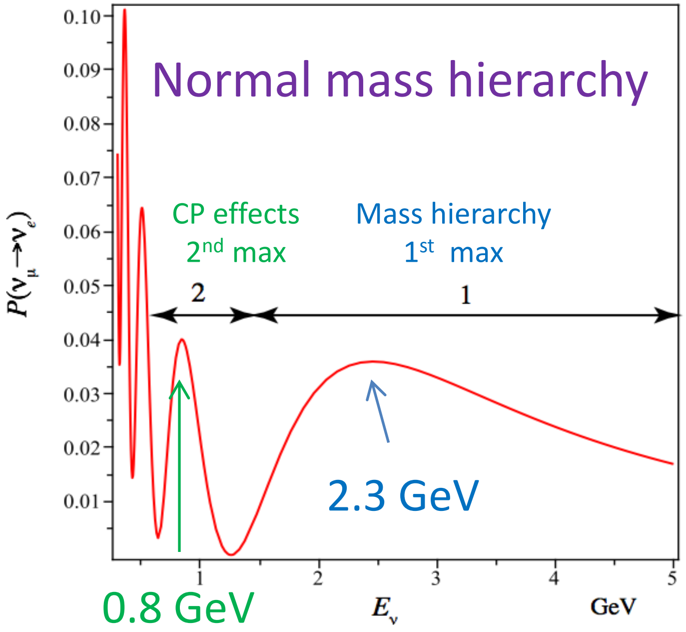
NuMI Multi-batch slip- stacking in Recycler	
MI cycle time (s)	1.333
MI intensity (ppp)	$4.9x10^{13}$
NuMI beam power (kW)	700 (at 120 GeV)
PoT/year to NuMI	$6.0x10^{20}$

Main Injector World Record(120 GeV): 18 Feb. 2011
401 kW, 4.6 $x10^{13}$ every 2.2 sec

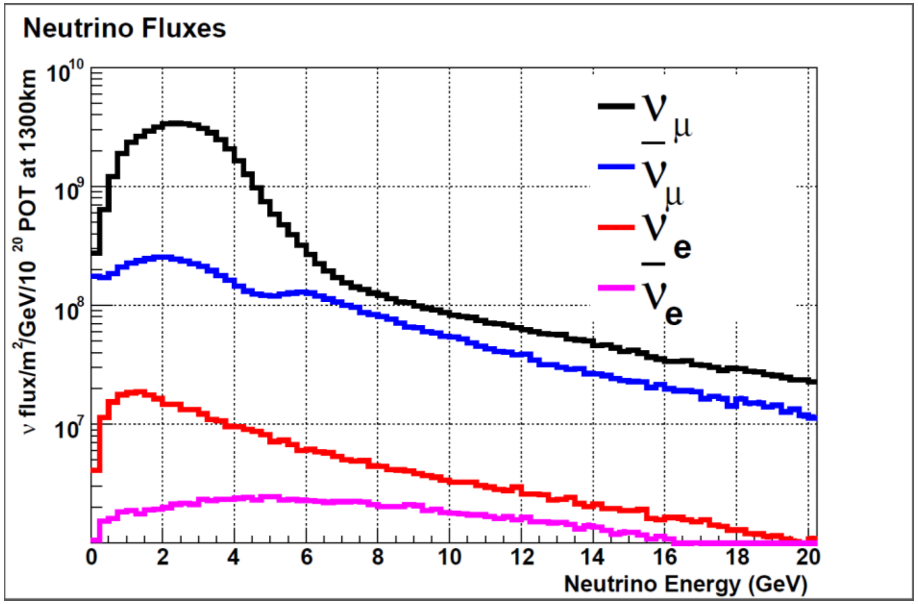
In the past 15 years the Fermilab Accelerator complex has delivered $14x10^{20}$ POT to NuMI and $18x10^{20}$ POT to the Booster Neutrino Beamline!!

Requirements driven by the physics

- The driving physics considerations for the LBNE Beamline are the long-baseline neutrino oscillation analyses.
- Wide band, sign selected beam to cover the 1st and 2nd oscillation maxima. Optimizing for Eν in the range 0.5 – 5.0 GeV.
- The primary beam designed to transport high intensity protons in the energy range of 60-120 GeV to the LBNE target.



Neutrino flux at Far Detector



Requirements and assumptions

- We have been planning so far to start with a 700 kW beam (NuMI/NOvA at 120 GeV) and then be prepared to take significantly increased beam power (~2.3 MW) allowing for an upgradeability of the facility when more beam power becomes available.
- Fermilab has recently set a goal to try to raise the beam power to >1 MW by the time LBNE starts operation (to be presented to P5 at the BNL meeting in December) and we have taken 1.2 MW as our target for evaluation.
  - Just starting to understand how we would modify the initial beamline configuration to accommodate this beam power.
- The lifetime of the Beamline Facility including the shielding is assumed to be 30 years.

LBNE Beamline Reference Design: MI-10 Extraction, Shallow Beam

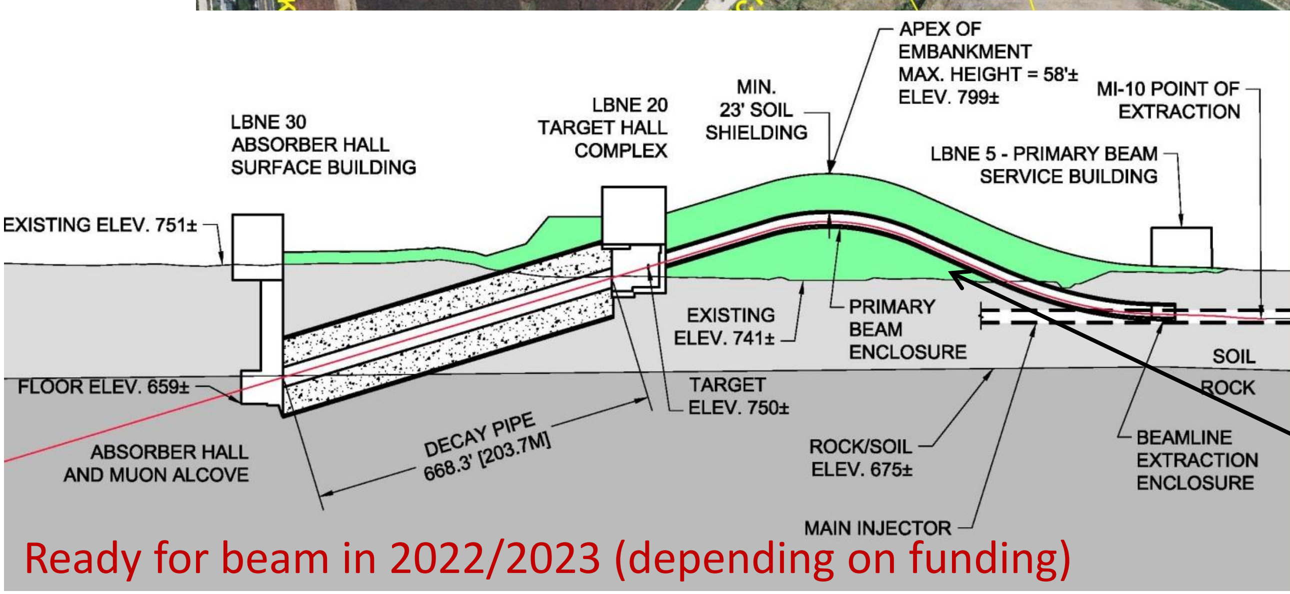
Beamline Facility contained within Fermilab property

Antiproton Source

Kirk Rd

Tevatron

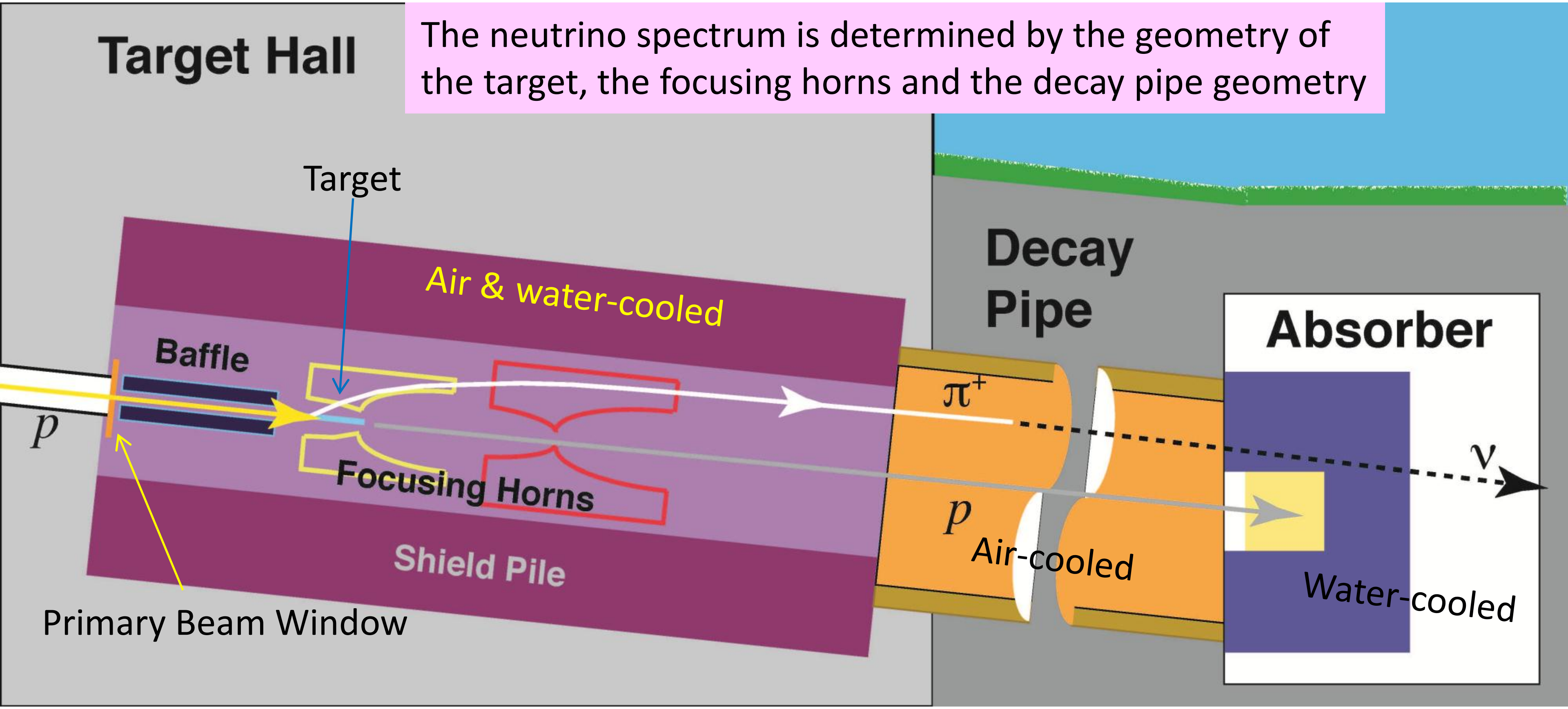
Main Injector



Ready for beam in 2022/2023 (depending on funding)

The lattice design of the primary proton beam requires about 80 conventional magnets

Major Components of the Neutrino Beam

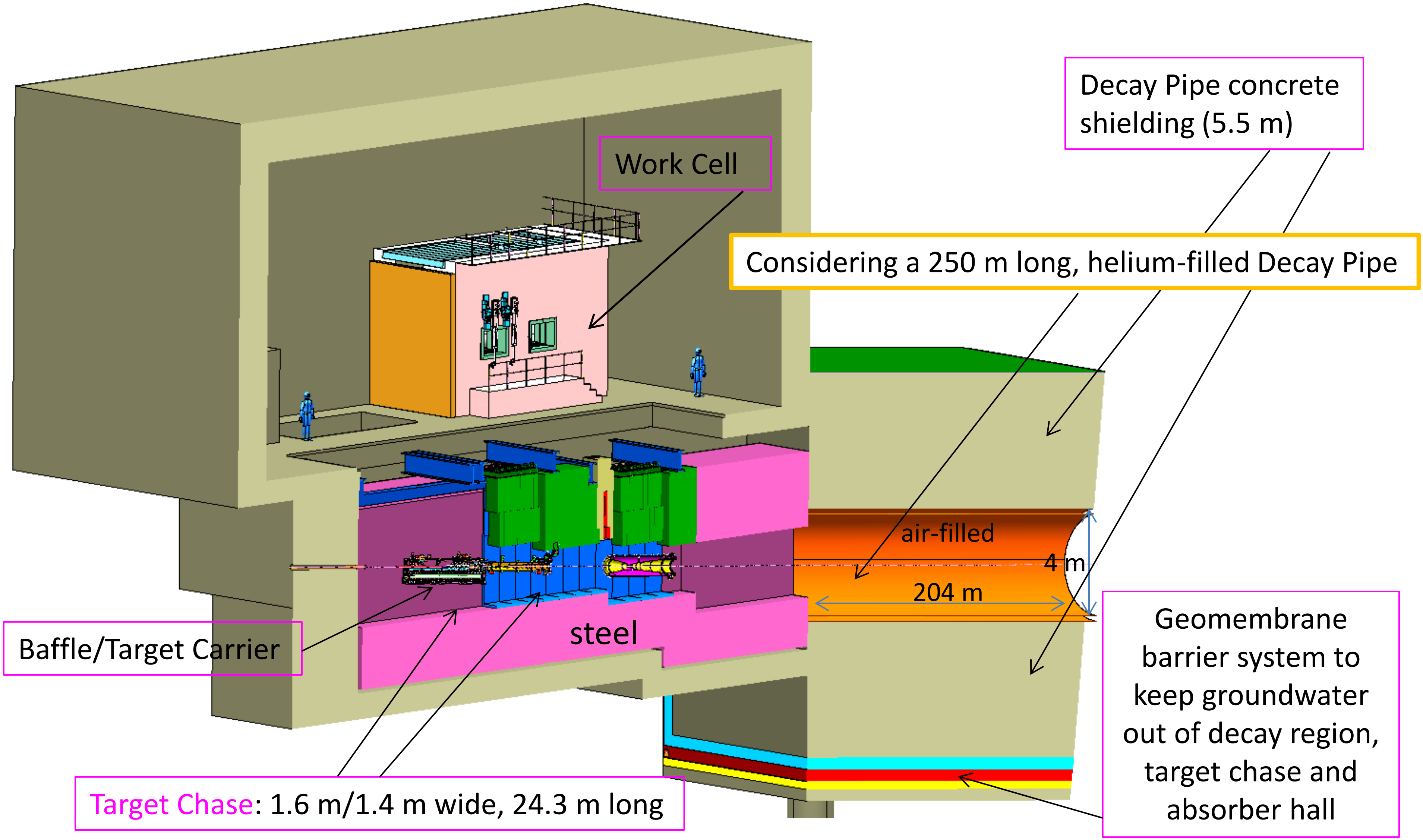


NuMI design Horns

NuMI-like low energy target for 700 kW operation

Tunable neutrino energy spectrum

Target Hall/Decay Pipe Layout



Considered design changes that increase the physics potential

Ratio of $\nu_\mu \rightarrow \nu_e$ CC appearance rates at the far detector

Change	0.5-2.0 GeV	2.0-5.0 GeV
DK pipe Air → He *	1.07	1.11
DK pipe length 200 m → 250 m (4m D)	1.04	1.12
DK pipe diameter 4 m → 6 m (200m L)	1.06	1.02
Horn current 200 kA → 230 kA	1.00	1.12
Proton beam 120 → 80 GeV, 700 kW	1.14	1.05
Target graphite fins → Be fins	1.03	1.02
Total	1.39	1.52

* Simplifies the handling of systematics as well

There will be some cost or programmatic impact (depending on the change)

Dealing with increasing beam power

- Systems that are technically impractical and cost inefficient to upgrade from 700 kW to 2.3 MW in the future are designed for 2.3 MW power now.
- Replaceable components are being designed for 700 kW and will need to be re-evaluated for 1.2 MW beam power.
- Some upgrades are straightforward (e.g. water cooling of target shield pile).
- Some upgrades require R&D (e.g. targets).
  - A small amount of R&D is still needed for 700 kW beam power.
- The upgrade of the replaceable components from 700 kW to 2.3 MW is roughly estimated to cost ~$ 35 M in $FY13.
- To start at beam power > 700 kW we will need a development and prototyping cycle of a couple of years for some components but we can accomplish this on time for the 1.2 MW beam.

What is being designed for 2.3 MW and what will need to be re-evaluated or replaced at >700 kW

- Designed for 2.3 MW, to allow for an upgrade in a cost efficient manner:
  - the radiological shielding of enclosures (primary beam enclosure, the target shield pile and target hall except from the roof of the target hall, the decay pipe shielding and the absorber hall) and size of enclosures
  - beam absorber
  - decay pipe cooling
  - remote handling
  - radioactive water system piping
- What would have to be re-evaluated or replaced if we got >700 kW beam power:
  - Beam Profile Monitors in the Primary Beam
  - Primary Beam Window, Baffle, Target, Horns and Target & Horn Instrumentation (Target and Horn alignment monitors and Hadron monitor) in Neutrino Beam
  - Water cooling of panels already installed in the target shield pile for shielding purposes
  - Upstream Decay Pipe window if helium in Decay Pipe

Beamline R&D topics

- For 700 kW operation Beamline R&D is focusing on Neutrino Beamline components:
  - target (materials) – to improve target lifetime
  - hadron monitor (located in front of the hadron absorber) – increased particle flux due to shorter decay pipe in LBNE
  - 2[nd] generation horn (inner conductor shape optimization) – to improve the flux
- For > 700 kW operation additional R&D will be needed on:
  - target (materials, shape, cooling,…)
  - horns
  - hadron monitor
  - primary beam window

Collaboration Opportunities

- Magnets
  - Dipoles (providing dipole coils or building the magnets as well)
  - Correctors
- Quadrupole magnet power supplies
- Primary Beamline instrumentation (BLMs/TLMs, Profile monitors, IPMs,…)
- Target and Baffle support module
- Target R&D
- Support modules for the two horns
- Upstream decay pipe window if Helium in the decay pipe
- Hadron Monitor (both R&D and building it)
- Remote handling contributions (steel for shield doors, lead glass windows, vision systems,…)
- Design and manufacturing of stainless steel cooling panels for the target chase shield pile and additional steel for it

Collaboration Opportunities

- Contributing to the design of the hadron absorber, providing steel and aluminum for it and manufacturing of its cooling channels
- Participation in horn R&D for higher beam power
- Corrosion studies for target chase, decay pipe and absorber
- Radionuclide handling (Na^{22}, H^3, Ar^{41})
- Radiation simulation verification – simulate known irradiations at known facilities and compare with actual measurements
- Hadron production studies that provide essential input for the prediction of the neutrino flux
- Beam simulations
- ……

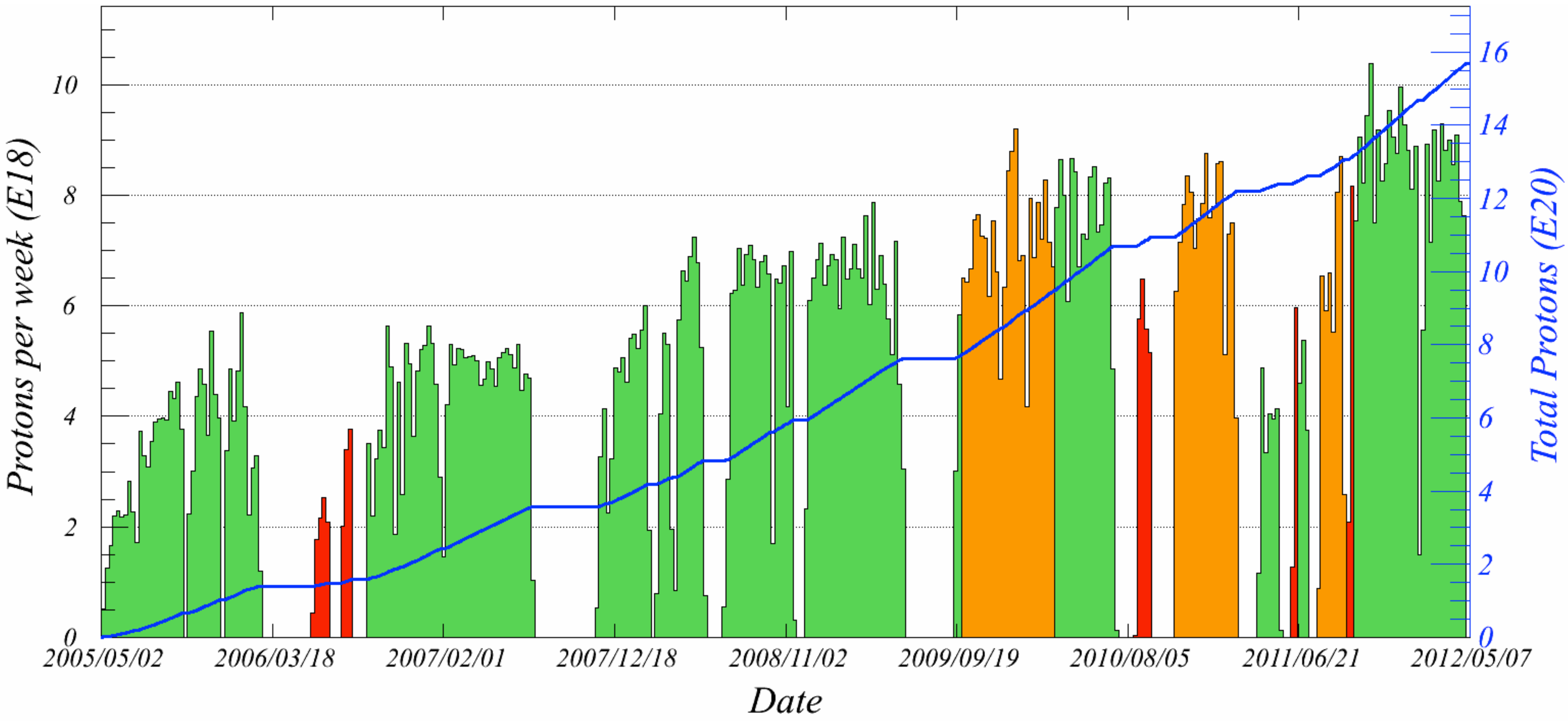
Summary

- The Beamline conceptual design is complete and in some systems well beyond the conceptual level. (Independently reviewed and validated for CD-1).
- Following closely the design and lessons learned from NuMI and many LBNE team members have the experience of NuMI.
- The high power LBNE Beamline is the key application for the MW class facility at Fermilab. The strategy to design for a facility upgradeable to 2.3 MW will serve us well in the long run.
- There are some technical challenges to start with a beam of 1.2 MW but we know how to deal with them.
- Exploring several improvements to the design (beyond CD-1) which could increase the number of neutrinos per proton by up to 50%.
- Plenty of opportunities for international collaboration.
- An excellent team is working on the Beamline design. We are looking forward to complete this design soon and build the LBNE Beamline!!

Backup Slides

BACKUP SLIDES

NuMI performance 2005-2012



Accelerator upgrade plan

- Main Injector (MI) is a rapid cycling accelerator at 120 GeV
  - **Booster batches injected into MI at 15 Hz**
  - **MI is 7 times the circumference of the Booster**
- Using the Recycler to accumulate protons from the Booster while MI is accelerating, saves 0.4 s for each 6 Booster batches injected
- Recycler momentum aperture large enough to allow slip-stacking operation in Recycler, for up to 12 Booster batches injected
  - **6 batches are slipped with respect to the other 6 and, at the time they line up, they are extracted to MI in a single turn and there re-captured and accelerated**
  - **MI will run at its design acceleration rate of 240 GeV/s (1.333 s cycle time)**
  - 4.3×10^{12} p/batch, 95% slip-stacking efficiency
  - 4.9×10^{13} ppp at 120 GeV every 1.333 s $\Rightarrow$ 700 kW
- **New Recycler injection line, new transfer lines MI-Recycler, new 53 MHz RF system & instrumentation in Recycler, 2 additional RF stations in MI**
- **Proton Source improvements**

Primary Beam Design Parameters (Main Injector)

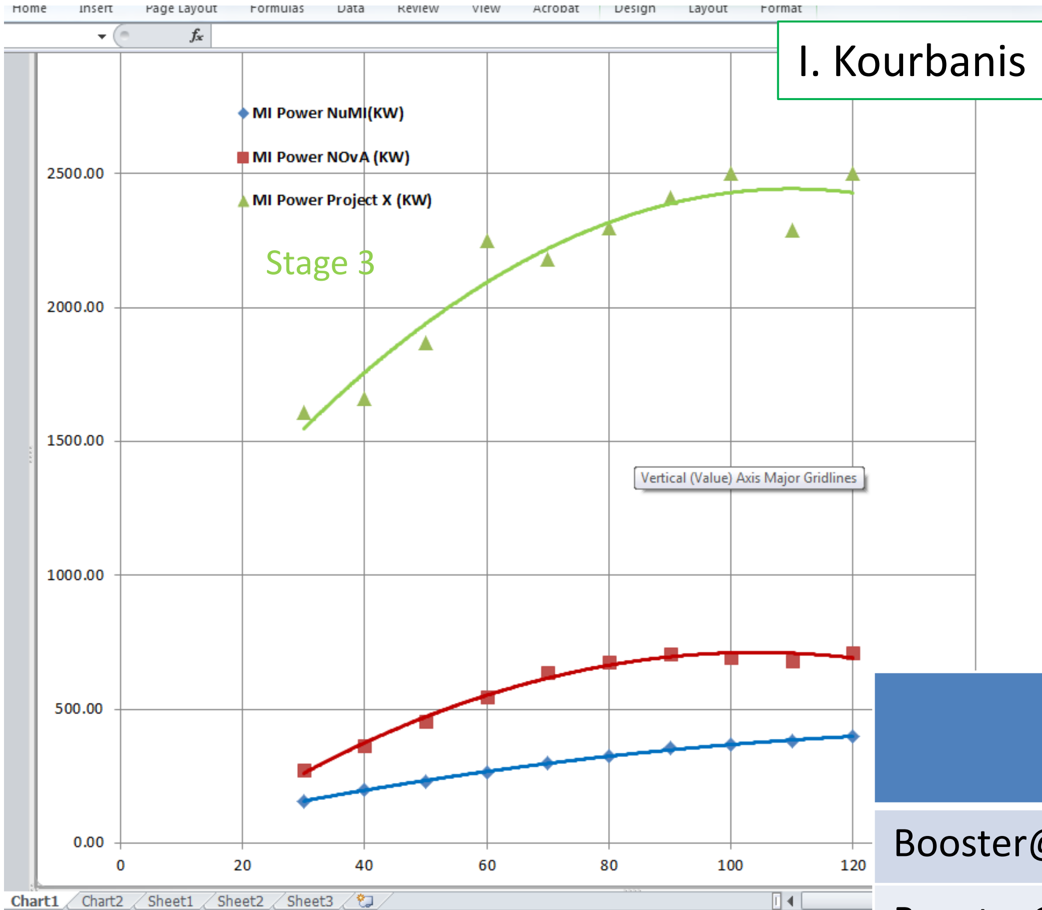
Beam Parameter	Value
Protons per cycle	4.9×10^{13}
Cycle time (120 GeV)	1.33 sec
Pulse duration	1.0×10^{-5} sec
Proton beam energy	60 to 120 GeV
Beam power at 120 GeV	700 kW
Operational efficiency	56% (MI+LBNE Beamline)
Protons on target per year	6.5×10^{20}
Beam size at target	1.3 – 1.5 mm
Beam divergence x,y	17 μrad

Constant beam power above ~80 GeV

Tunable between 1.0 to 3.2 mm

Main Injector Beam Power vs Beam Momentum

Beam Power



Beam Momentum

Stage 1 Project X

	Energy	Power	Cycle time
Booster@15 Hz	120 GeV	1.2 MW	1.2 s
Booster@15 Hz	60 GeV	0.9 MW	0.8 s
Booster@20 Hz	120 GeV	1.2 MW	1.2 s
Booster@20 Hz	60 GeV	1.2 MW	0.6 s

Considered design changes that increase the physics potential

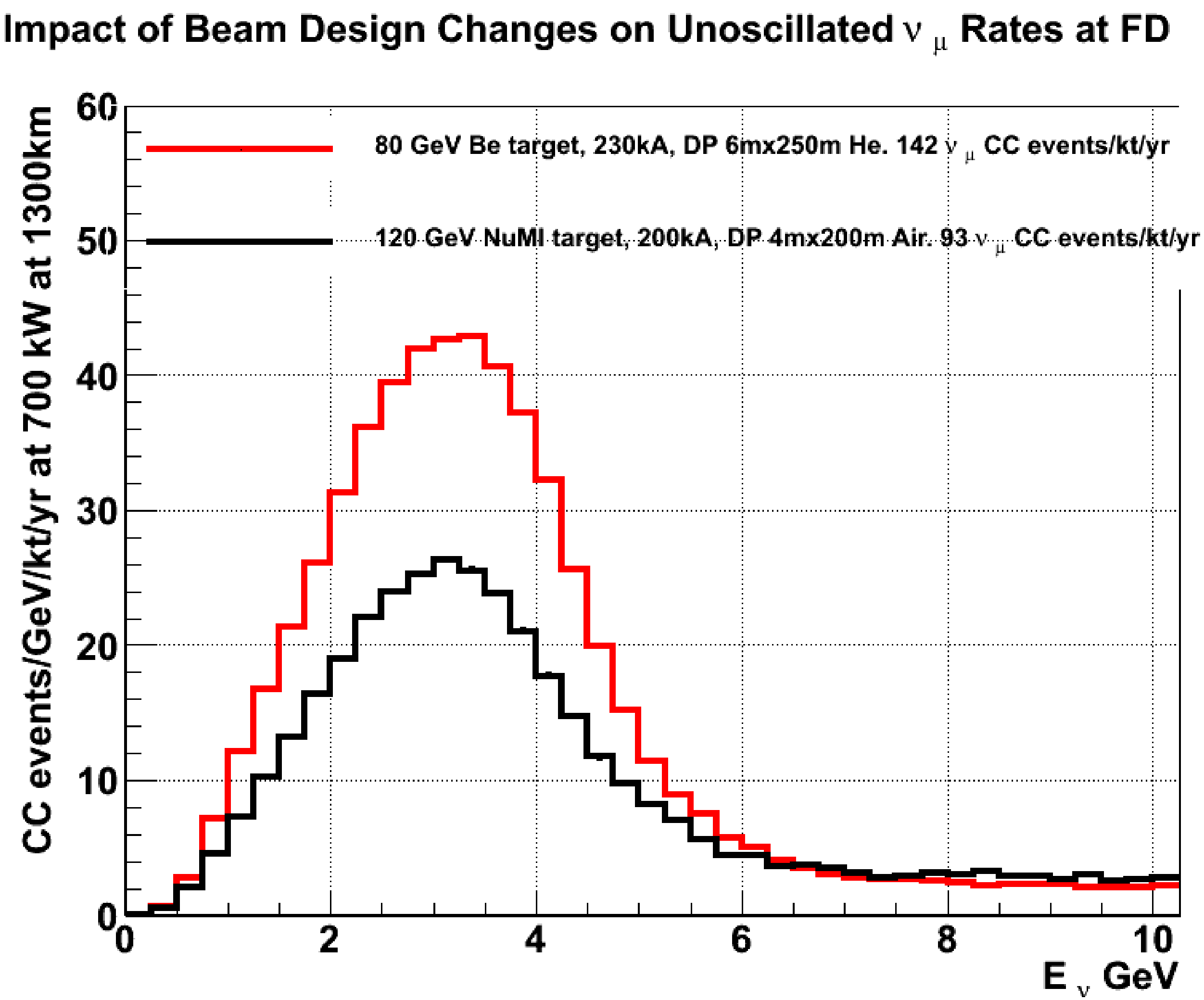
Ratio of $\nu_\mu \rightarrow \nu_e$ CC appearance rates at the far detector

Change	0.5-2.0 GeV	2.0-5.0 GeV	Impact
DK pipe Air → He *	1.07	1.11	~$ 8 M
DK pipe length 200 m → 250 m (4m D)	1.04	1.12	~$ 30 M
DK pipe diameter 4 m → 6 m (200m L)	1.06	1.02	~ $17 M
Horn current 200 kA → 230 kA	1.00	1.12	small
Proton beam 120 → 80 GeV, 700 kW	1.14	1.05	Programmatic impact
Target graphite fins → Be fins	1.03	1.02	Increase target lifetime
Total	1.39	1.52	

If both (DK pipe length and diameter) $55 M

* Simplifies the handling of systematics as well

Considered design changes that increase the physics potential



Optimization of Decay Pipe Size

For current default size of Decay Pipe

ν_e appearance event rate per $M TPC (the higher the better)

2.0 < E < 5.0 GeV

Air in Decay Pipe

Length \ Dia > V	2m	3m	4m	6m
175m	0.827	0.909	0.907	0.848
200m	0.820	0.916	0.914	0.874
225m	0.792	0.893	0.905	0.857
250m	0.794	0.868	0.887	0.846

Helium in Decay Pipe

Length\Dia>	4m	6m
200m	0.980	0.946
250m	0.972	0.935

Optimization of Decay Pipe Size

For current default size of Decay Pipe

ν_e appearance event rate per $M TPC (the higher the better)

0.5 < E < 2.0 GeV

Air in Decay Pipe

Length \ Dia > V	2m	3m	4m	6m
175m	0.110	0.123	0.125	0.122
200m	0.107	0.121	0.123	0.122
225m	0.103	0.116	0.120	0.118
250m	0.099	0.112	0.117	0.115

Helium in Decay Pipe

Length\Dia>	4m	6m
200m	0.126	0.126
250m	0.121	0.120

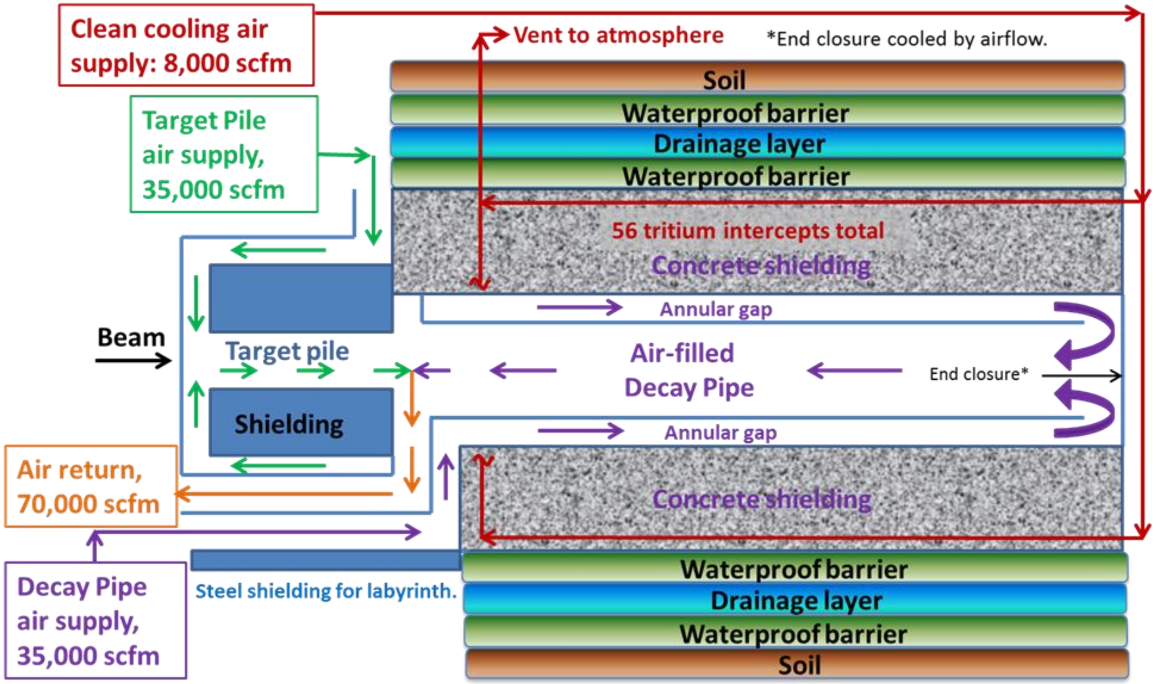
Cooling Task Force Conclusions
Decay Pipe Filling/Cooling

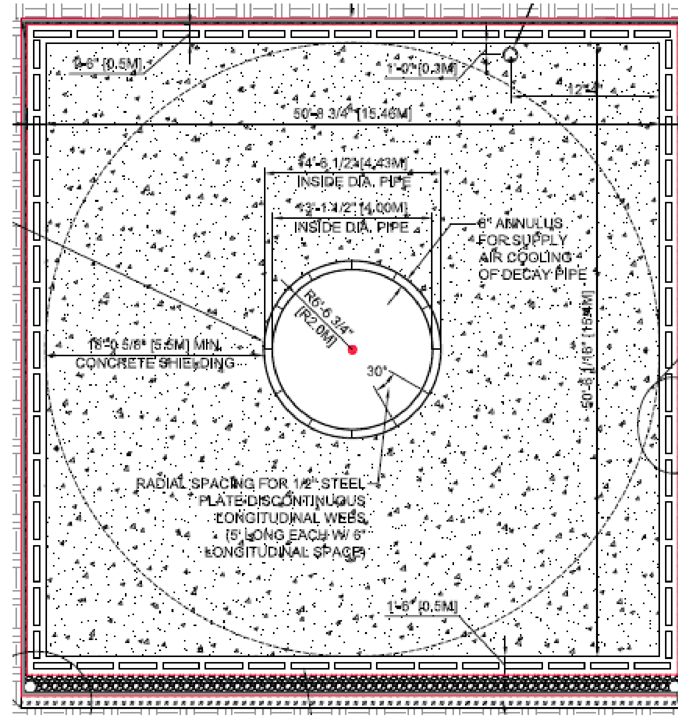
- **Three options were examined in detail for a 4m diameter, 204m long Decay Pipe:**

Case 1: air-filled/air-cooled; Case 2: He-filled/air-cooled; Case 3: He-filled/water-cooled.

- **Both the air-filled/air-cooled and the helium-filled/air-cooled decay pipe options are viable alternatives for cooling the decay pipe to remove the energy deposited by the beam.**
- The helium-filled/water-cooled decay pipe option is also technically viable but the recommendation is to not pursue further because of: a) its poor cooling capacity, particularly in case of failure of one or more cooling pipes; b) larger operating risks, due to the huge impact of possible water leaks in decay pipe lines, even if with small probability; c) higher cost.

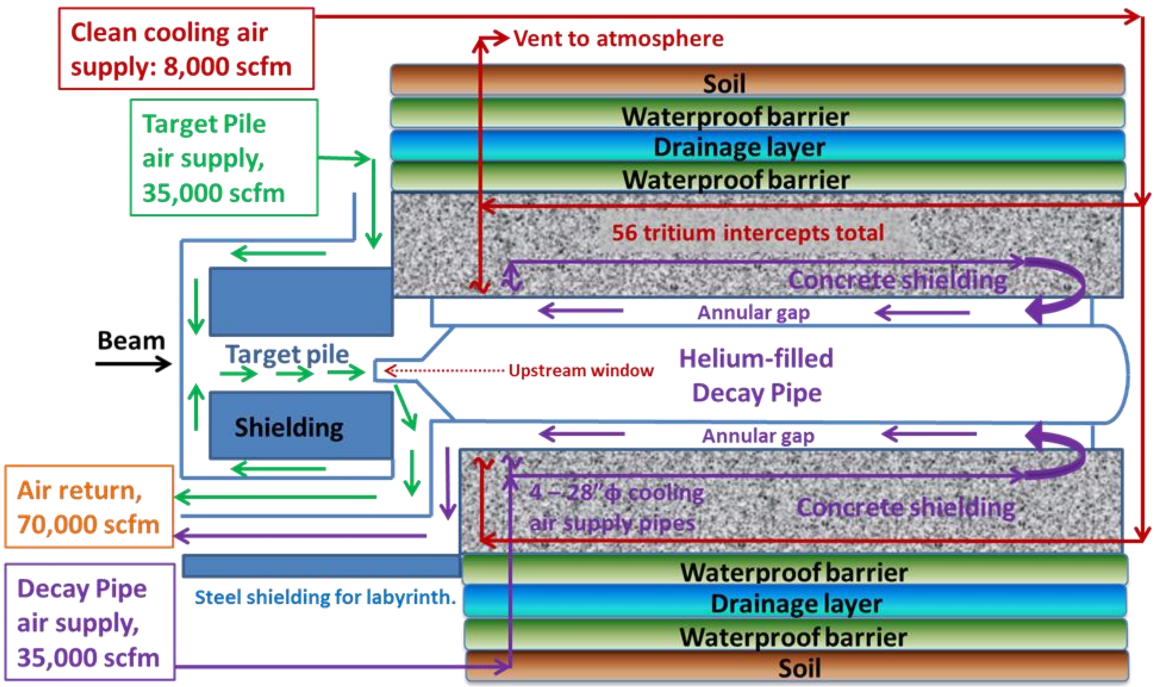
Case 1: Air-filled/air-cooled decay pipe

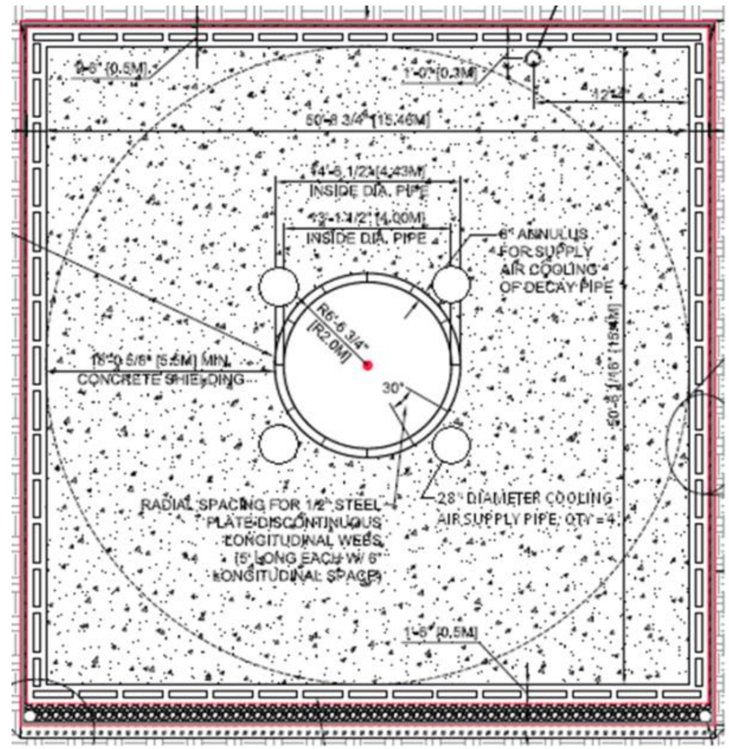




- Concentric Decay Pipe. Both pipes are ½” thick carbon steel
- The minimum air flow rate flowing through the tritium/moisture interceptors is set by the cooling analysis to keep the geomembrane layer below the maximum operating temperature limit of 40 °C

Case 2: Helium-filled/air-cooled decay pipe

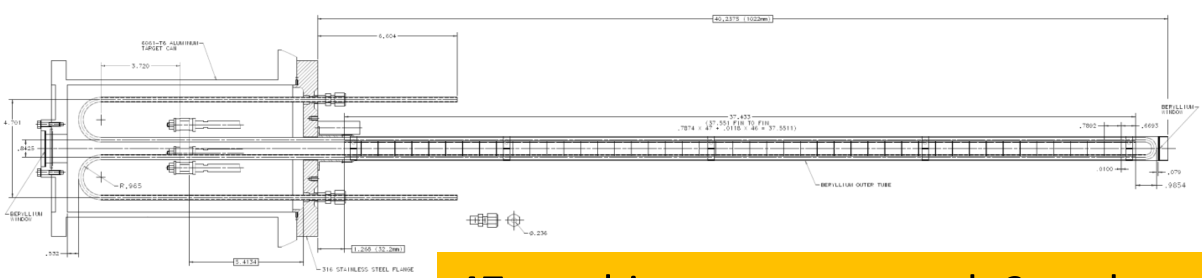




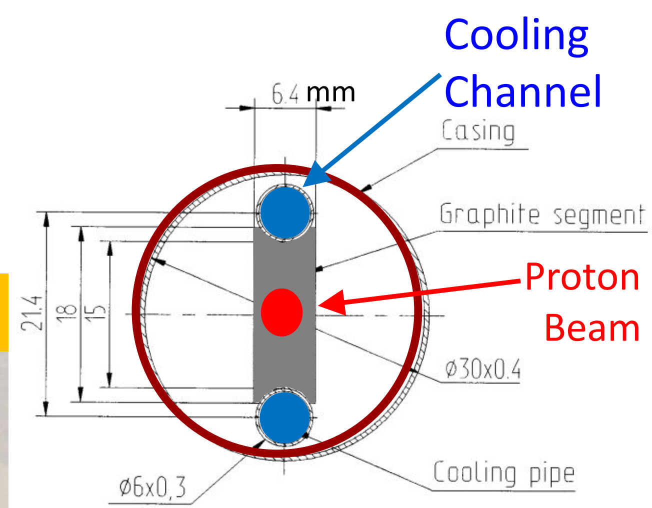
- Concentric Decay Pipe. Both pipes are ½" thick carbon steel
- Decay pipe cooling air supply flows in four, 28-inch diameter pipes and the annular gap is the return path (purple flow path)
- The helium-filled decay pipe requires that a replaceable, thin, metallic window be added on the upstream end of the decay pipe to make the decay pipe a closed volume to contain the helium

LBNE Target Design for 700 kW

- Developed from the NuMI Low-Energy Target
  - Same overall geometry and material (POCO Graphite)
- Key change 1: Cooling lines made from continuous titanium tubing instead of stainless steel with welded junctions
- Key change 2: Outer containment can be made out of beryllium alloy instead of aluminum
  - Be generates less heat load and is stronger at higher temperatures
  - An all Be construction eliminates brazing joint to the DS Be window
  - Titanium alloys also being investigated
- Initial development of design started already for NuMI and it can be produced at Fermilab
- Expect to change target ~twice a year for 700 kW operation
  - Limited lifetime due to radiation damage of graphite
  - Annealing? (subject of RADIATE R&D)
- Option remains for Be as target material pending validation.
  - Radiation damage a factor of 10 less than graphite (subject of RADIATE R&D)



47 graphite segments, each 2 cm long



RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Broad aims are threefold:

- to generate new and useful materials data for application within the accelerator and fission/fusion communities
- to recruit and develop new scientific and engineering experts who can cross the boundaries between these communities
- to initiate and coordinate a continuing synergy between research in these communities, benefitting both proton accelerator applications in science and industry and carbon-free energy technologies
- MOU signed between BNL, FNAL, Oxford, PNNL, STFC/RAL. (CERN, FRIB, PSI, SNS also interested)
- The stage I exploratory study is complete for Be, Tungsten and graphite.
- Postdoc to start in January 2014 at Oxford on Be studies.

Fermilab

Pacific Northwest NATIONAL LABORATORY

UNIVERSITY OF OXFORD

Science & Technology Facilities Council

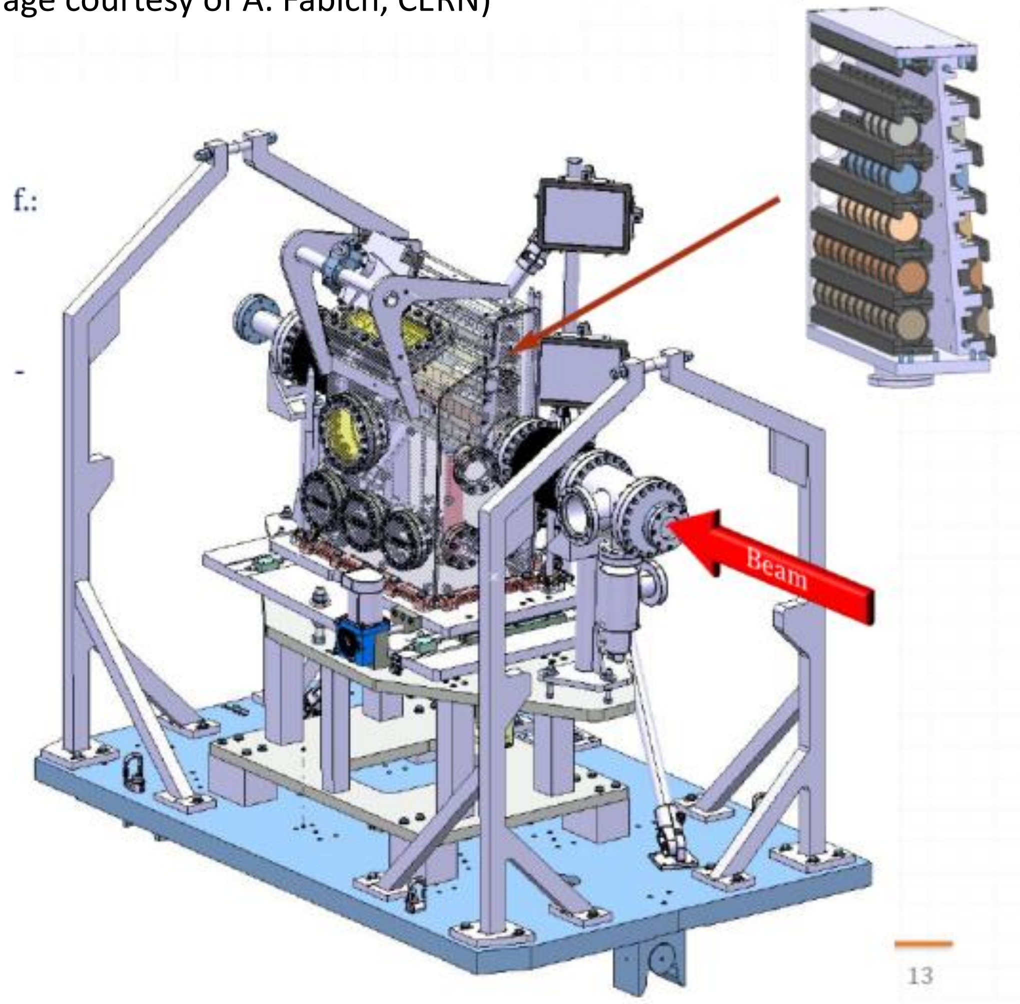
BROOKHAVEN NATIONAL LABORATORY

High Intensity Beam Single Pulse Test at CERN's HiRadMat Facility

Planning to do single pulse beam tests on Be (and possibly other materials) for application to targets and beam windows

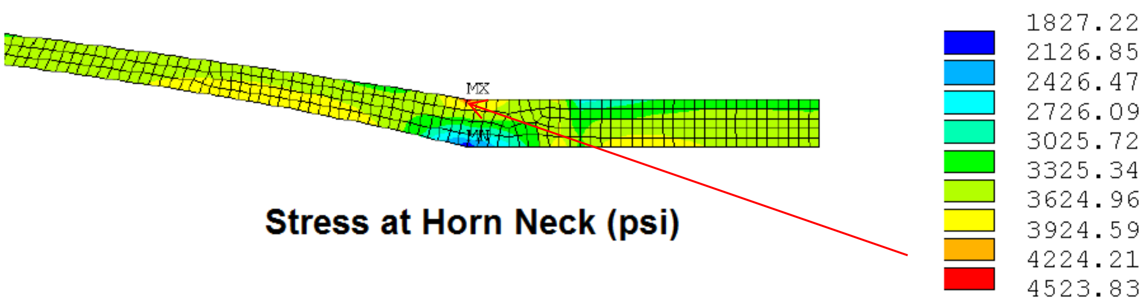
- Proton beam capabilities:
  - up to 4.9e13 ppp
  - 440 GeV
  - 0.1 mm – 2.0 mm sigma radius
- Test on Be windows/targets to detect:
  - Onset of plastic deformation (Diff. Image. Corl., strain gauge)
  - Fracture (DIC, leak detection, high speed camera)
  - Effect of mis-steered beam (DIC, strain gauge, leak detection)
  - Beam induced resonance (Strain gauge, LDV, High speed camera)
- May also use previously irradiated Be

HRMT-14 Collimator materials test rig (image courtesy of A. Fabich, CERN)

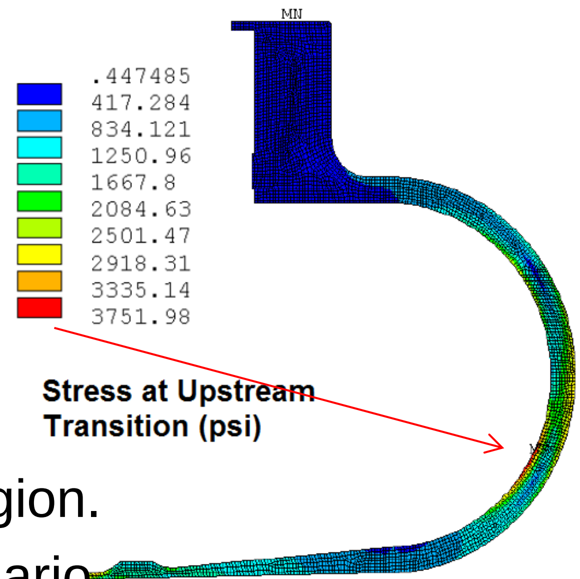


Horn Studies

- NuMI design horns with currents of 200 kA. Investigated higher currents as well, up to 230 kA.
- MARS energy deposition studies and cooling test complete.
- The FEA analysis has been completed as well and shows promising results.
- Final report in LBNE-doc-7509

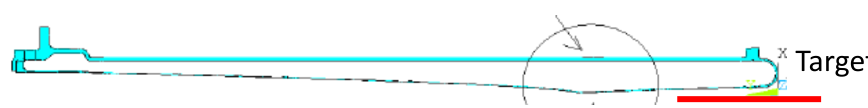


Stress at Horn Neck (psi)



Stress at Upstream Transition (psi)

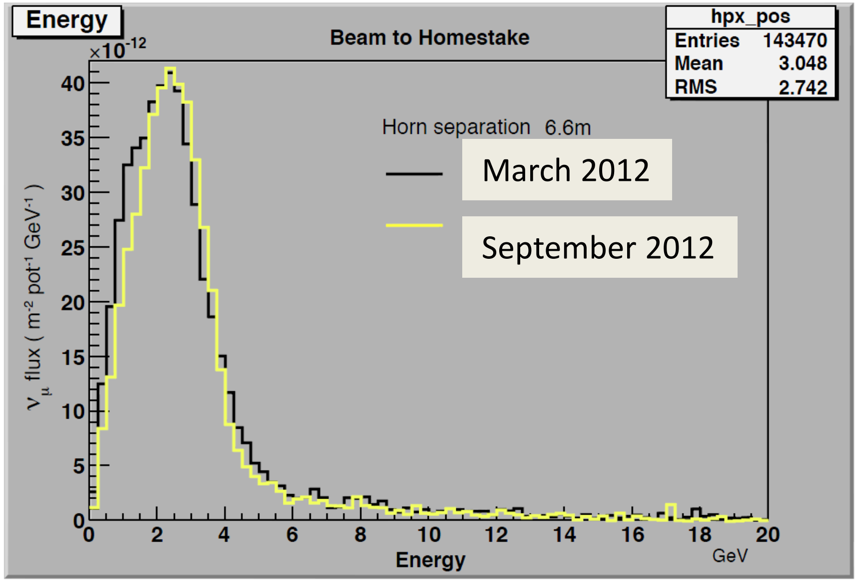
- Stresses are consistent with expectations
- Minimum acceptable safety factor is 3 for any region.
- Resulting safety factor of 3.2 for worst case scenario is judged acceptable but not excessive



NuMI design Horn 1 and NuMI-style low energy target for LBNE

	LBNE Sept. 2012	LBNE March 2012
Beam Power	708 kW	708 kW
Horn 1 shape	Double Parabolic	Cylindrical/Parabolic
Horn current	200 kA	300 kA
Distance between two horns	6.6 m	6.6 m
Horn Power Supply	Re-use NuMI P.S.	New
Target	Modified MINOS	IHEP cylindrical
Target "Carrier"	NuMI-style baffle/ target carrier	New handler, target attaches to Horn 1

MINOS target was designed for 400 kW operation



~ 25% less flux on the 2nd oscillation max.

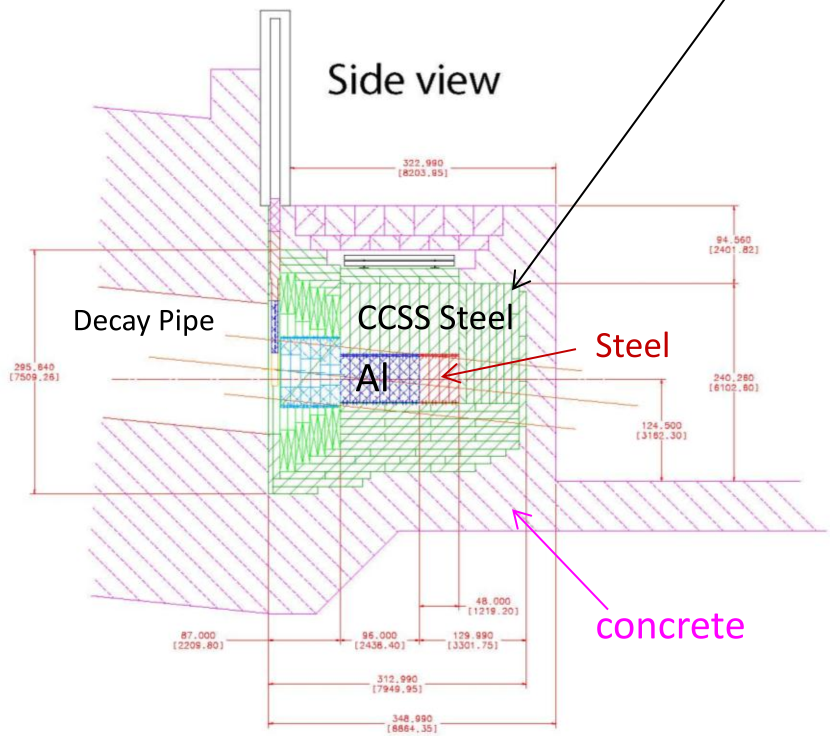
~ 3% more flux on the 1st oscillation max.

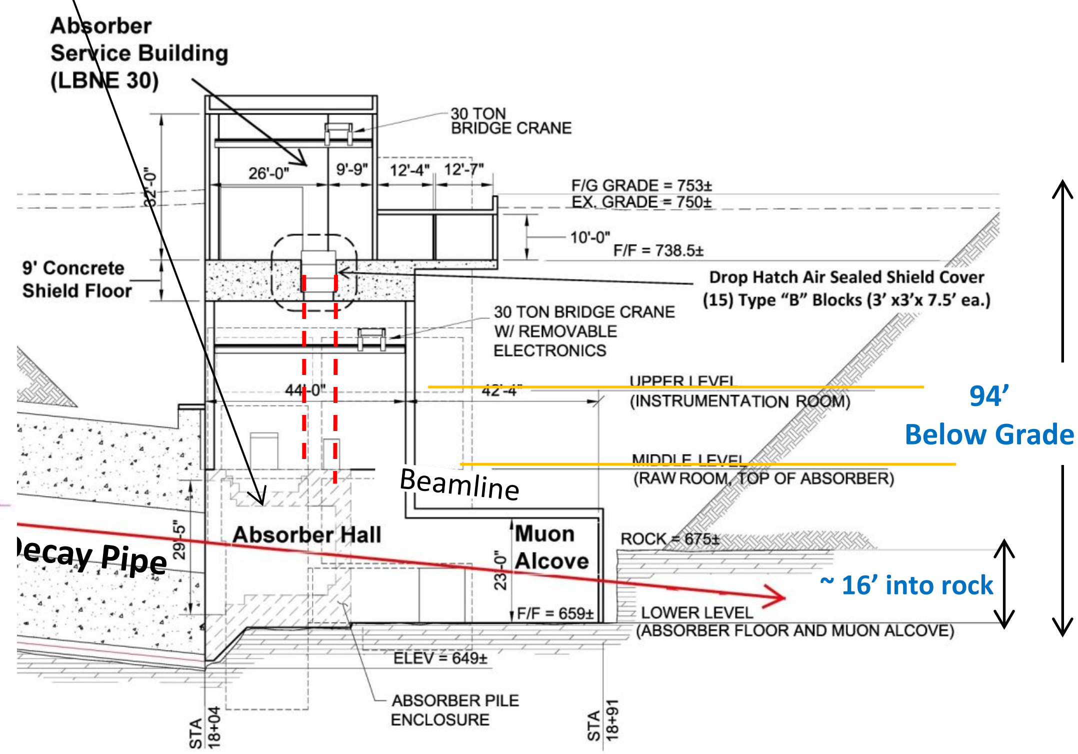
Tunable E_ν spectrum

LBNE Absorber Complex – Longitudinal Section

The Absorber is designed for 2.3 MW

A specially designed pile of aluminum, steel and concrete blocks, some of them water cooled which must contain the energy of the particles that exit the Decay Pipe.

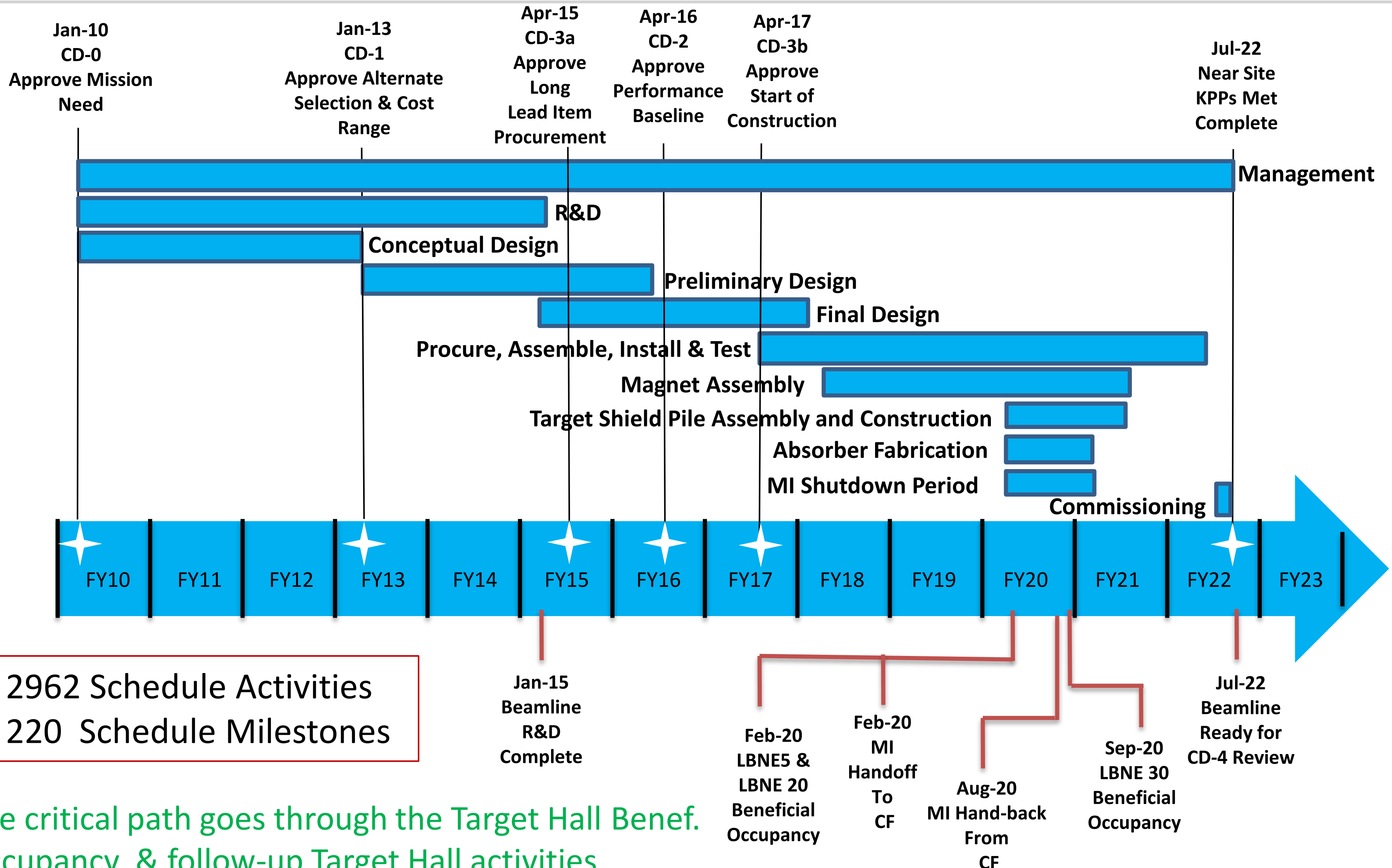




Prototyping planned

- Corrector magnet
- Kicker magnet (x2)
- Beam position monitors (already operational in NuMI beamline)
- Target
- Decay Pipe window (if He in Decay Pipe)
- Horn components for > 700 kW (e.g. horn neck for 1.2 MW, entire horn inner conductor for 2. 3 MW)

130.02 Beamline
Schedule Summary Overview at CD-1



2962 Schedule Activities
220 Schedule Milestones

The critical path goes through the Target Hall Benef. Occupancy & follow-up Target Hall activities