Review of Neutrino Beamline R&D
for NNN2015

M. Friend

KEK

October 30, 2015

Disclaimer !

- Suggestion from the organizers:

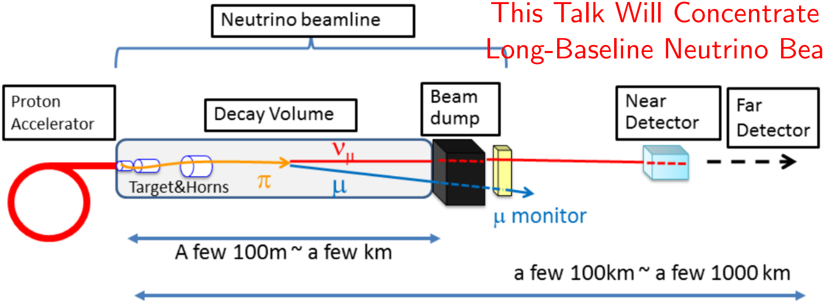
  "Spend most of your time on overview of both shorter and longer term R&D that are relevant for our quest for CPV"

  (That's difficult to know... Is it a political question...?!?)

- But anyway, I will concentrate on high energy, high power conventional beams $\rightarrow$ superbeams
- Please forgive me if I've left out your favorite beamline/project !

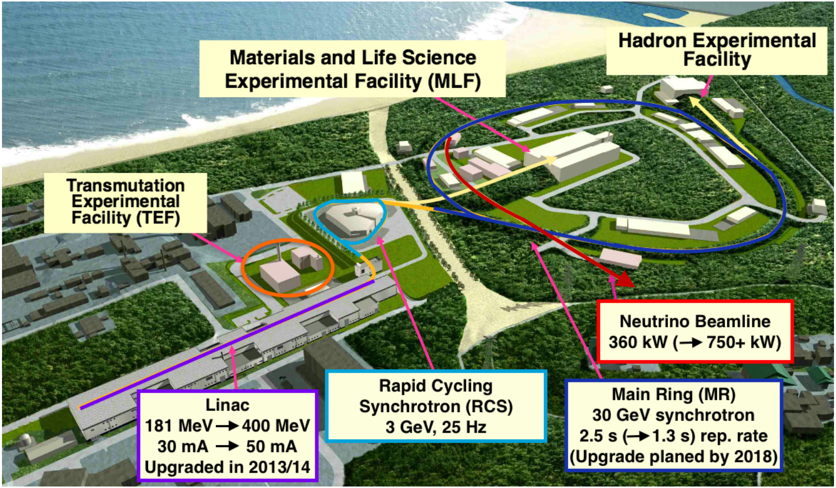
Outline

This Talk Will Concentrate on Long-Baseline Neutrino Beams



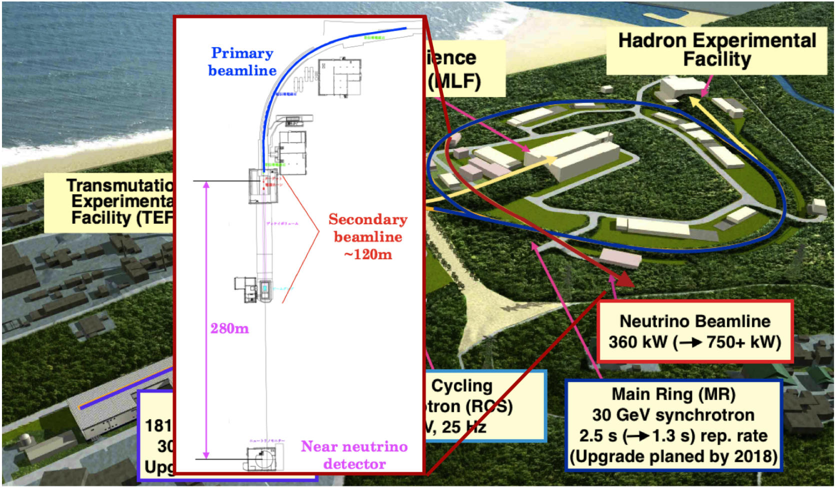
- J-PARC, FNAL (NuMI, LBNF)
- Conventional Superbeams – ν beamline R&D
  - Accelerator – high power, high energy proton beam
  - Proton beam monitoring
  - Target
  - Horns
  - Decay volume, beam dump
  - Secondary beam monitoring

J-PARC Overview



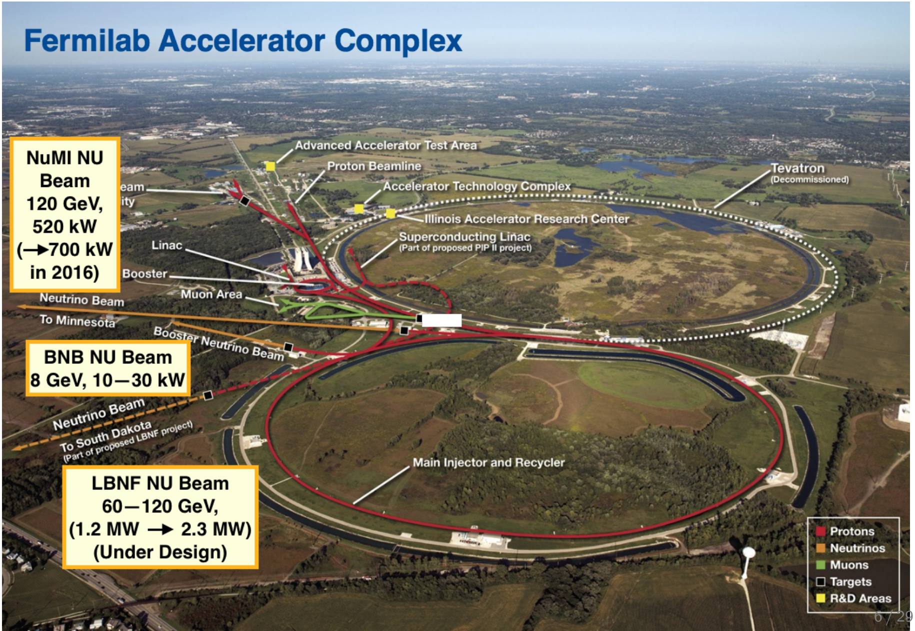
- Composed of 400 MeV Linac, 3 GeV RCS, 30 GeV MR
- Design beam power: 750 kW (Currently ∼360 kW)

J-PARC Overview

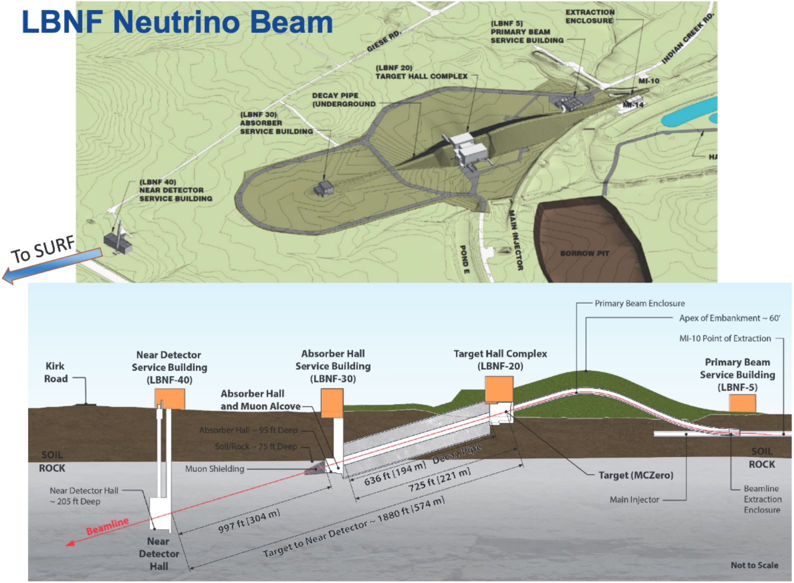


- Composed of 400 MeV Linac, 3 GeV RCS, 30 GeV MR
- Design beam power: 750 kW (Currently ∼360 kW)

Fermilab Overview



LBNF Beamline Concept (for 2025?): Beam-on-a-Hill



How to Increase the Beam Power..?

- Two equivalent ways to increase the proton beam power:
  1. Increase the number of protons per bunch/spill
  2. Increase the frequency, number of beam spills
- #1 is difficult – beam size blows up due to space charge effect
- J-PARC MR is now undergoing upgrade work to increase the beam spill rate from 2.25 s to $\sim$1.3 s
  - In 2017–2018
- NuMI beam employs "slip-stacking" – 2 beam bunches in the same physical location with different momenta
  - $6 + 6$ achieved in 2015, still improving..
  - 15 Hz spill rate
  - PIP-II, PIP-III
- Anyway, in order to increase the beam power, it's essential to:
  - Reduce beam instabilities
  - Reduce beam loss
- Of course, after increasing the beam power, all parts of the neutrino beamline must be able to handle the increased power !

J-PARC MR Power Supply Upgrade

- J-PARC must upgrade MR power supplies for 1 Hz operation
  - Power supplies to be replaced in 2017–2018
- High gradient RF system also under development

JFY	2014	2015	2016	2017	2018	2019	2020
	Li. current upgrade		New PS buildings				
FX power [kW] (study/trial)	320	> 360	400	450	700	800	900
SX power [kW] (study/trial)	-	33 - 40	50	50-70	50-70	~100	~100
Cycle time of main magnet PS	2.48 s				1.3 s	1.3 s	1.2 s
New magnet PS	R&D	Large scale 1st PS		Mass production installation/test			
High gradient rf system	Manufacture, installation/test						
2nd harmonic rf system		R&D, manufacture, installation/test					
VHF cavity	R&D						
Ring collimators		Add.collimators (2 kW)	Add.collimators (3.5kW)				
Injection system	Kicker PS improvement, Septa manufacture /test						
FX system	Kicker PS improvement, LF septum, HF septa manufacture /test						
SX collimator / Local shields			Local shields				
Ti ducts and SX devices with Ti chamber	Beam ducts	ESS					

J-PARC New Beam Tune, etc

- J-PARC linac energy increased (181 MeV $\rightarrow$ 400 MeV) in 2013
  $\rightarrow$ Decrease of space-charge effects at injection to RCS
- Following this upgrade, and other improvements such as:
  - Newly developed intra-bunch feedback system – reducing beam instabilities
  - Tuning of MR injection kicker
- Also have found and are testing a new MR beam tune which should allow an increase in intensity

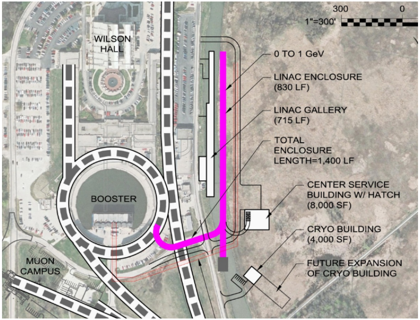
Results of 2 Bunch High-Power Beam Test at New Tune in 2015:

Bunch number	repetition period (sec)	Beam power (kW)	Beam loss (kW)	Notes
2	***2.48***	***132***	***0.42***	***measurement***
8	2.48	530	*1.7*	estimation
8	1.3	1000	*3.2*	estimation

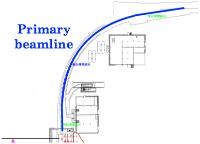
MR can achieve >1 MW with this beam tune w/ 1 Hz operation !
(Although beam loss needs to be further reduced)

LBNF Proton Improvement Plan: PIP-II, PIP-III

- Mid-term PIP-II:
    - Replace the existing 400 MeV linac with a new 800 MeV superconducting linac
    - Shorten Main Injector cycle time
        - 1.03 MW at 60 GeV
        - 1.07 MW at 80 GeV
        - 1.20 MW at 120 GeV
    - Ready by 2025
- Long-term PIP-III:
    - Replace booster with Rapid Cycling Synchrotron (RCS) or super-conducting linac
        - $\geq$2.0 MW at 60 GeV
        - $\geq$2.3 MW at 120 GeV



Preparation of J-PARC ν Primary Beamline for High Power



Primary beamline consists of:

- 21 normal conducting magnets
- 28 super conducting magnets
  - In general magnets and magnet power supplies are all designed for high power
  - Could need to make some magnet configuration change?
- Proton beam monitors
  - Beam current, position, loss monitors are designed to go to high power (750kW $+$)
  - Could be some issue with beam loss/radiation/monitor degradation for destructive beam profile monitoring
    - Now working on R&D for new beam profile monitors
  - Readout (flashADC) for some monitors must be upgraded to read-out at 1Hz rate
    - Now developing 1Hz-readout SiTCP FADC

NuMI/LBNF Beam Profile Monitor Upgrade R&D

Beam profile monitoring is essential for protecting beamline equipment and understanding the proton beam properties

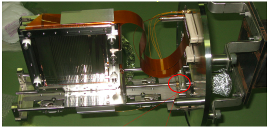
- Towards higher beam power, need:
  - Monitors that are more robust
  - Cause less beam loss
- Secondary Emission Monitor (SEM) – use secondary emission from wires in the proton beam to measure the profile
- As beam power is increased, must decrease wire size (beam loss), increase wire robustness
- Three wire materials now in use:
  - Pure Ti (grade 1) – 25 μm wires
  - Ti alloy (grade 5) – 20 μm wires
  - Carbon (lower density than Ti) – 33 μm wires
- Want to decrease wire size as much as possible
  - 5 μm C may be best at 2 MW; fabrication challenging

FNAL 1mm pitch Ti wire c-frame SEM:

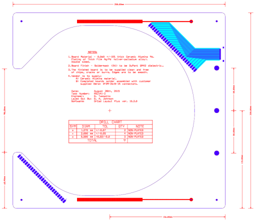
J-PARC Profile Monitor Upgrade R&D

- Towards higher beam power, need:
  - Monitors that are more robust
  - Cause less beam loss
- Segmented Secondary Emission Monitor (SSEM) used to monitor beam profile during beam-tuning (destructive monitor)
  - 3 5-μm-thick Ti foils
  - Each monitor causes 0.005% beam loss
- FNAL-style SSEMs are more robust/have less material in the beamline
  - Use thin fibers or wires (rather than foils) – less material in the beam $\rightarrow$ less beam loss
  - C-shape frame: monitor can be moved into and out of the beam automatically
  - Now fabricating FNAL-style Ti wire SEM with new design for J-PARC NU beamline
    - Will finish fabrication this year
    - Install and test new monitor in 2016

J-PARC Ti foil SSEM:



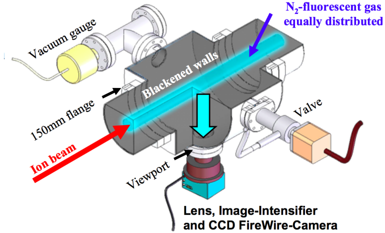
New Monitor Frame Design:



Non-Destructive Profile Monitor R&D

Beam Induced Fluorescence (BIF) monitor:

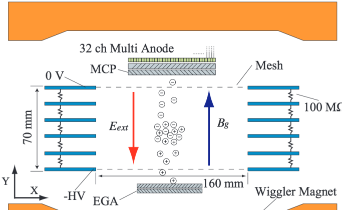
- Detect fluorescence induced by proton beam interactions with gas in the beamline
- Need enough gas for visible signal
    - Must inject gas at J-PARC
- Under development in J-PARC ν beamline now



NIMA 492 (2002) 74-90

Ionization Profile Monitor (IPM):

- Electrons/ions produced by proton beam interactions with gas drift to multi-channel plate
- Larger signal than BIF
    - Can often use residual gas
- Ions/electrons move in the beam field – distorts signal
    - Need a magnet
- Under development/in use at FNAL and J-PARC accelerator



K. Satou *et al.*, Proc. of EPAC 2

High Power J-PARC Secondary Beamline

J-PARC secondary beamline infrastructure (shielding, decay volume, hadron absorber) were all designed for 3–4 MW

Conponent	Limiting factor	Acceptable value
Target	Thermal shock	3.3×10^{14} ppp
	Cooling capacity	0.75 MW
Horn	Conductor cooling	2 MW
	Stripline cooling	0.54 MW
	Hydrogen production	1 MW
	Operation	2.48 sec. & 250 kA
He Vessel	Thermal stress	4 MW
	Cooling capacity	0.75 MW
Decay Volume	Thermal stress	4 MW
	Cooling capacity	0.75 MW
Beam Dump	Thermal stress	3 MW
	Cooling capacity	0.75 MW
Radiation	Radioactive air disposal	1 MW
	Radioactive water	0.5 MW

J-PARC Secondary Beamline Upgrades

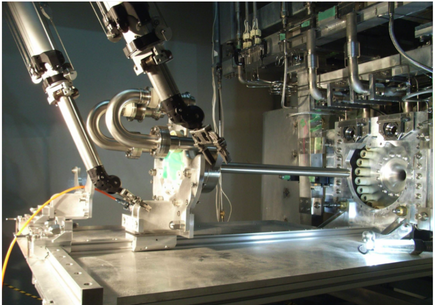
However, need upgrades to improve cooling capacity, radiation containment, and irradiated cooling water disposal for 1+ MW

Conponent	Limiting factor	Acceptable value
Target	Thermal shock	3.3×10^{14} ppp
	Cooling capacity	>1.5 MW
Horn	Conductor cooling	2 MW
	Stripline cooling	>1.25 MW
	Hydrogen production	>1 MW
	Operation	1 sec. & 320 kA
He Vessel	Thermal stress	4 MW
	Cooling capacity	>1.5 MW
Decay Volume	Thermal stress	4 MW
	Cooling capacity	>1.5 MW
Beam Dump	Thermal stress	3 MW
	Cooling capacity	>1.5 MW
Radiation	Radioactive air disposal	>1 MW
	Radioactive water	0.75→1.3 or 2 MW

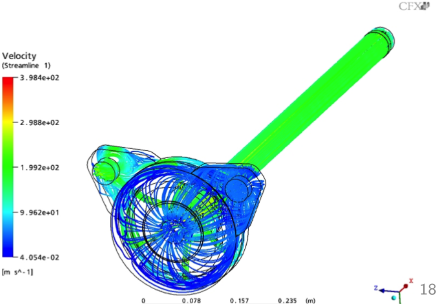
J-PARC Target R&D

- J-PARC target is He-cooled solid 91-cm-long graphite rod
- Ready for 750 kW beam
- Target material itself can withstand 1.3 MW beam
- Need to increase target cooling capacity to go to 2 MW
    - Reinforce the He cooling capacity
    - He pressure must be increased
      → Hardware modifications can be done within 1 year (design may take longer)

J-PARC Target + Remove Handling System

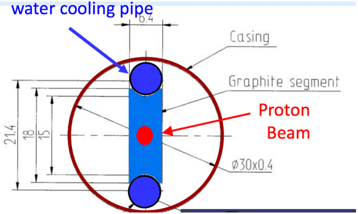


Target Cooling Flow



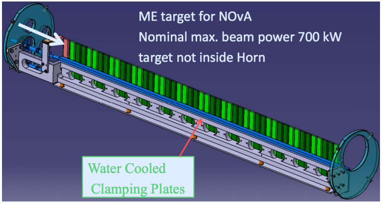
NuMI/LBNF Target R&D

Low Energy MINOS target



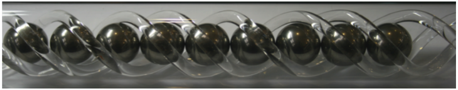
→

Medium Energy NOνA target



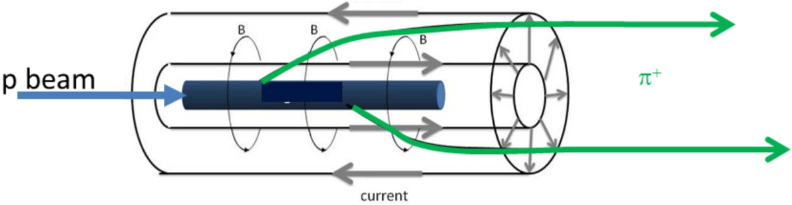
- Target water cooling changed from 2 sides for LE target to 1 for ME NOνA target, allowing for pions to exit from 3 sides of the target
- Target moved from inside horn to upstream of horn
- Similar nominal target design for LBNF (much R&D ongoing):

- Pressurized helium cooled beryllium/graphite spherical array idea:



  - LBNF target cross-section increased for increased spot-size

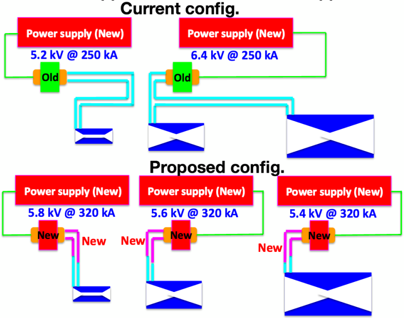
Horn Overview

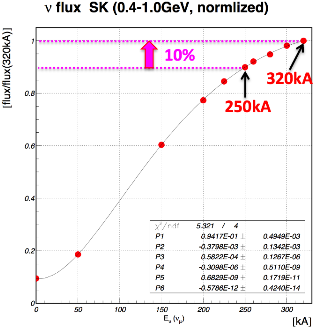


- Electromagnetic focusing horn consists of inner and outer conductor
  - Large magnetic field between conductors achieved by operating at high current (generally 100–300 kA)
- Pions of the correct sign traveling between two conductors are focused
  - Sign of focused pions can be chosen based on horn polarity setting
- Generally cooled by spray water
  - Beam power limits on horn cooling, horn stripline cooling, and activation/disposal of horn cooling water must be considered
- J-PARC – 3 horn configuration; NuMI – 2 horn configuration

J-PARC Horn Power Supply Upgrade for

- Move from 2 to 3 power supplies $\pm 250 \rightarrow \pm 320$ kA
    - New power supplies with energy recovery system
    - New striplines with low R & L
    - New transformers optimized for 320 kA operation
    - 10% increase in neutrino flux at far detector
    - 5$\sim$10% reduction of wrong-sign neutrinos around peak energy
- Upgrade planned in 2016–2017
- Can the flux be further improved by using other horn configurations?



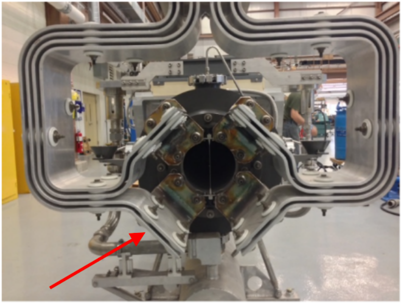


Courtesy of T.Nakadaira

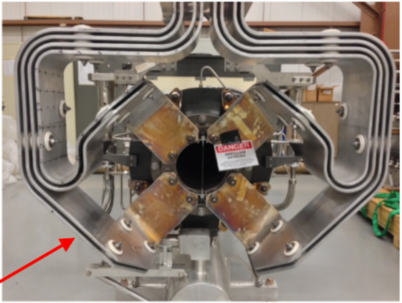
Flux Improvement @ 320 kA

NuMI Horn Upgrade

Original Design



Upgraded Design

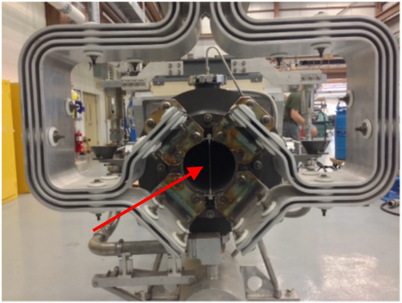


- Stripline shape changed – new design can accept 700 kW beam (from 400 kW original design)
- Crosshair used for horn alignment during installation changed from Aluminum to Beryllium

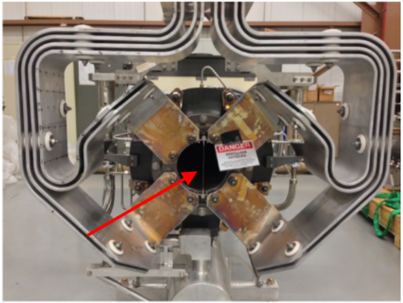
- LBNF baseline design is similar, although horn power supply upgrade required for reduced pulse width
- See next talk (L. Fields) for LBNF horn optimization study details

NuMI Horn Upgrade

Original Design



Upgraded Design

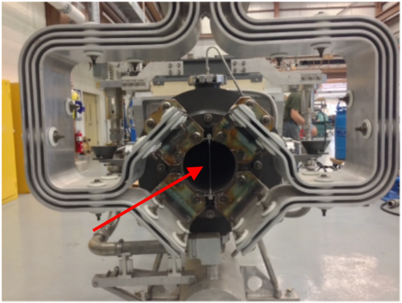


- Stripline shape changed – new design can accept 700 kW beam (from 400 kW original design)
- Crosshair used for horn alignment during installation changed from Aluminum to Beryllium

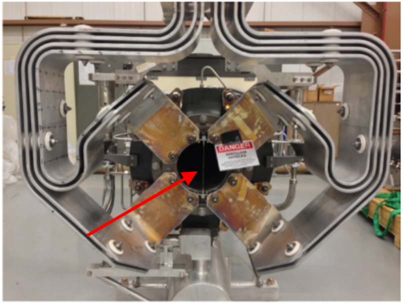
- LBNF baseline design is similar, although horn power supply upgrade required for reduced pulse width
- See next talk (L. Fields) for LBNF horn optimization study details

→ LBNF Horn

Original Design



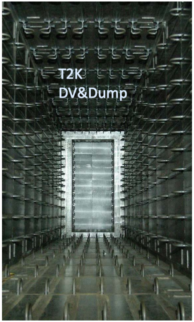
Upgraded Design



- Stripline shape changed – new design can accept 700 kW beam (from 400 kW original design)
- Crosshair used for horn alignment during installation changed from Aluminum to Beryllium

- LBNF baseline design is similar, although horn power supply upgrade required for reduced pulse width
- See next talk (L. Fields) for LBNF horn optimization study details

J-PARC/LBNF Decay Volume, Beam Dump



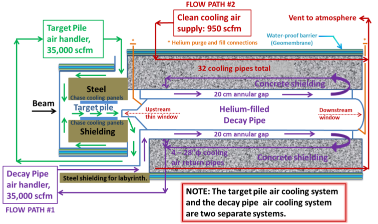
J-PARC decay volume and beam dump:

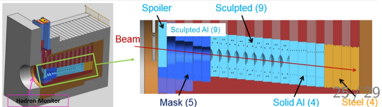
- Designed for 3 MW
- Decay pipe: water-cooled iron walls
  - Increase water flow-rate for >1 MW
  - Helium filled to prevent activation of air
- Beam dump: Graphite core

LBNF current design:

- Designed for 2.4 MW
- Target chase: air filled, air/water cooled
- Decay pipe: helium filled/air cooled
- Beam dump: water cooled aluminum core, forced air cooled shielding

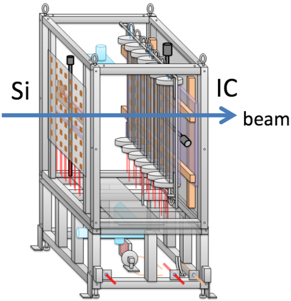
LBNF Decay Volume, Dump



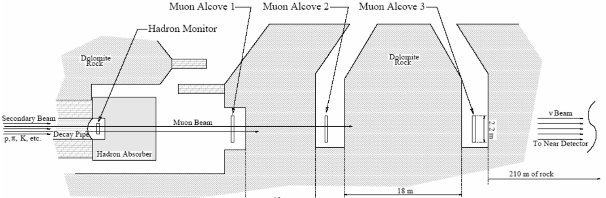


J-PARC/NuMI Secondary Beam Monitors

- J-PARC muon monitors – 2 redundant measurements
  - Ionization chamber (IC) – designed based on NuMI muon monitors
  - Silicon photodiode sensors (Si)
- Some upgrade ideas:
  - IC now uses Ar gas – may saturate at higher beam power
    - Considering He or Ne gas
  - Si sensors degrade over time
    - Now testing diamond and SiC sensors



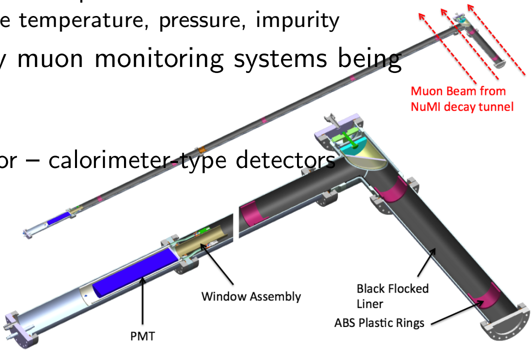
NuMI hadron and muon monitors (IC with He gas):



LBNF Secondary Beam Monitors

- LBNF hadron monitor design:
  - Idea is to use IC with low pressure Ar
  - Improvement on NuMI (atmospheric pressure He) design which showed:
    - Saturation at high beam power
    - Variability with He temperature, pressure, impurity
- Two new complementary muon monitoring systems being developed:
  - Gas Cherenkov
  - Stopped muon monitor – calorimeter-type detectors

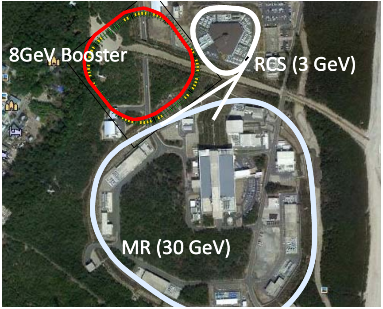
Stopped Muon Monitor Prototype



Gas Cherenkov Muon Monitor Design

2 Very Long-Term Ideas to Increase the J-PARC Beam Power

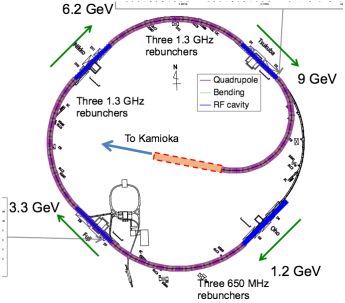
New 8 GeV Booster Ring



- New 8 GeV booster ring for injection into the J-PARC MR
- Fixes J-PARC beam size blow up (due to space-charge effect) at injection to MR (current power increase bottleneck)
- MR $\rightarrow >3.2$ MW possible

- 4 LINACs to 9 GeV in the current KEKB tunnel
- 9 MW beam possible !
  - If ν experiment can find a way to handle CW beam
- Not at J-PARC; at KEK site

Proton Driver in the KEKB Tunnel



Conclusion

- We are well on the way to having the world's first multi-MW proton accelerators $\rightarrow$ neutrino superbeams !
- But, still much R&D work to get us there in the coming years

- Some references:
  - Talks at HINT2015 – M. Bishai, C. Densham, T. Koseki, T. Sekiguchi, B. Zwaska
  - Talks at NBI2014 – P. Derwent, K. Gollwitzer, T. Hiraki, Z. Liptak, G. Mills, P. Schlabach, G. Tassotto...
  - Talk at Neutrino2014 – A. Ichikawa
  - LBNF/DUNE Technical Design Report