



# BNB Upgrade

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Workshop on Short Baseline Neutrino Oscillation Physics

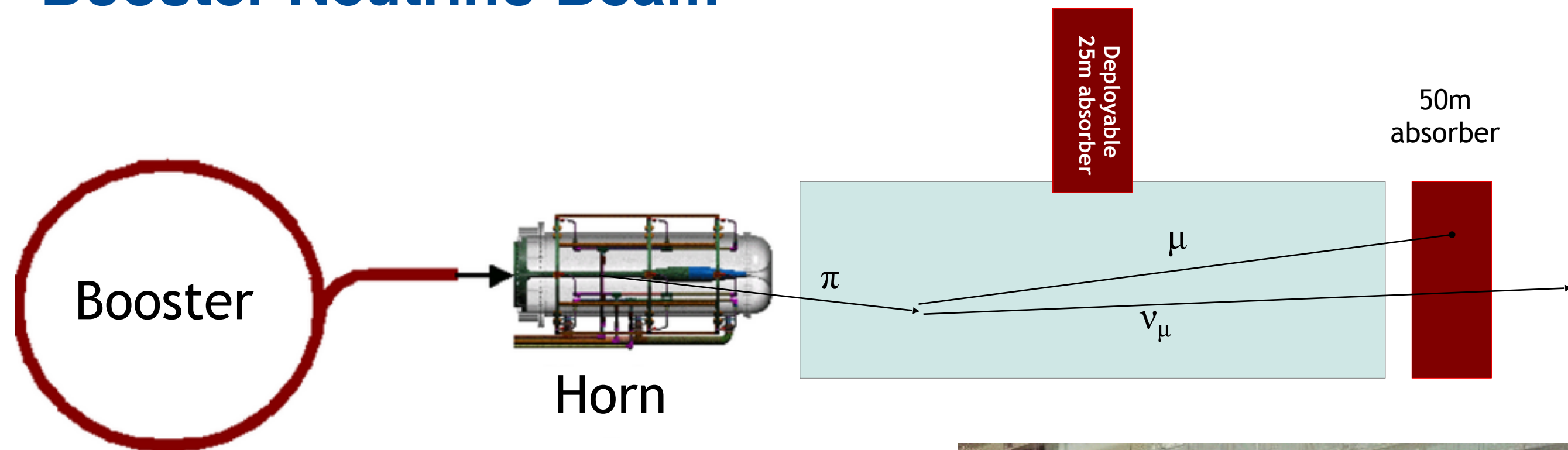
University of Pittsburgh

January 2016

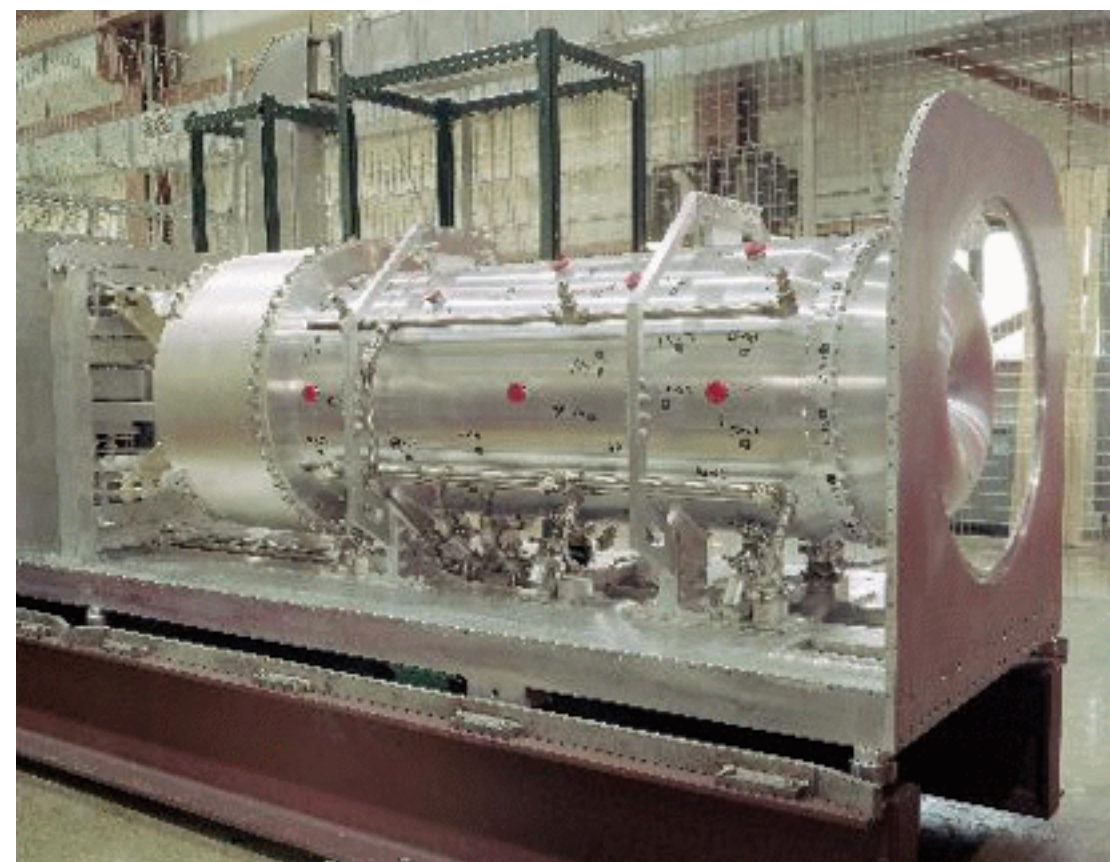
# Outline

- Overview of BNB
- Optimization strategy
- Status of design
- Conclusion

# Booster Neutrino Beam



- 8GeV protons from Booster
- $4\text{--}5 \times 10^{12}$  protons per pulse
- Up to 5Hz average rate (10 pulses in a row on 15Hz clock)
- 1.7 interaction lengths Beryllium target
- Horn  $\pm 174\text{kA}$  (neutrino or antineutrino running)
- 50m long decay pipe

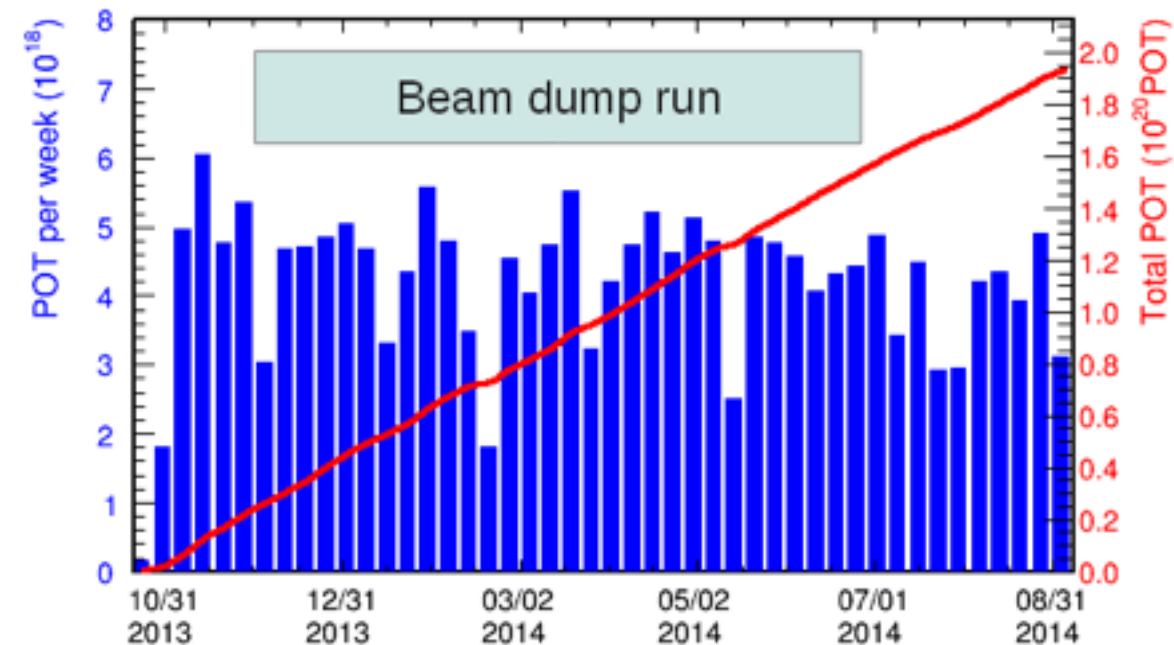
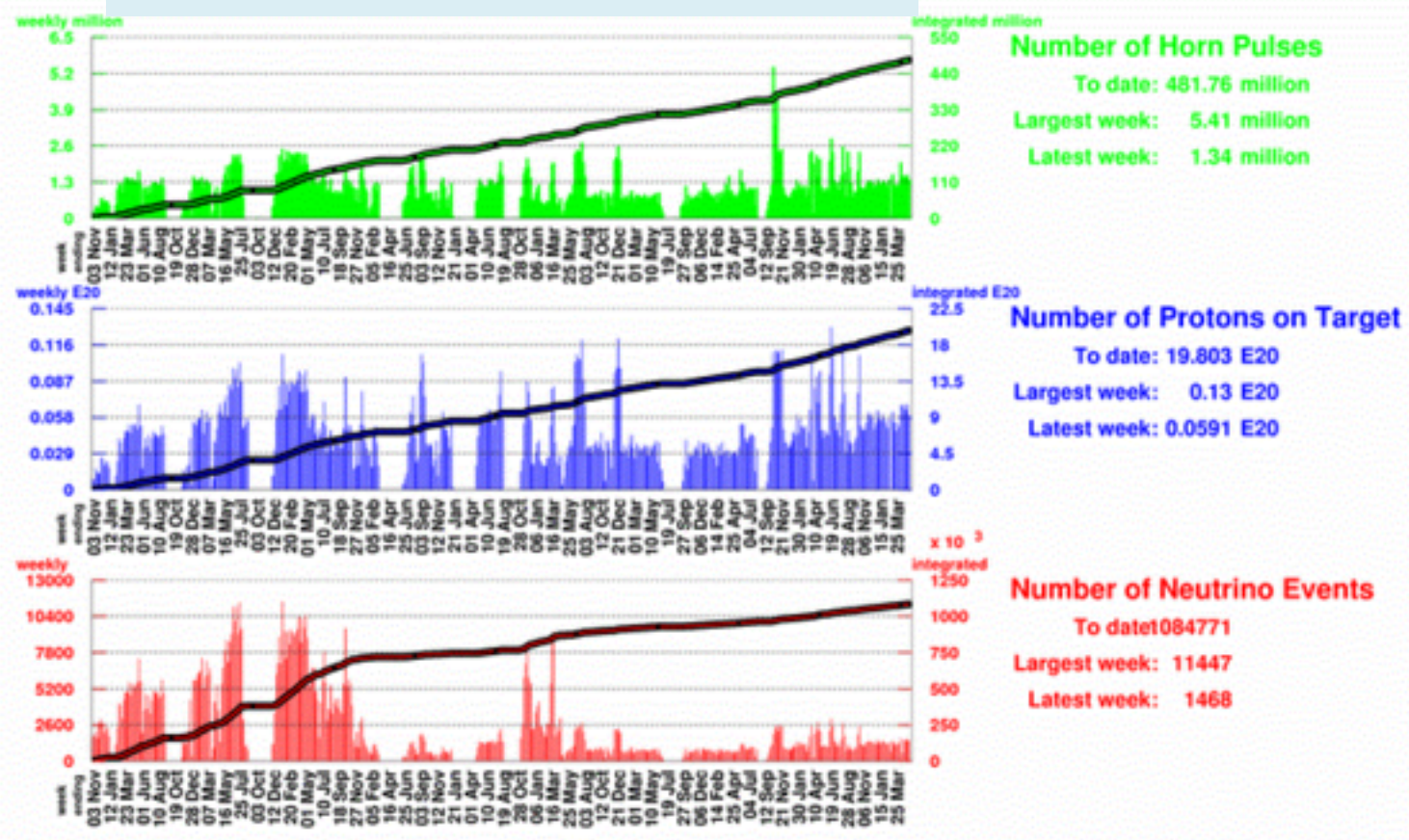




# 12 years of running

- BNB delivered more than  $2e21$  protons on target
- Two target/horn assemblies
  - 1<sup>st</sup> horn 2002-2004: 97 million pulses
  - 2<sup>nd</sup> horn 2004-2015: 375 million pulses

## Neutrino + Antineutrino run

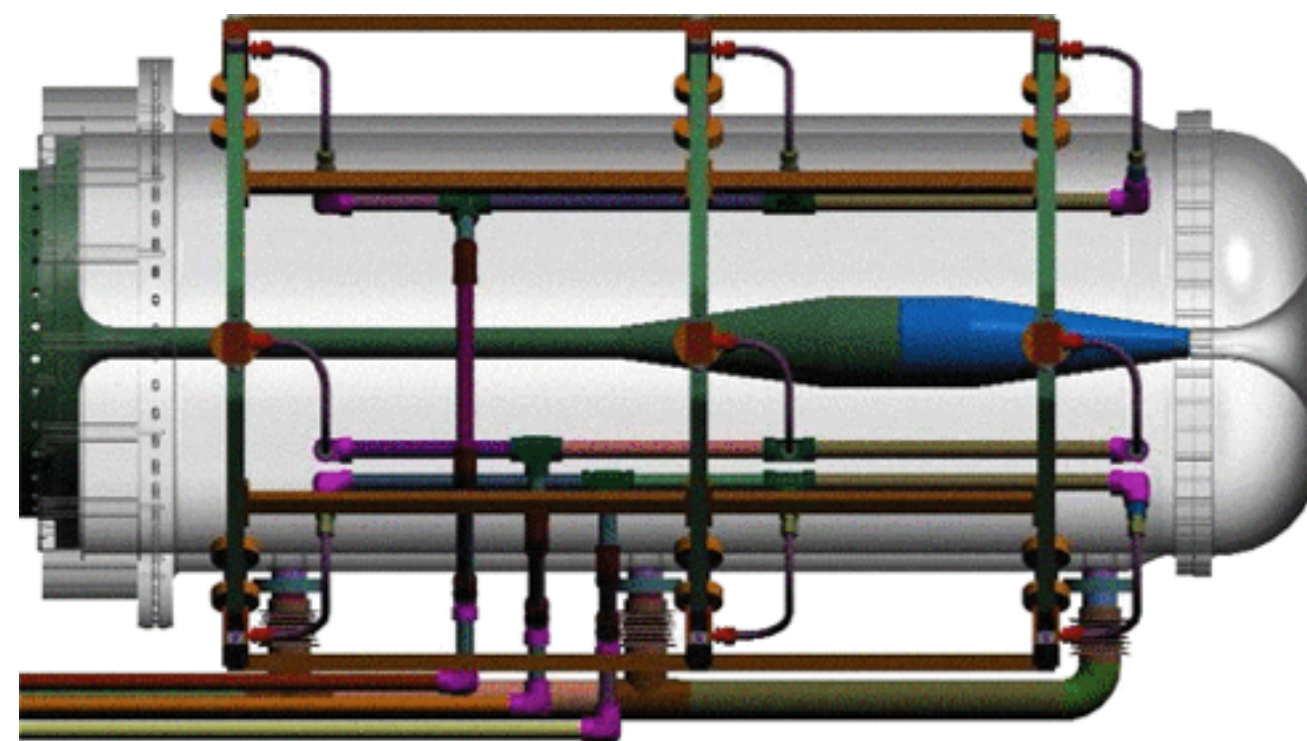
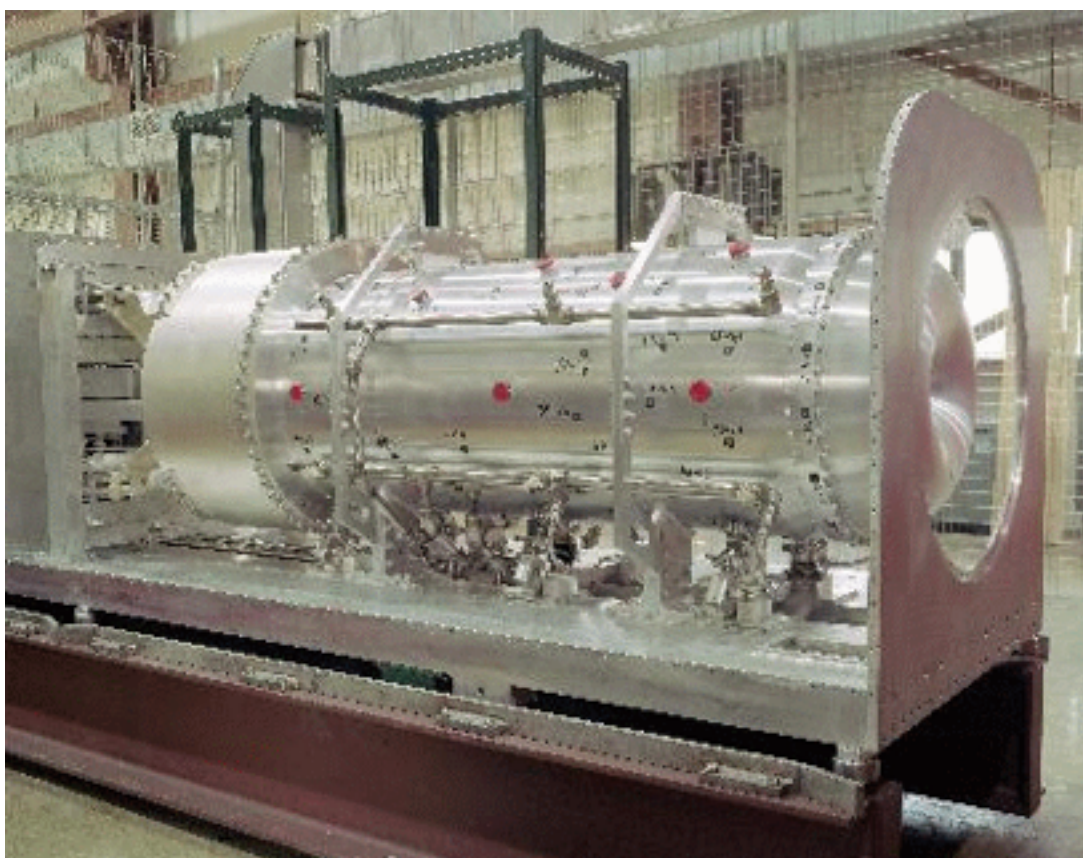




# BNB horns

- Both horns suffered water system failure
  - 1<sup>st</sup> horn developed leak and short to ground due to stagnant water (late 2004)
  - 2<sup>nd</sup> horn had plugged cooling lines
- 3<sup>rd</sup> horn installed in spring 2015
  - Tested in June 2015
  - Started MicroBooNE run in October 2015
- 4th horn under construction
- Horns designed to last >200M pulses

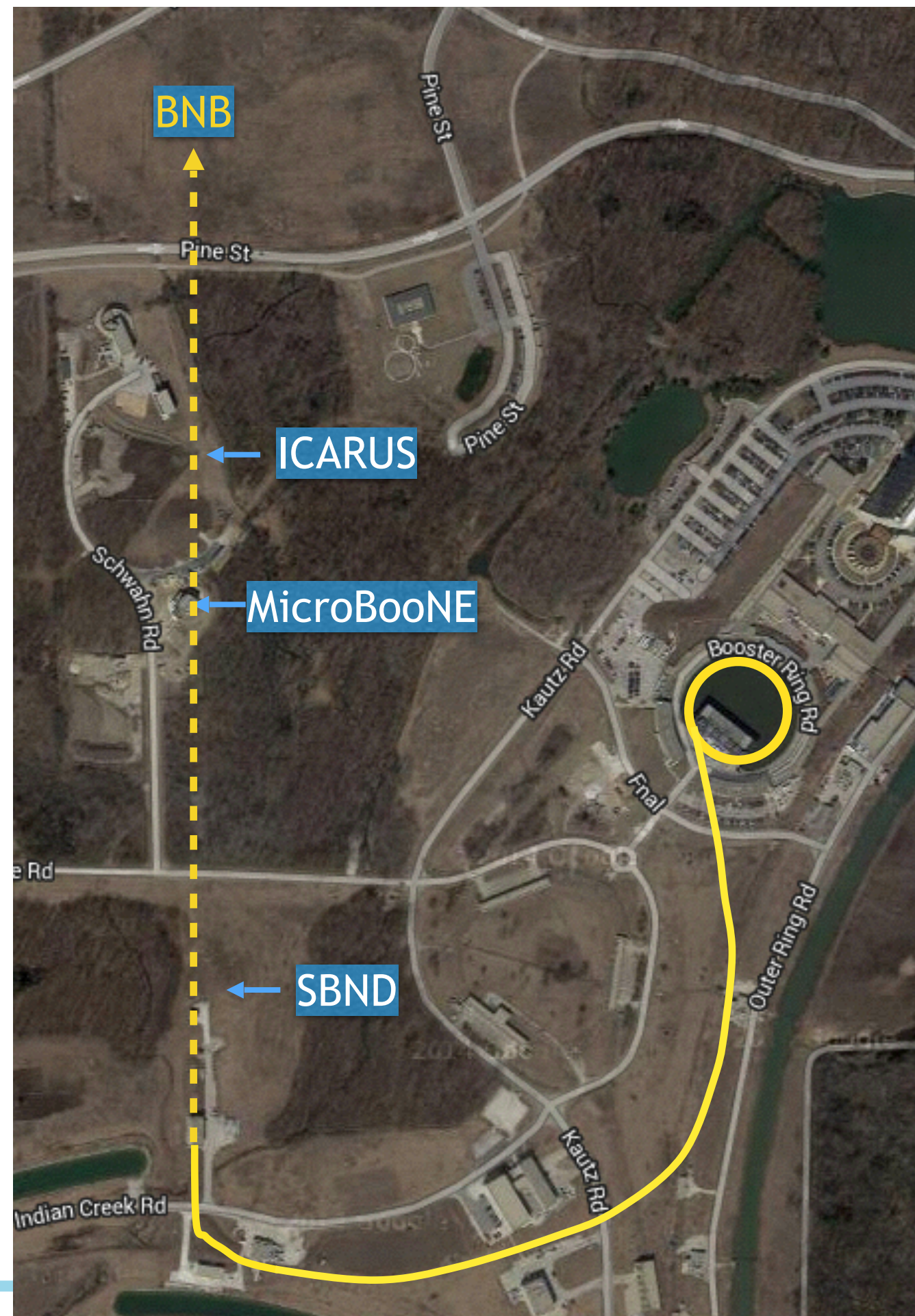
Horn	Pulses	POT
1	97M	3.7E+20
2	375M	1.6E+21





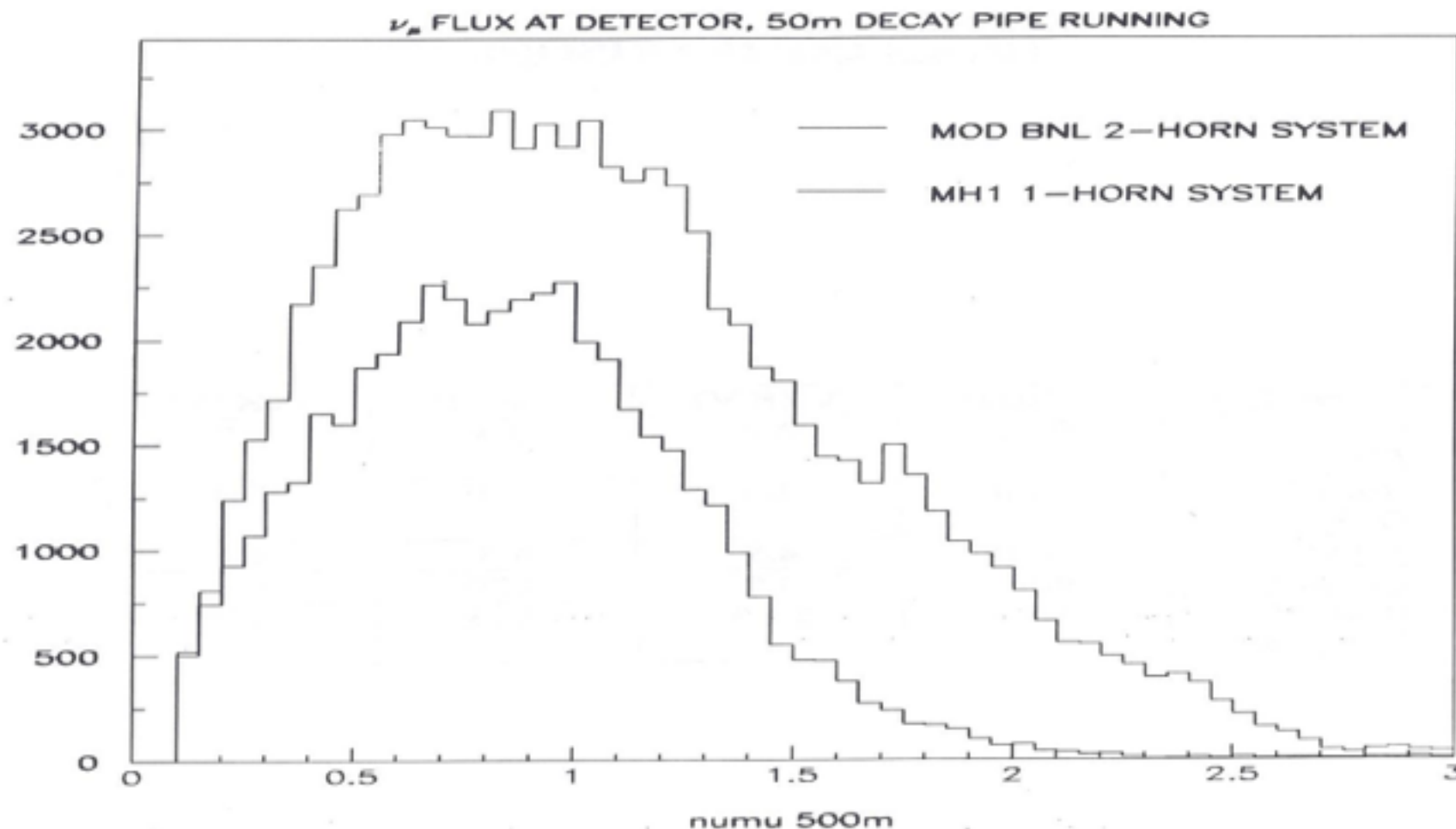
# Future running

- MicroBooNE running starting October 2015
  - 6.6e20 POT to be delivered
- MITPC, ANNIE, SciBath
- Short baseline program (SBND + ICARUS) 2018-
  - Additional 6.6e20 POT
- BNB upgrades considered for SBN program and future running to maximize physics reach
  - Better focusing with new longer horn capable of running at higher rate and current



# MiniBooNE design

- BNB optimization for MiniBooNE started from BNB 2-horn design
- Final design with single horn
  - Significant loss of signal, however in Cherenkov detector higher energy neutrinos create  $\pi^0$  background so S/B remained similar



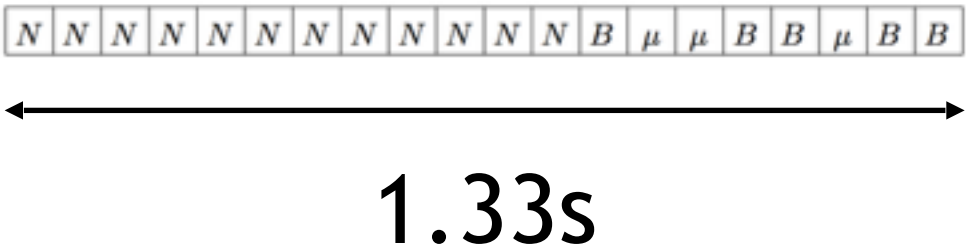
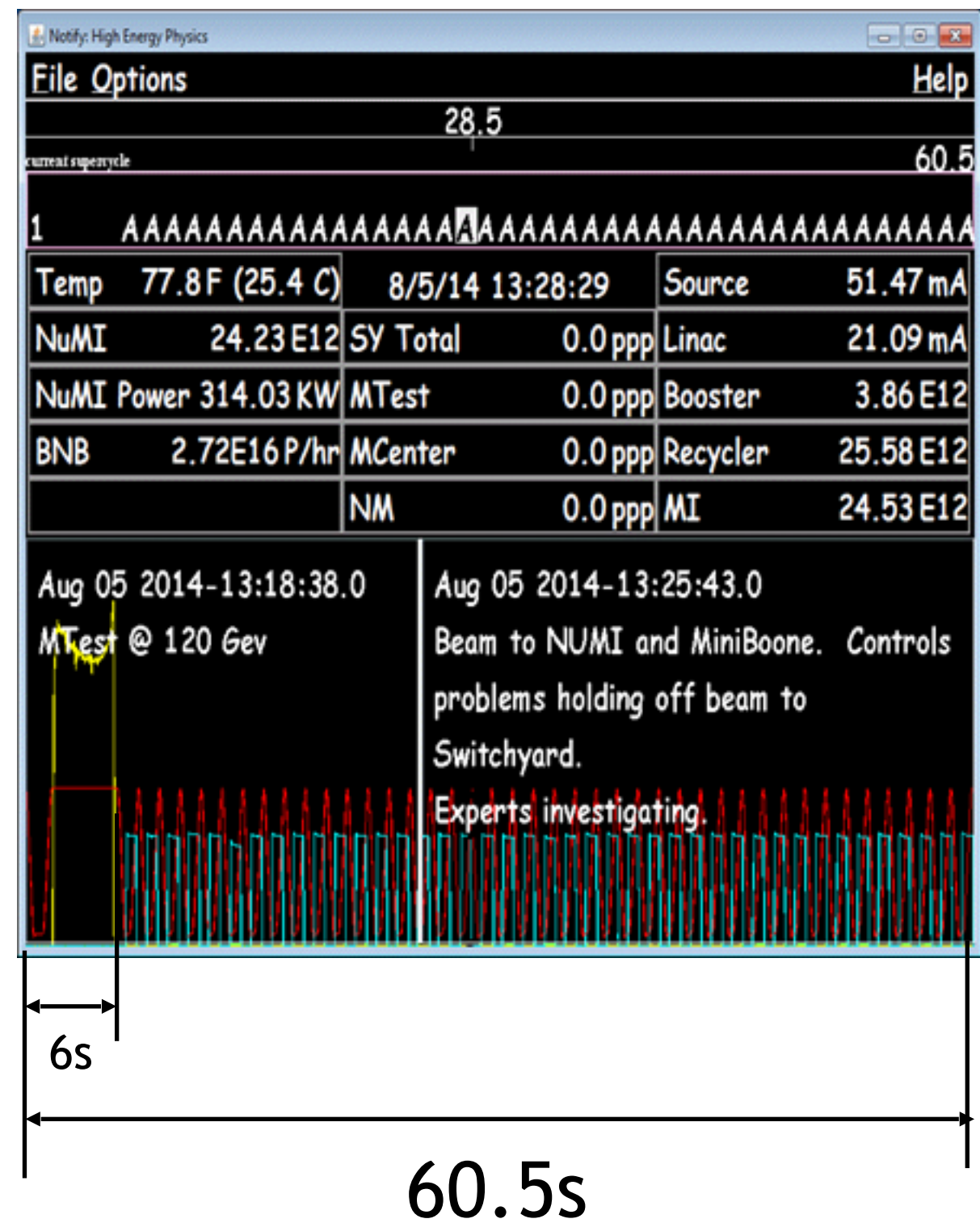
# Upgrade paths

1. Increase focusing efficiency of target/horn system
    - optimized horn length, inner conductor, and current
    - take into account physical constraints of present target hall, stripline limitations, and power supply capability
  2. Increase rate at which horn system is capable running
    - Booster will operate at 15Hz
    - Maximize use of available cycles (beyond those sent to NuMI and muon program)
    - Requires improvement in horn power supply, mechanical integrity of horn (both depend on horn current)
- Account for coupling between paths, i.e. higher focusing efficiency with higher current, but mechanical integrity and power supply push maximal rate down
  - Optimize cost/benefit with potentially affordable solutions

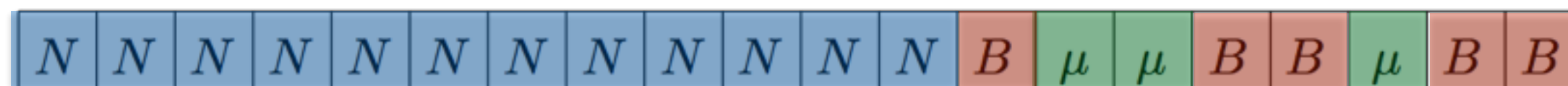


# Proton delivery

- Supercycle 60.5 sec long
- 1 MI slow extraction (6 sec)
  - beam to BNB
- 41 NuMI cycles each 1.33sec (54.5 sec)
  - beam to BNB, NuMI and muon campus



# Proton delivery (cont'd)



1.33s

- Booster runs at 15Hz => 20 booster cycles within 1.33s
- Protons shared between **NuMI (N)**, **muon program (μ)** and **BNB (B)**
- 5 proton beam batches to BNB over 1.33s long cycle (corresponds to 3.76Hz average rate)
- Additional rate if capable running at 15Hz:

$$2.4 f_{\text{NuMI}} + 0.6 f_{\mu} + 0.22$$

% NuMI downtime →  
 % Muon campus downtime →  
 Slow extraction →

BNB @ 12.8 Hz ↑  
 BNB @ 6 Hz ↑  
 BNB @ 15 Hz ↑



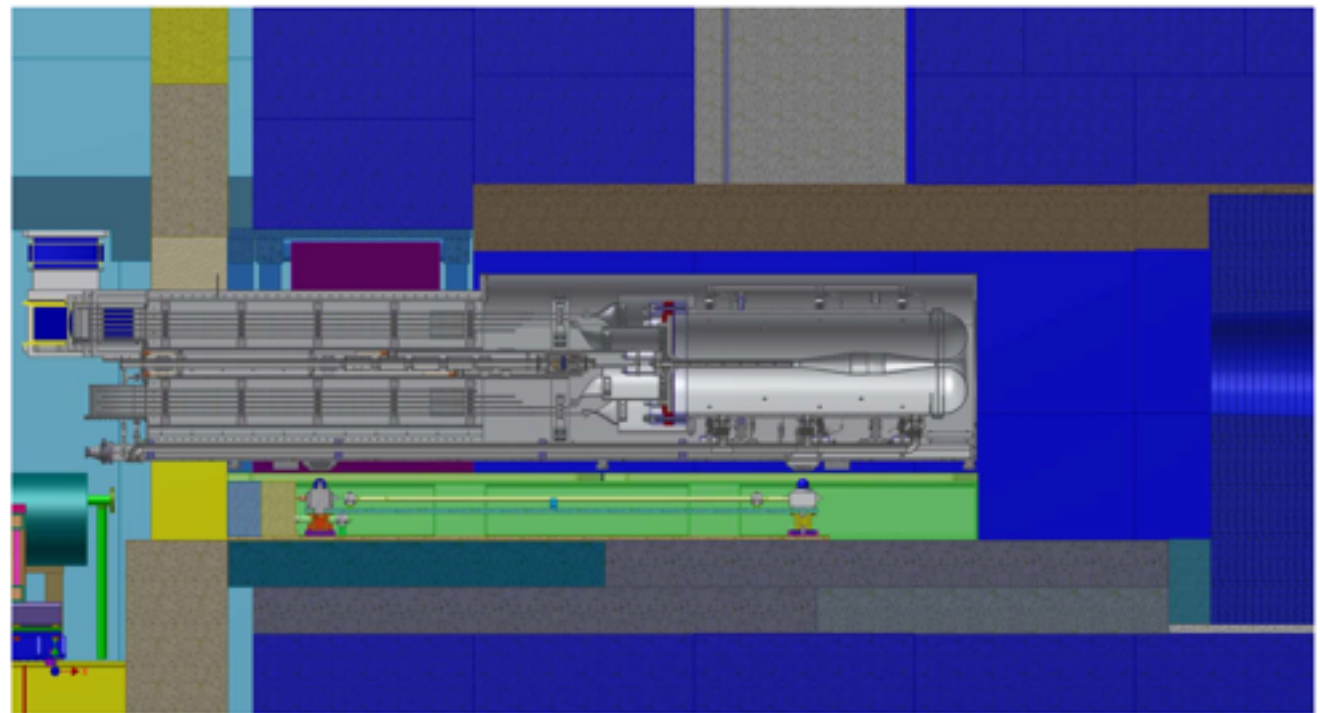
# Annual proton delivery

- Assuming 71.4% uptime
  - Historical proton source/linac/booster uptime 85%
  - Two months annual shutdown (uptime 84%)

	Average rate	Spills/year (M)	POT (10 <sup>20</sup> )	Spills/year (w/ uptime) (M)	POT (w/ uptime) (10 <sup>20</sup> )
3.76Hz	3.8	119	5.3	85	3.8
3.76Hz+(5Hz <i>slow spill</i> )	3.9	122	5.5	87	3.9
3.76Hz+5Hz( <i>slow spill</i> ) +5Hz(NuMI/muon down 10%)	4.0	126	5.7	90	4.0
3.76Hz+10Hz( <i>slow spill</i> )	4.3	137	6.1	98	4.4
3.76Hz+10Hz( <i>slow spill</i> ) +10Hz(NuMI/muon down 10%)	4.9	154	7.0	110	5.0

# Physical constraints

- Target pile shielding
  - Rebuilding prohibitively expensive (~\$15M) and would require long downtime (12-18 months)
- Hatch size matched to the coffin length
- Collimator at the entrance to decay pipe ( $r=30\text{cm}$ )
  - Matched horn outer conductor radius

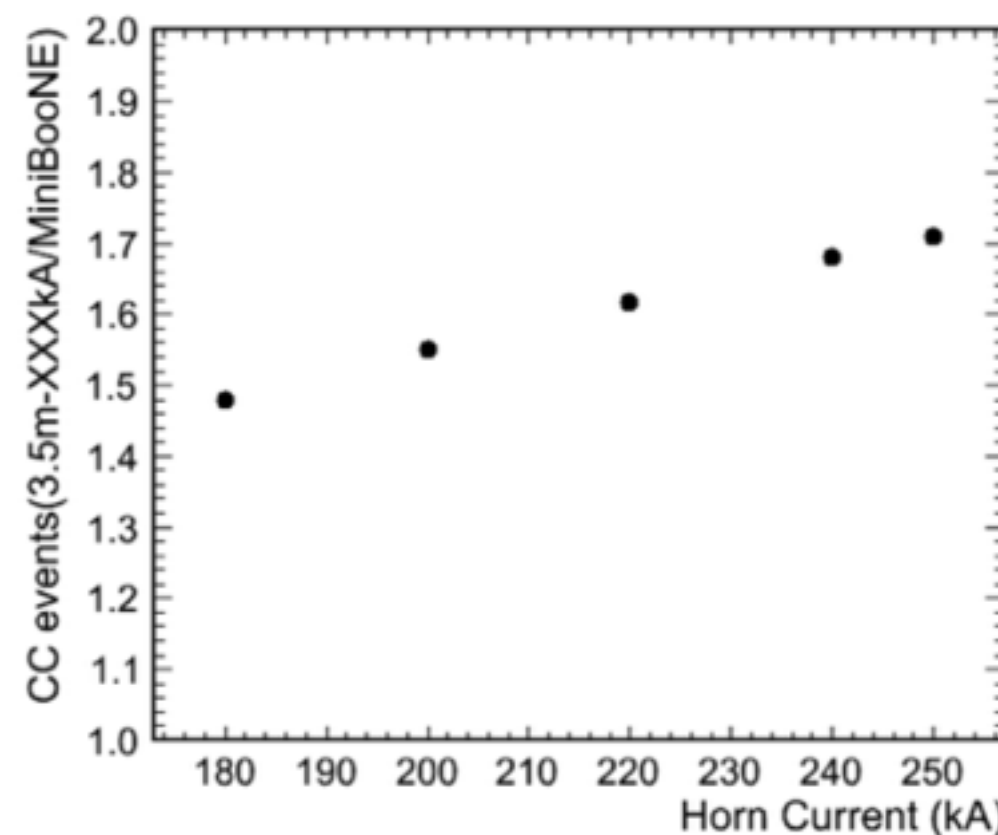
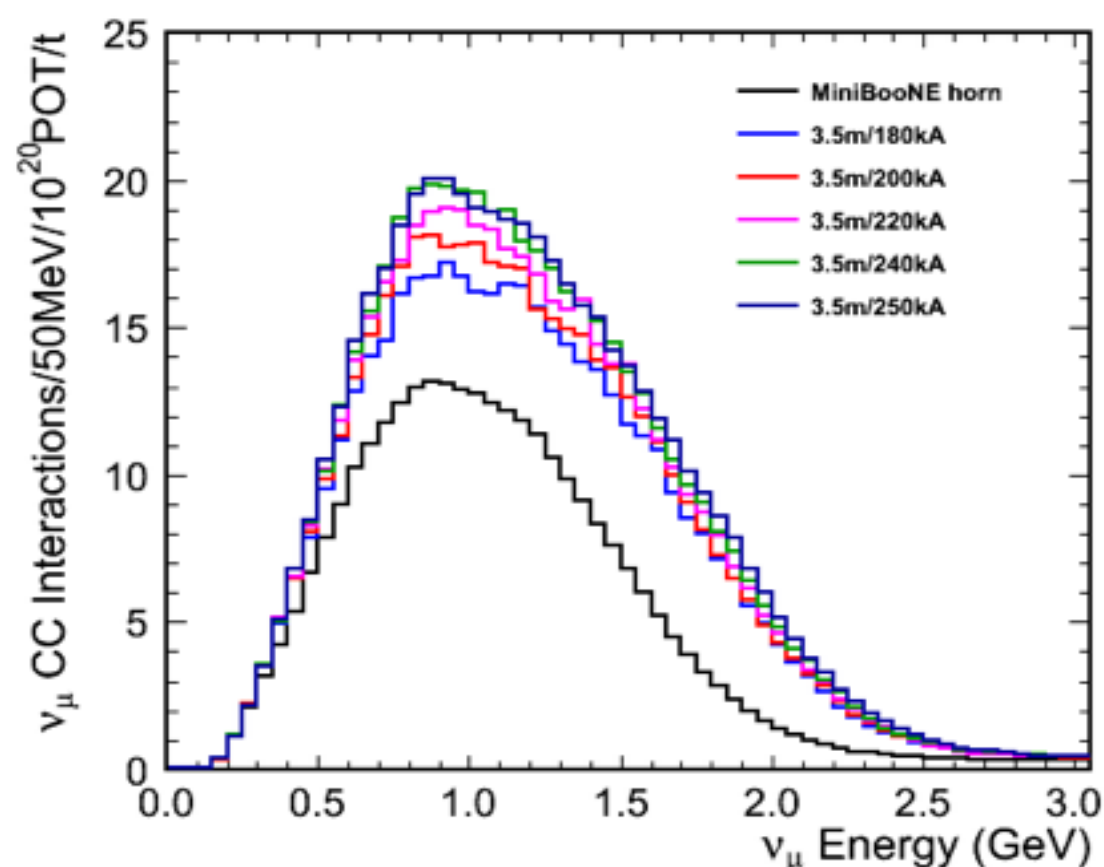




# Optimization

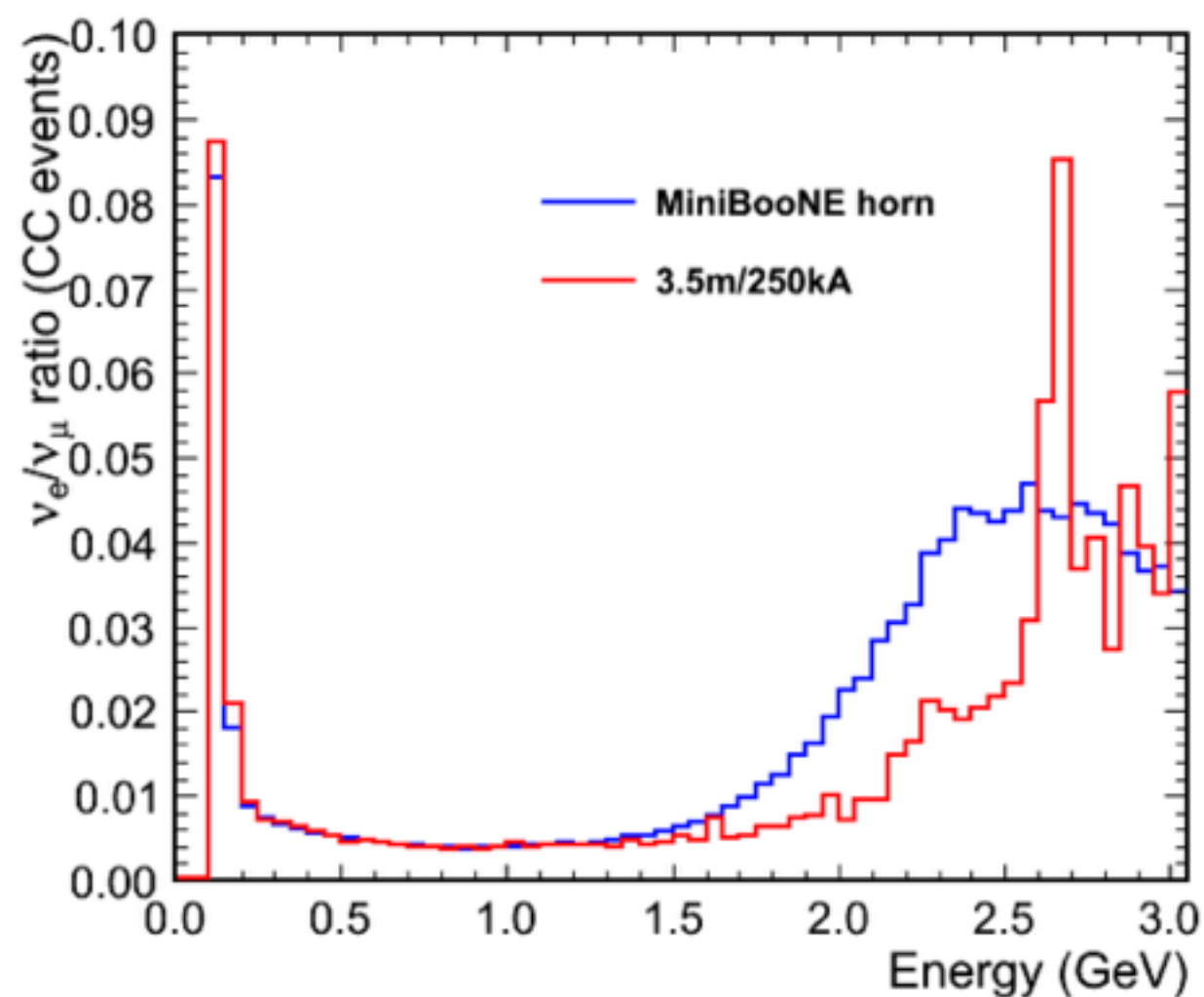
- Vary inner conductor shape, horn length, horn current
- Optimization prefers longer horns and higher current
- Longest horn that can fit 3.5m
- Power supply capable running up to 250kA

	Overall rate/ MiniBooNE
MiniBooNE	1
3.5m/180kA	1.48
3.5m/200kA	1.55
3.5m/220kA	1.62
3.5m/240kA	1.68
3.5m/250kA	1.71



# Backgrounds - Electron neutrinos

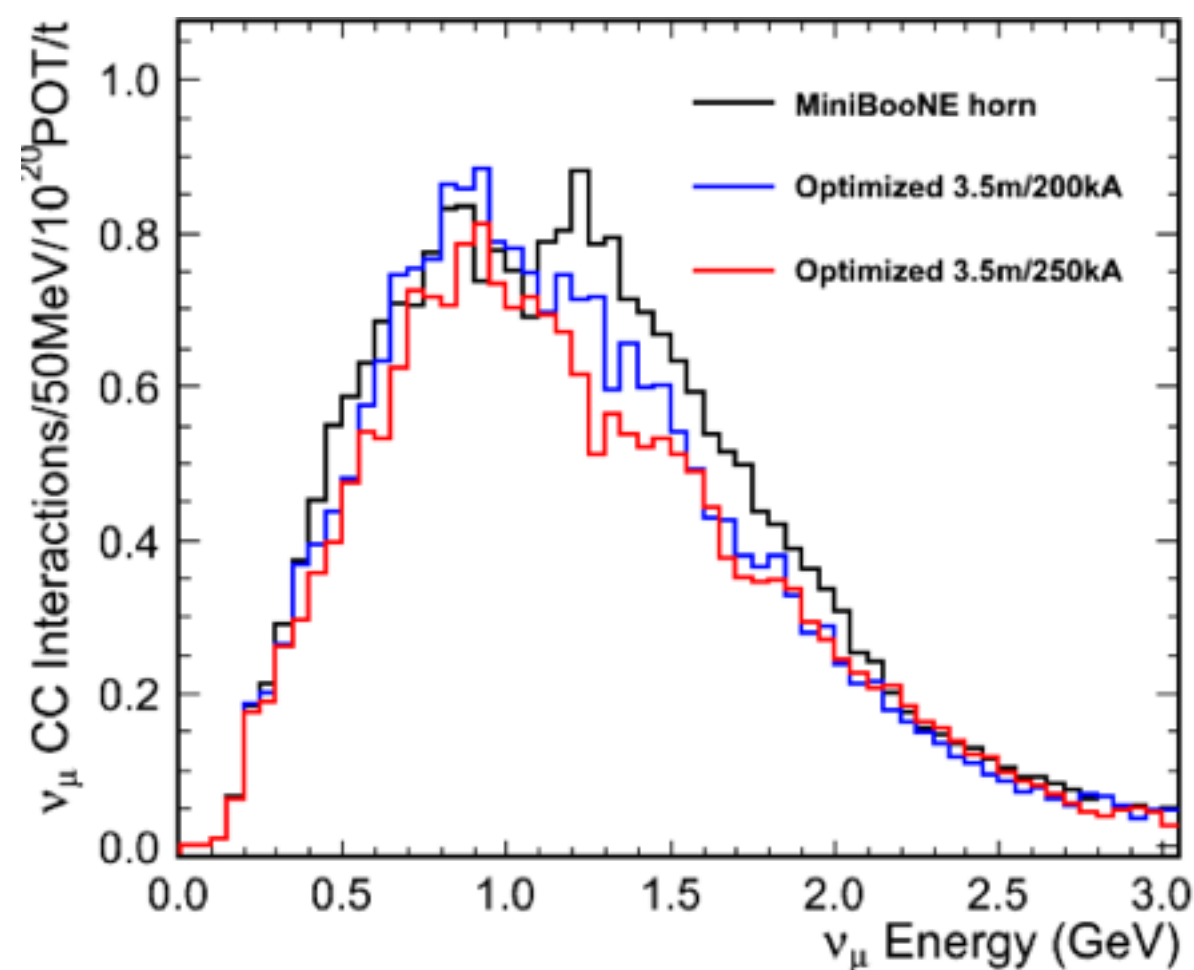
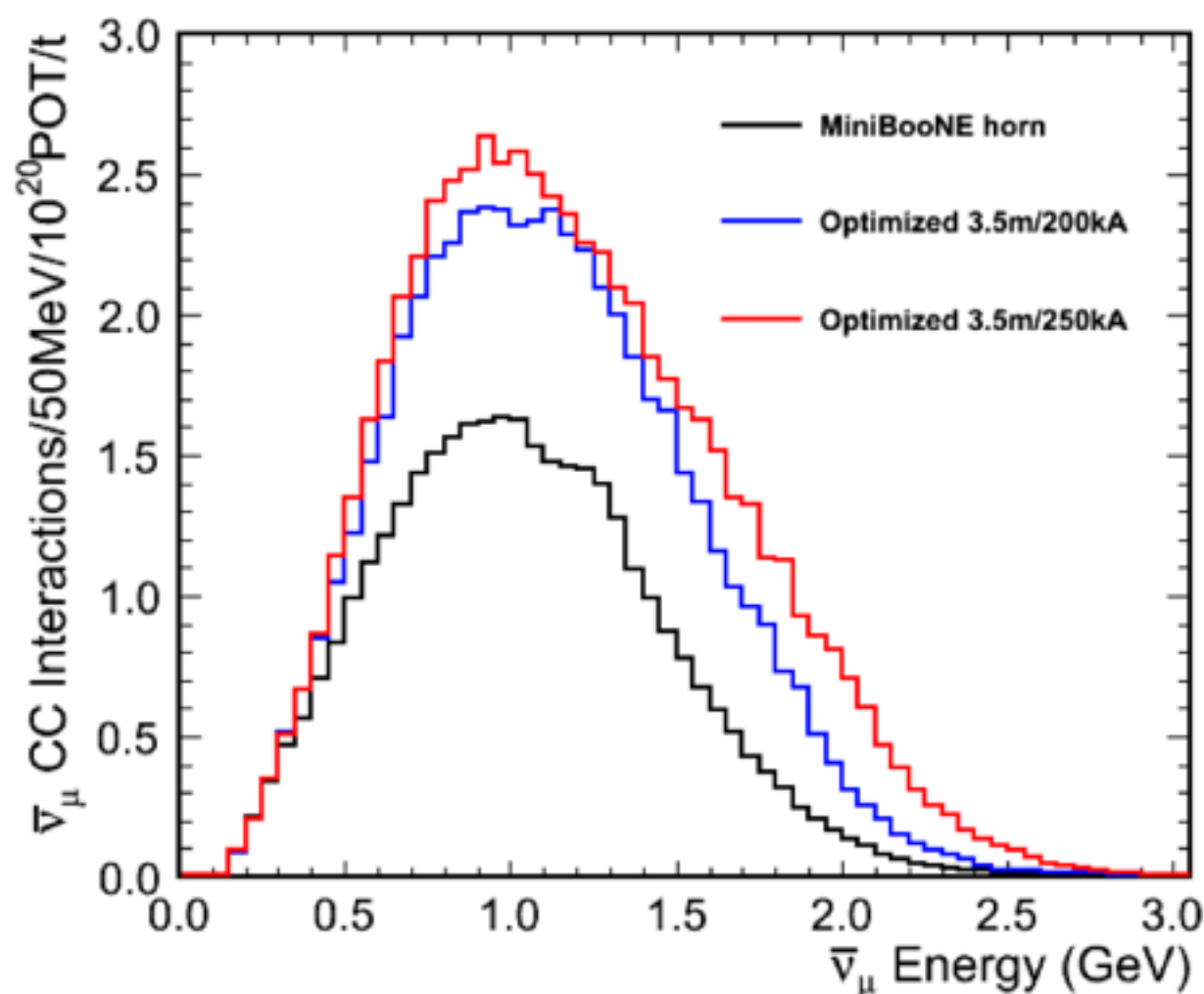
- Intrinsic electron neutrino component fractionally similar to MiniBooNE horn
  - Lower at higher energies





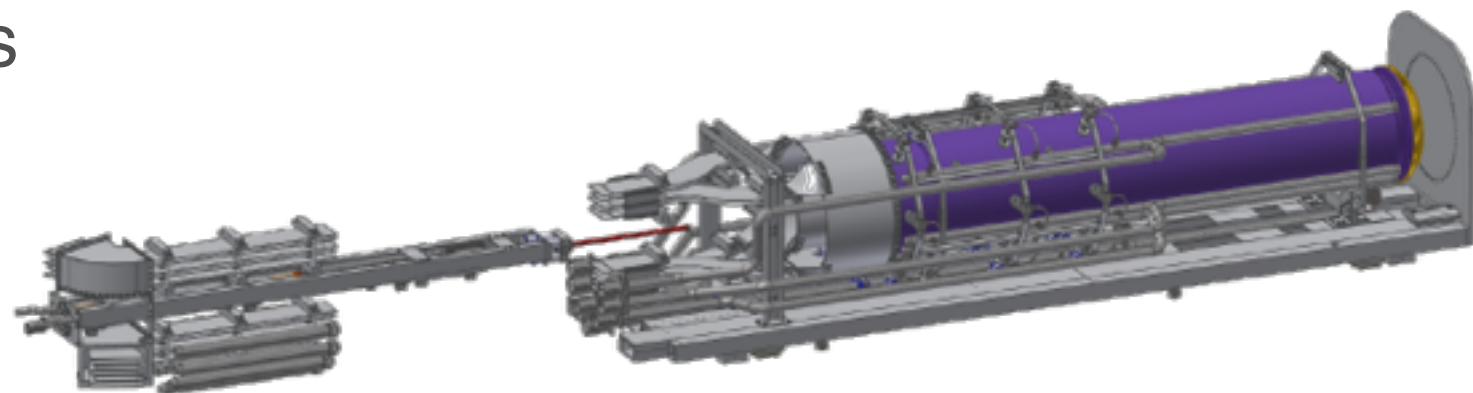
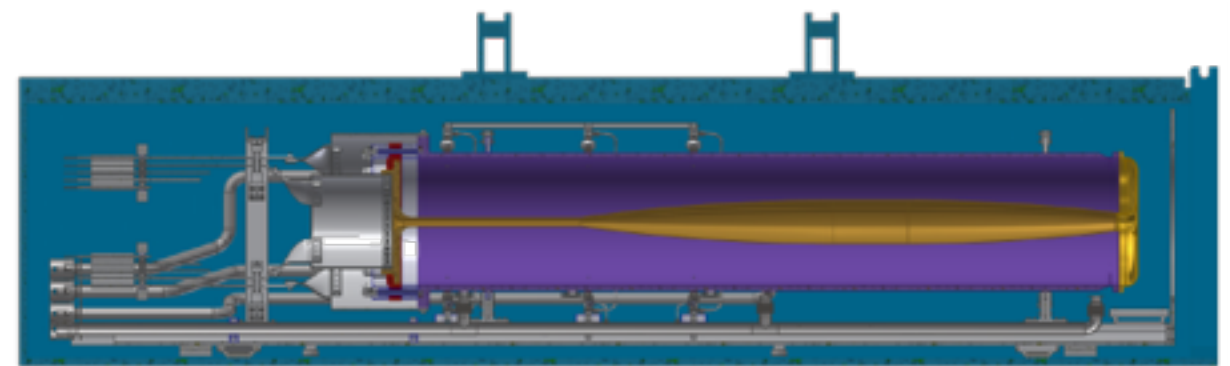
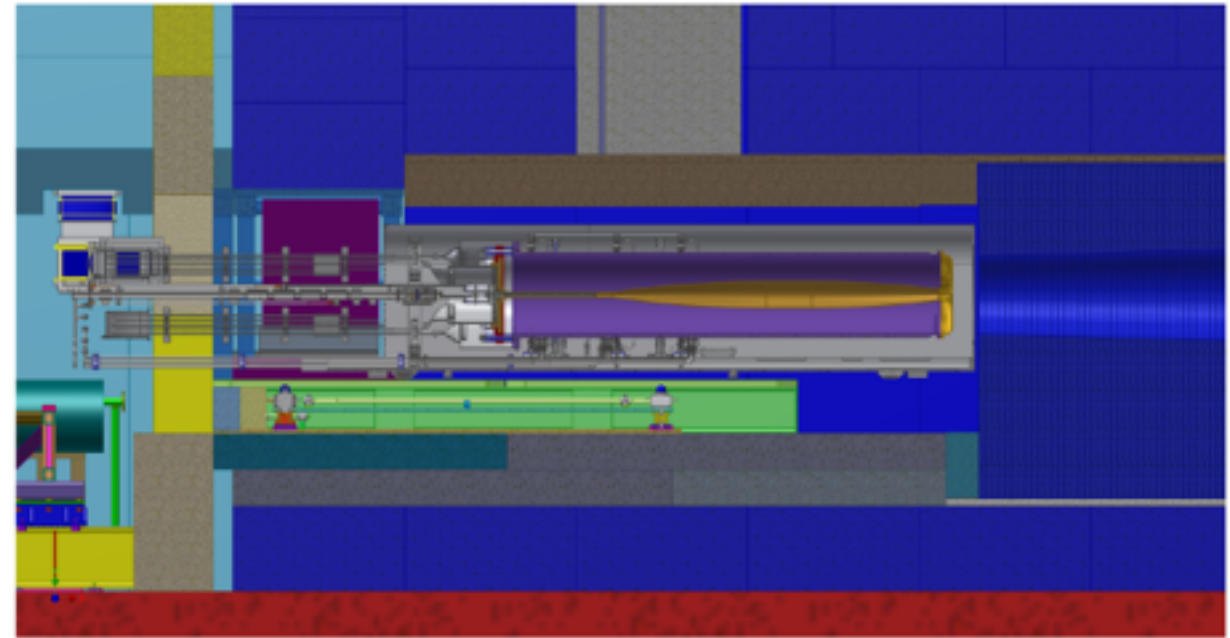
# Antineutrino running

- Even better improvement expected in  $\bar{\nu}_\mu$  rate in anti-neutrino mode
  - Gain 1.8@250kA and 1.56@200kA
- Wrong signs fractionally much smaller



# Horn engineering

- Larry Bartoszek built a model for 3.5m horn
- Target needs to be pulled about 50cm upstream
- Study stresses due to heat loads and magnetic forces
  - Heat load predominantly from joule heating
  - BNB rapid cycling, so need to sustain  $\sim 10^8$  cycles/year
- Preliminary finite element studies of optimized horn
- Feedback to design options

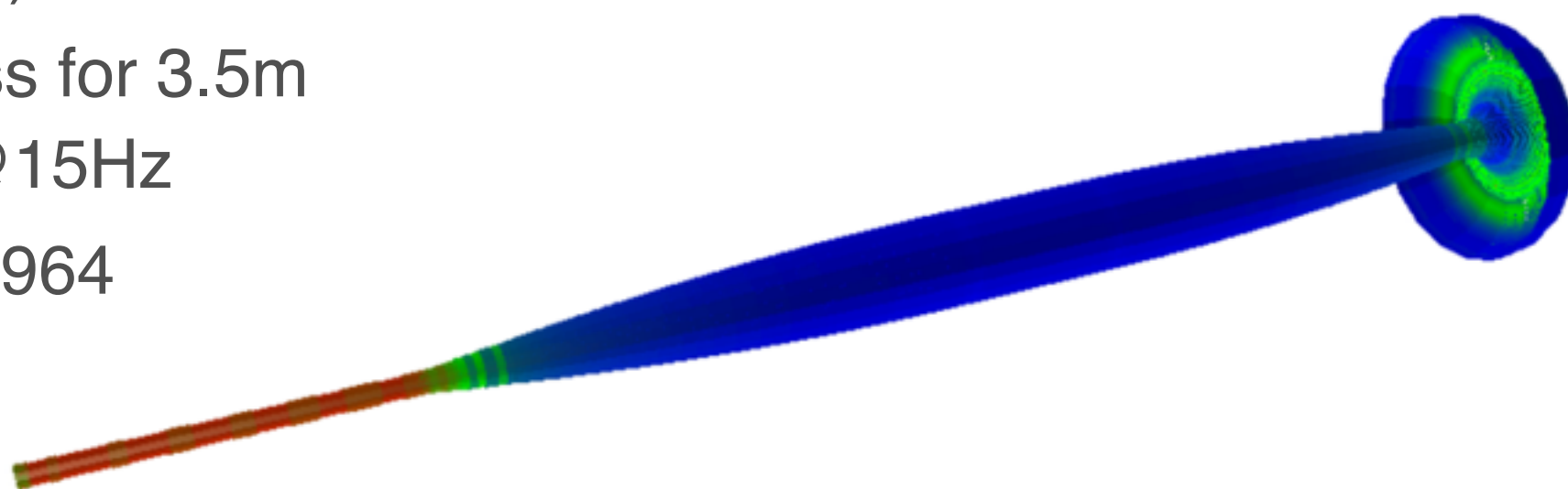
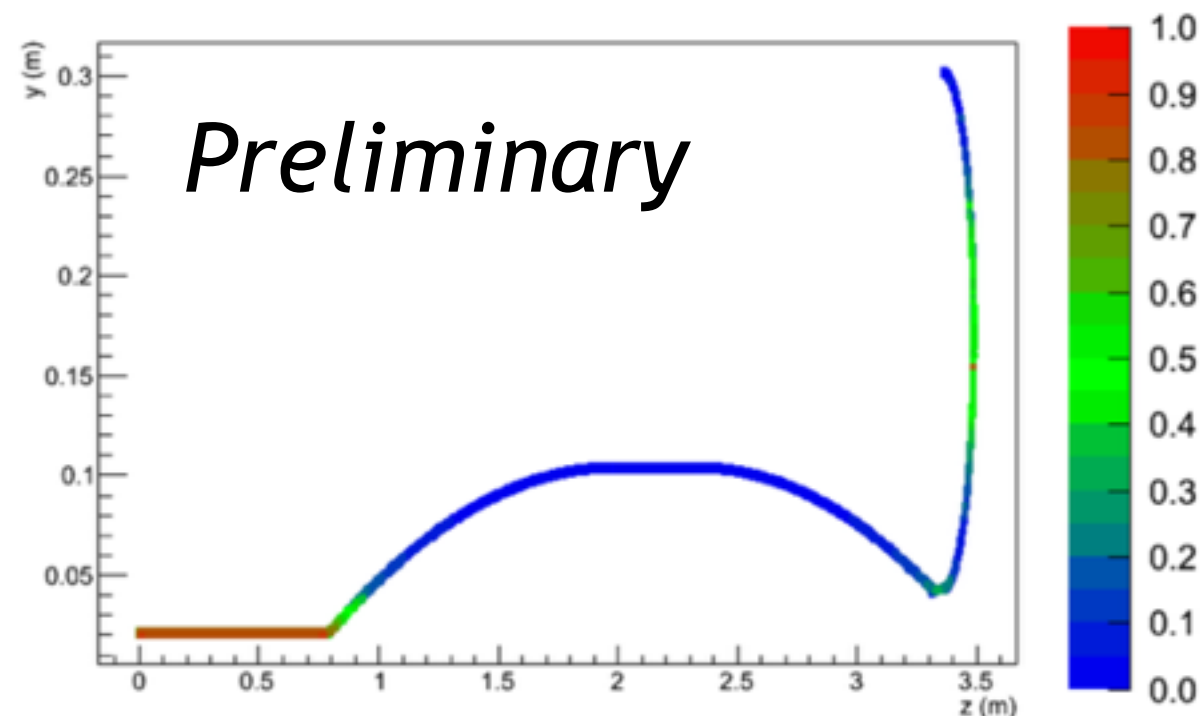


*Bartoszek engineering*



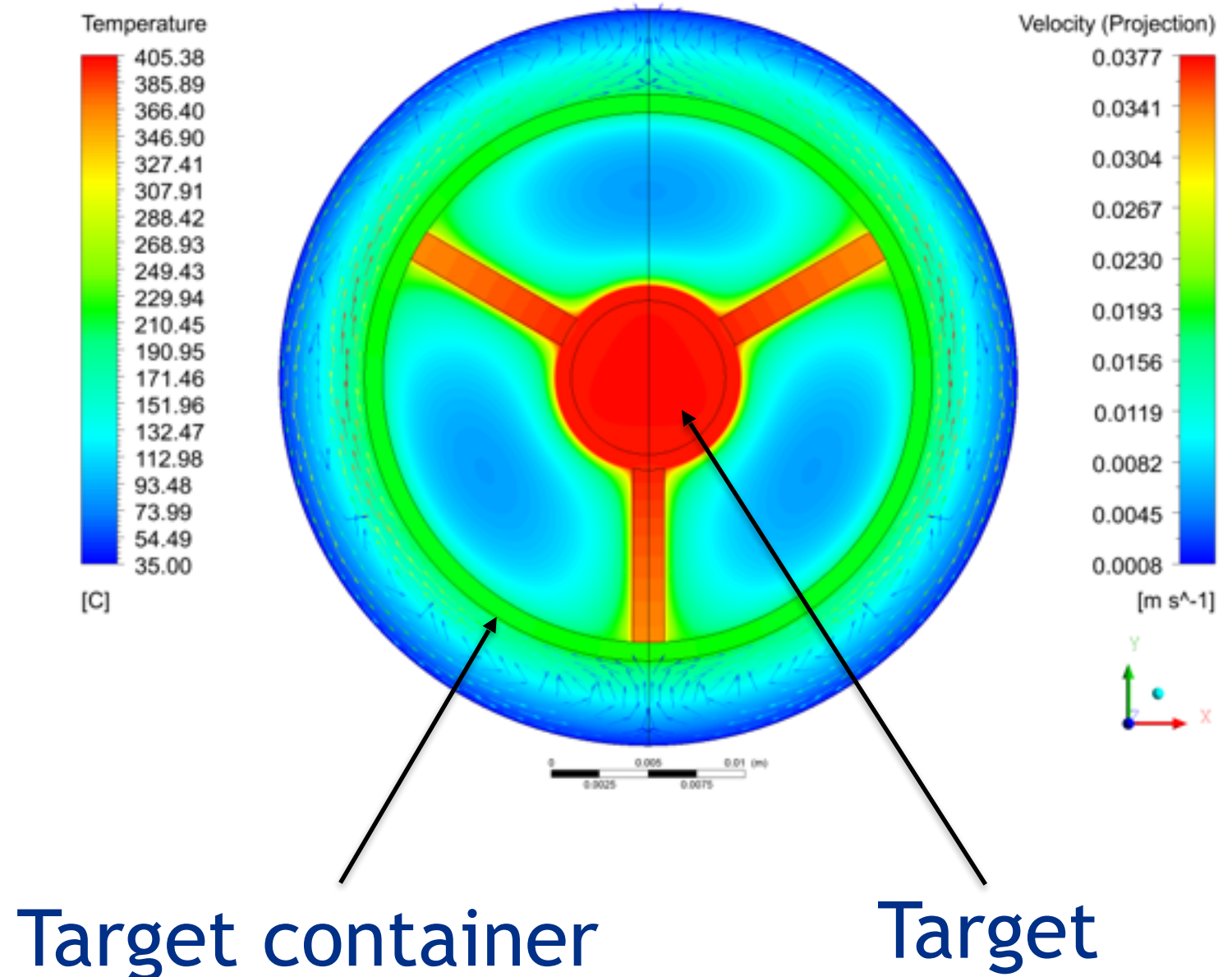
# Fatigue limit

- Fatigue limit analysis based on stresses calculated in FE analysis
- Based on analysis originally done for MiniBooNE horn
- Comparing with allowable stress for >200 million pulses lifetime
- Using available stress/cycle data
- Takes into account environmental factors (wetness, welds)
- Ratio to allowable stress for 3.5m horn pulsed at 210kA@15Hz
- Highest ratio point at 0.964



# Target heating

- Air cooled target
- ~600W deposited energy assuming  $5e12@5\text{HZ}$
- Preliminary studies predict manageable target temperature assuming  $5e12@10\text{Hz}$ 
  - Energy deposition (MARS)
  - Full FE analysis



# Horn power supply

Parameter	Limit	Present Horn	Max. Rep.	Max. Current
Cap Bank RMS (kA)	6.4	3.6	5.6	5.7
Recover choke (A)	132	84	130	132.8
Max. Peak (kA)	250	172	172	250
Max. Voltage (kV)	10.5	6.1	6.1	8.9
Ave. Power (kW)	168	27	65	573
Charge Time (ms)		33	33	44
Energy pulse <sup>-1</sup> (kJ)		5.4	5.4	9.2
Max. Avg. cycle (Hz)		5	12	6.25
Max. cycles in 1 sec		31 (16)	31 (16)	18.3 (9.2)

MiniBooNE  
horn load

- Consider upgrades that maintain the basic structure of power supply (enclosure, internal connections, SCR,...)
- Cooling to the recovery choke to increase the max current by 20-30%
- Add charging supplies to decrease charge time/increase power



# Power supply upgrade (cont'd)

- Power supply capable of driving 3.5m long horn
- Improved rate and/or peak current with modest upgrades

	Max current (kA)	Max rate (Hz)
No mods	250	4.3
	130	15
4 new charging supplies	250	5.1
	140	15
Recovery choke + Charging supplies	250	6.4
	160	15

# Total gains

Max rate depending  
on PS capabilities  
and horn load

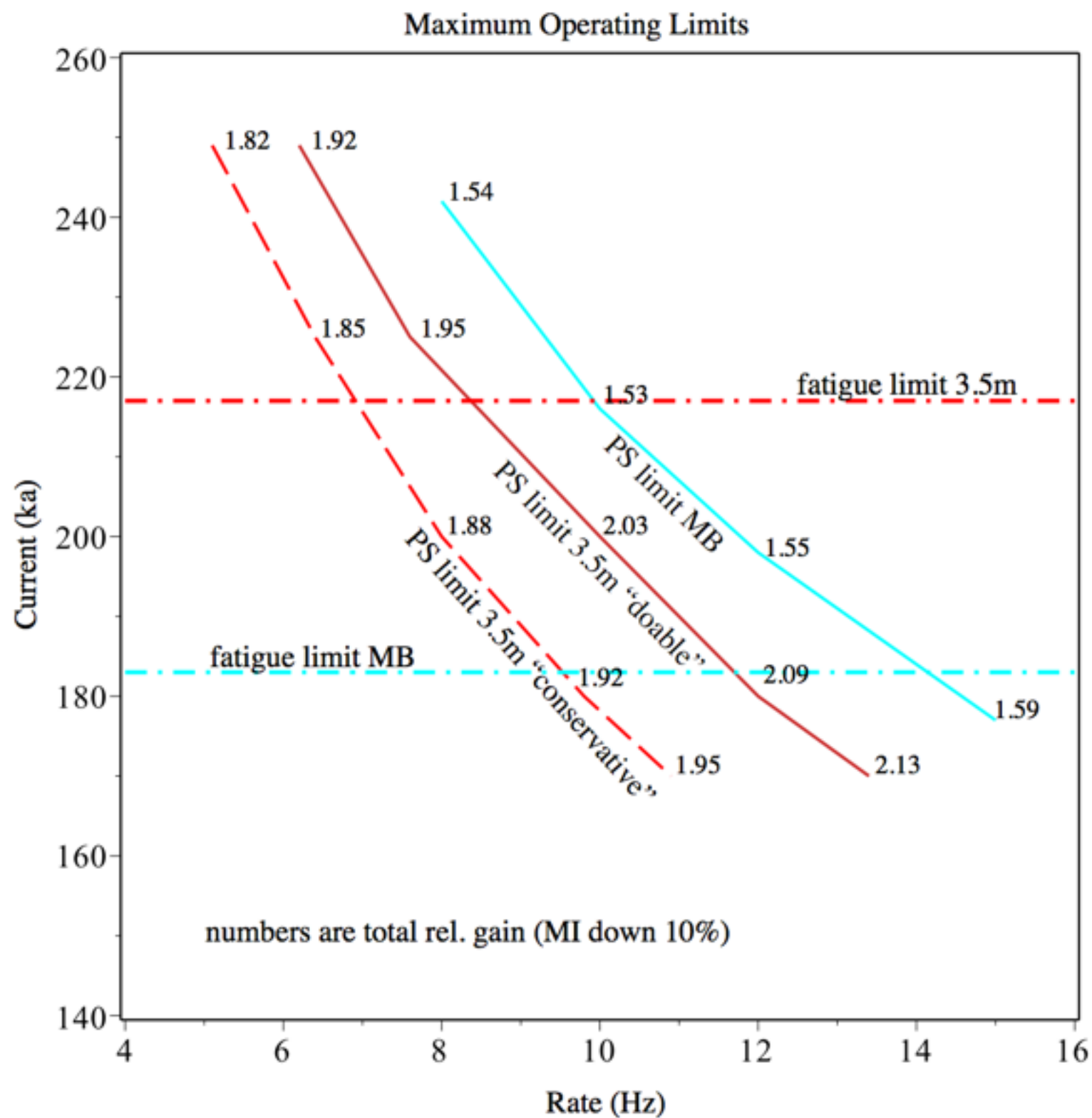
Gain from  
better focusing

Total gain from  
better focusing  
and using available  
cycles up to  
max rate

Total gain if  
10% downtime  
assumed for NuMI  
and muon program

Horn current	Max rate (Hz)	Gain (focusing)	Total Gain (focusing*rate)	Total Gain (10% BNB only)
180kA	12.3	1.48	1.77	2.11
200kA	10	1.55	1.77	2.03
210kA	9	1.58	1.78	2.01
220kA	8.2	1.62	1.78	1.97
250kA	6.4	1.71	1.81	1.93

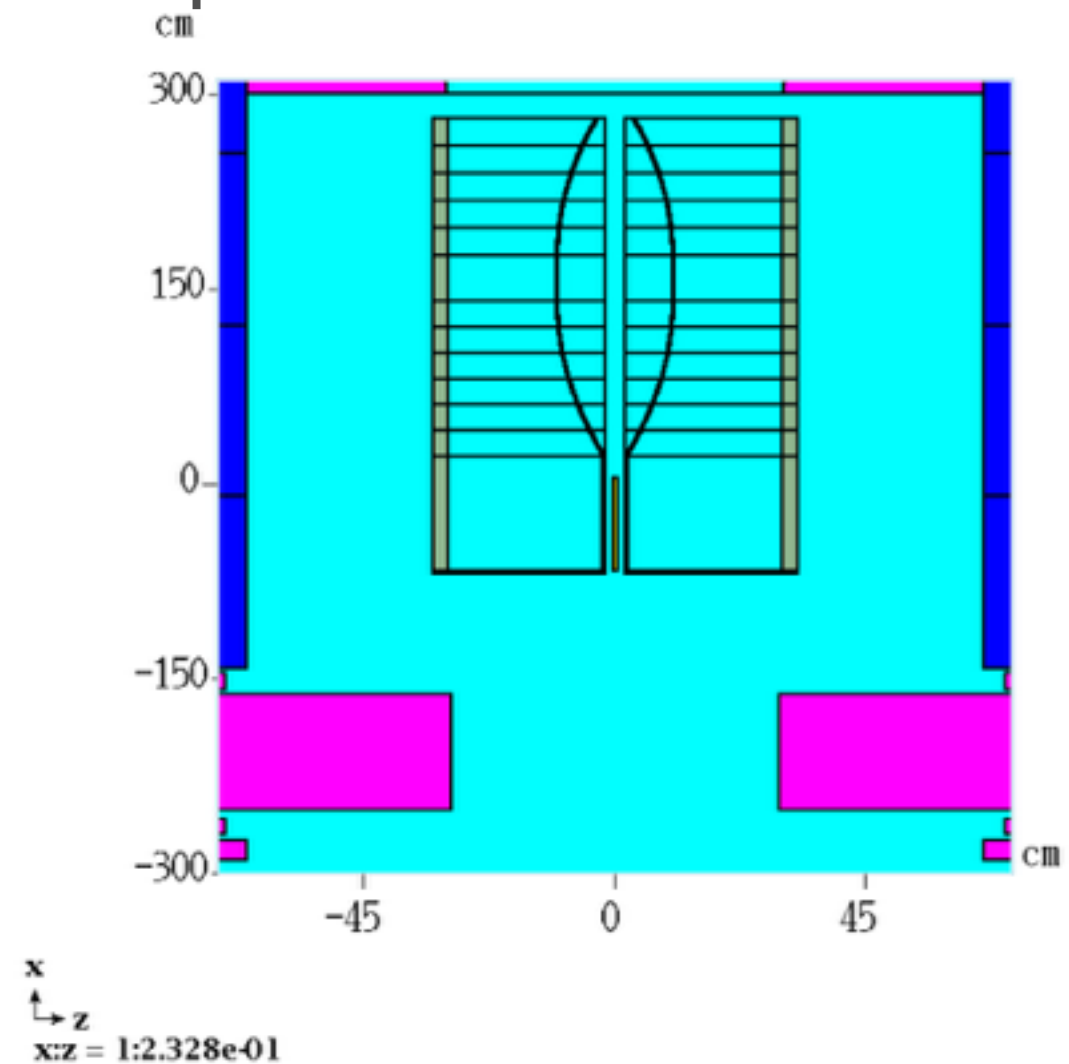
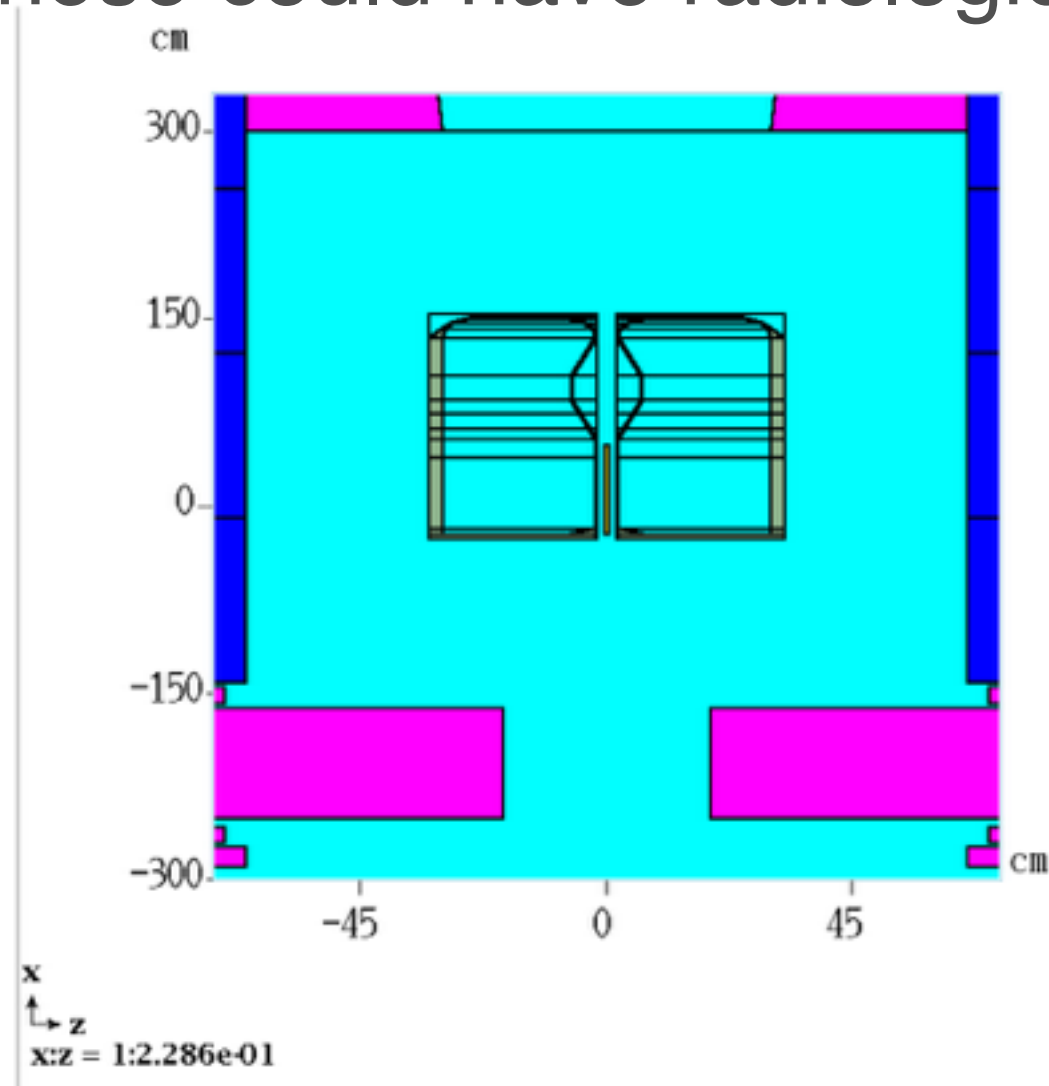
# Total gains (cont'd)





# Radiological limits

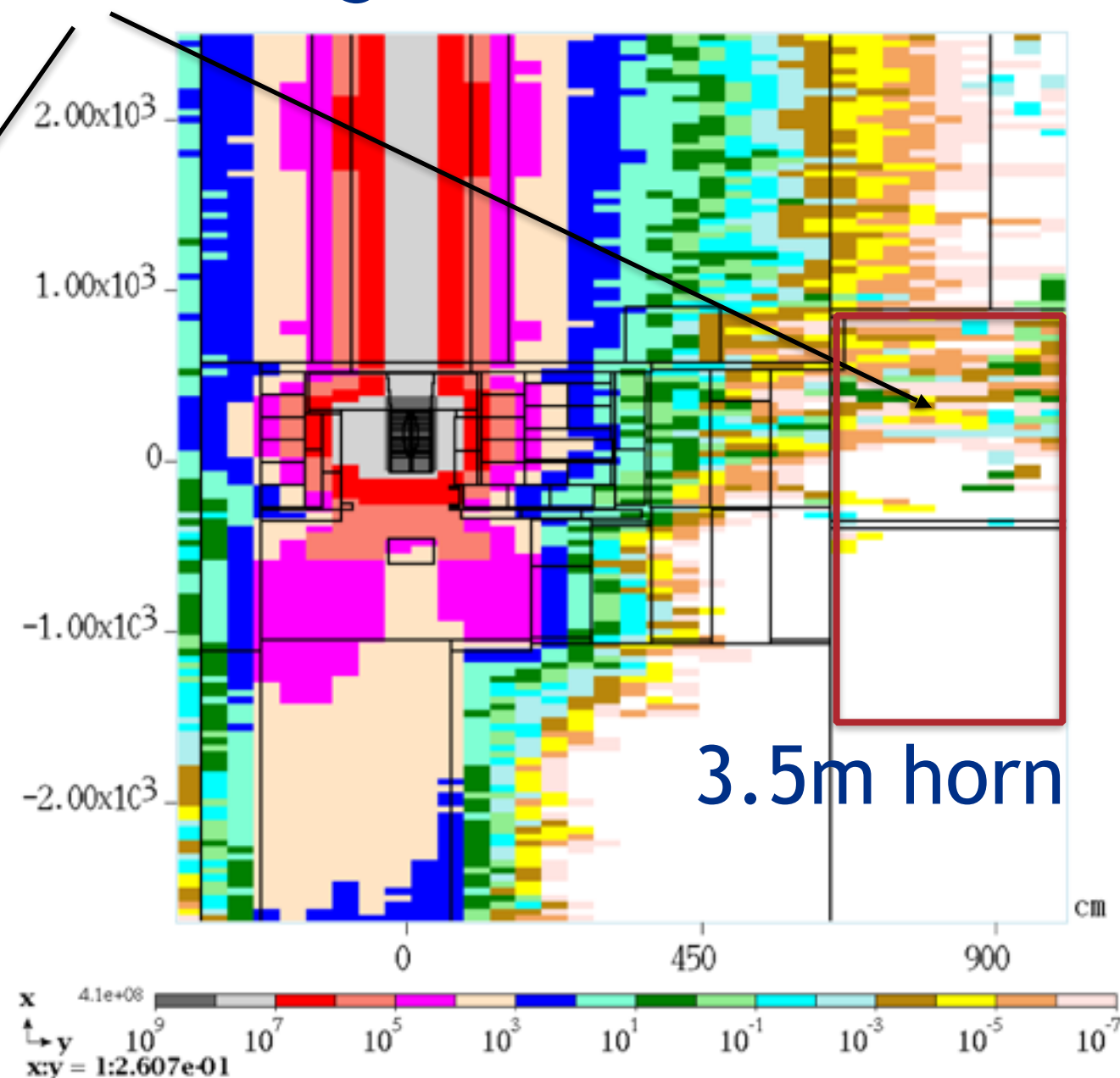
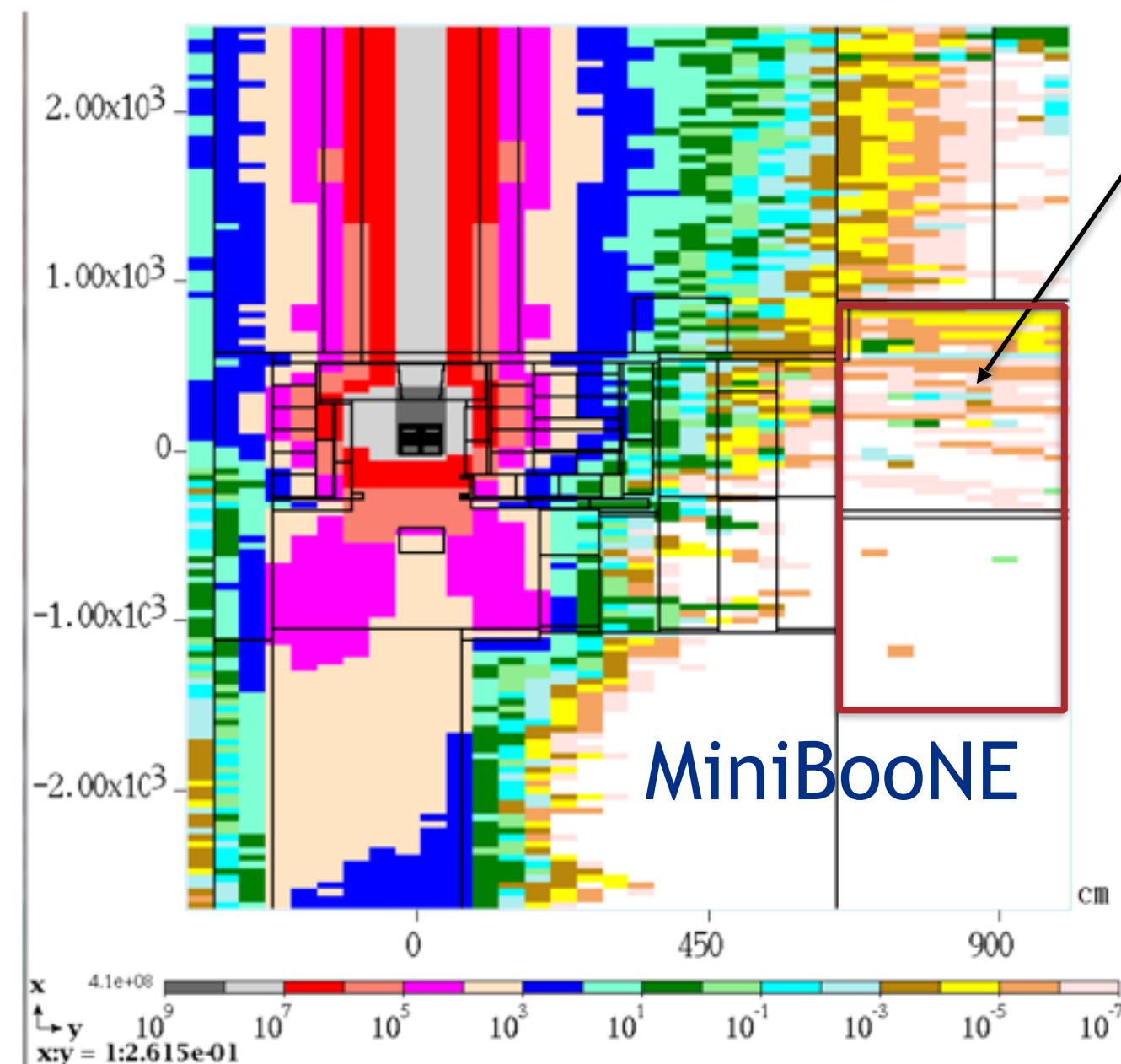
- 3.5m long horn requires target to be pulled 50cm upstream
- Service module and cooling pipes might require additional opening of shield doors
- These could have radiological impact



# Radiological limits (preliminary)

- Similar dose on surface with MiniBooNE and optimized horn running

## Surface building



# Director's review

- Two recommendations on BNB upgrade received after Director's Progress Review of the Short Baseline Neutrino Program (December 2015)

## Recommendations

13. Complete the conceptual design along with a bottom-up cost estimate, preliminary schedule, and cost profile for further review.
14. Perform simulations to clarify the additional sensitivity reach from the new flux spectrum, quantify at what POT systematics start to dominate, and the dependence on assumptions about NC  $\pi^0$  rejection and cancellation of errors in the near/far ratio.

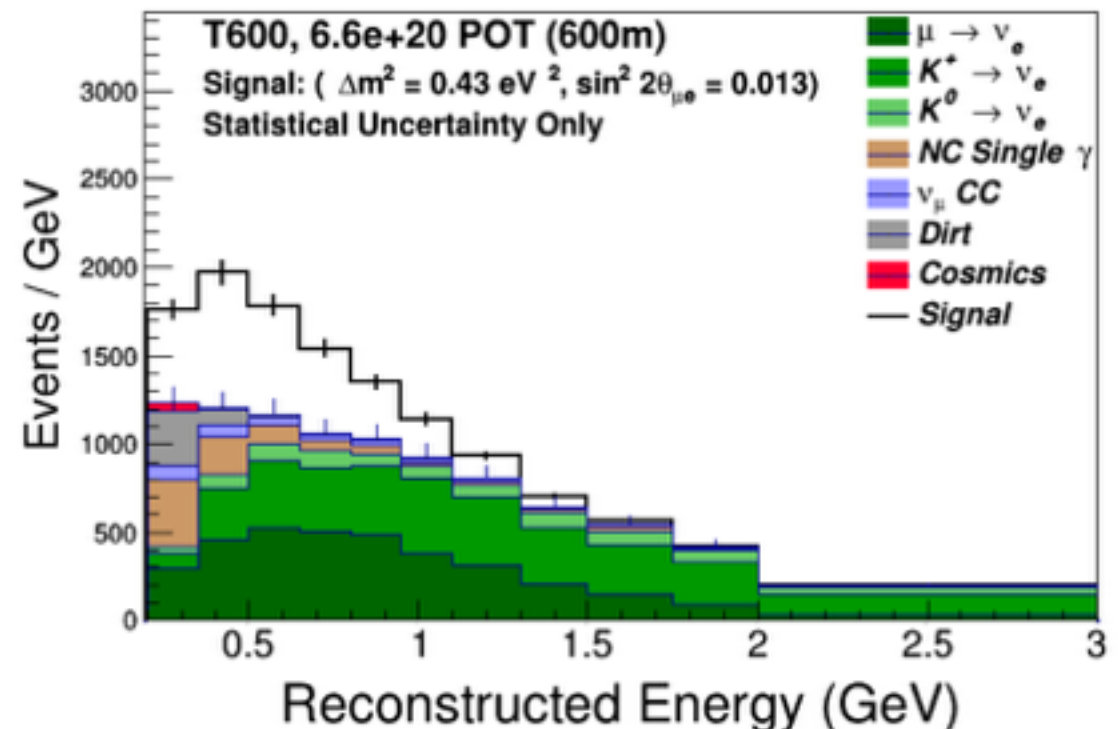
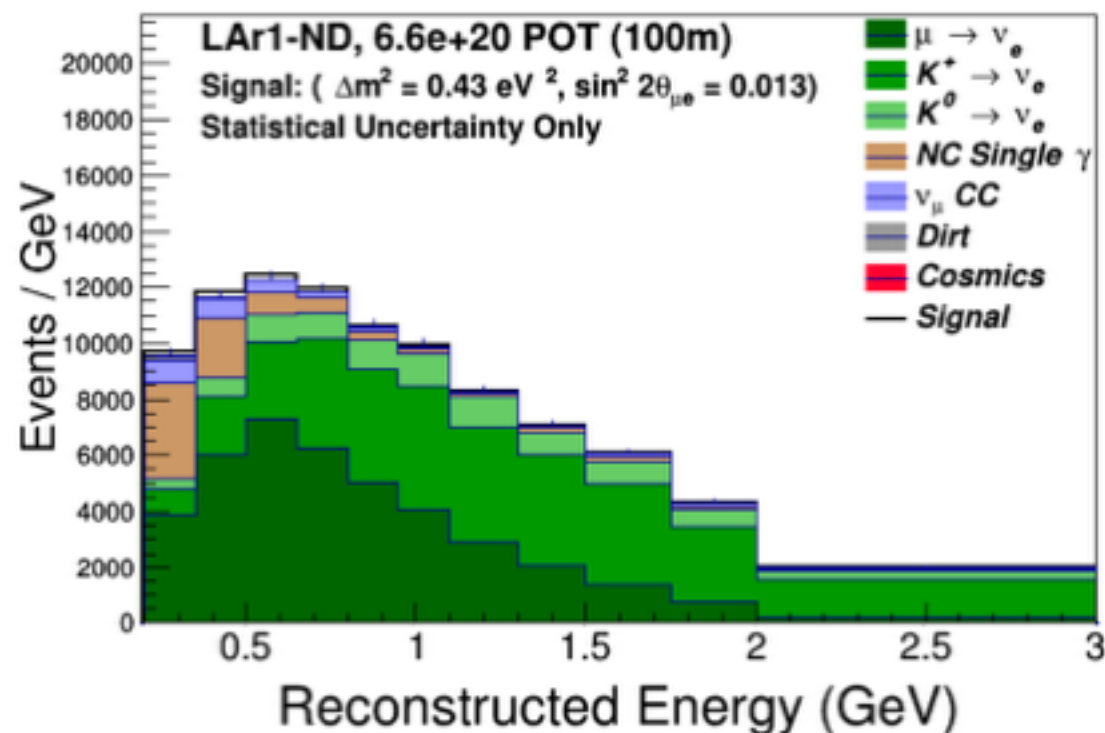


# Next steps

- Nearly complete with conceptual design
  - Finalize radiological studies
  - Finalize horn fatigue analysis, target analysis
  - Horn design, service module, coffins
  - Full conceptual design
- A better cost and schedule for upgraded power supply and new horn
- Technical review of conceptual design (spring 2016)
- Ready for AIP funds starting FY2017 for final engineering and production

# Sensitivity

- Preliminary studies indicate sensitivity scales with stats (not systematically limited)
- How sensitive is this to assumptions used in the proposal?
- Maximizing number of events increases high energy tail, but exact choice of inner conductor allows shaping of the spectrum (remove high energy tail, but maintain low energy gains)



*SBN Proposal (arxiv:1503.01520)*

# Conclusion

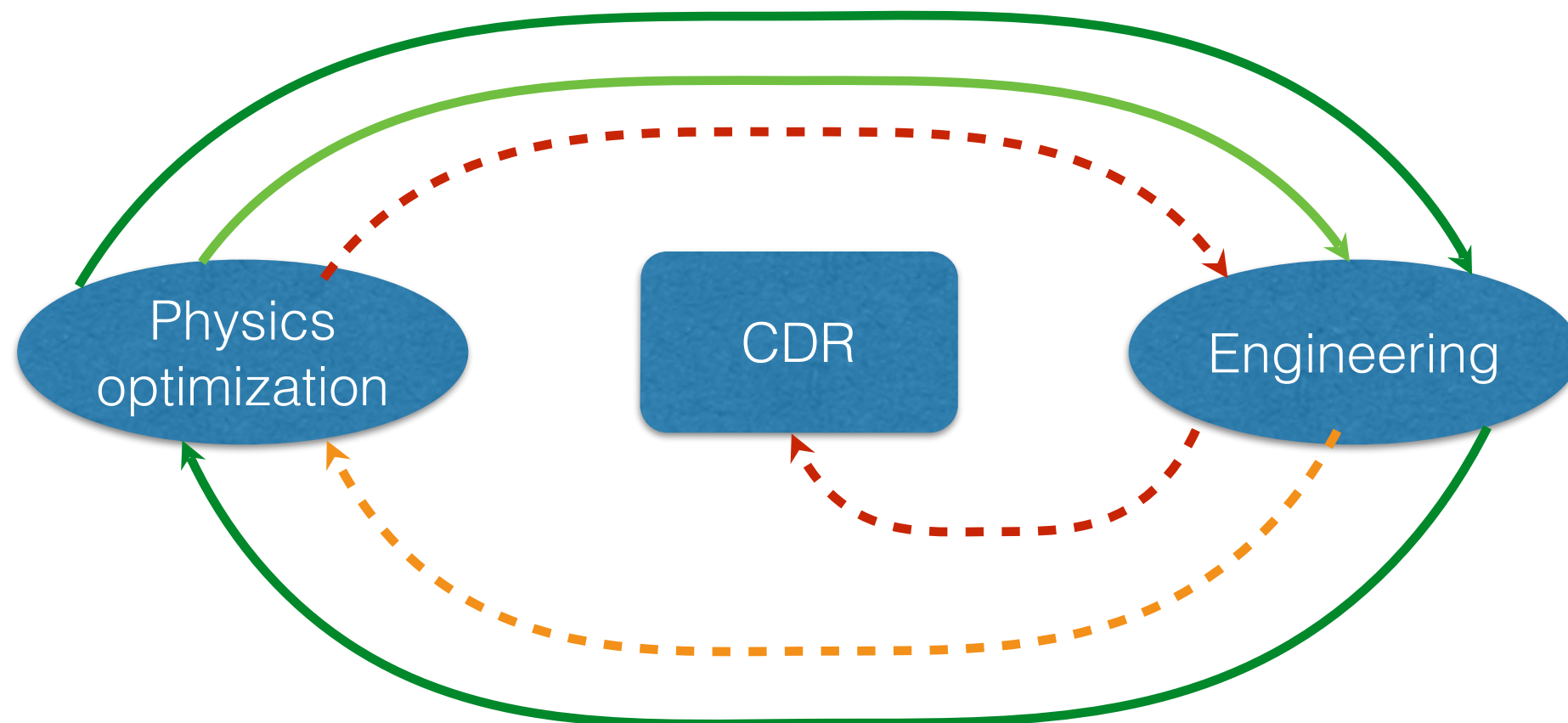
- BNB has provided stable and reliable beam
- Possible significant gains with upgraded horn system ( $\sim 1.8x$ )
  - New longer horn and upgraded power supply
  - Reusing existing target hall and power supply basic structure
- Upgraded beam at modest cost (\$6.5M)
  - Includes first horn
- Seamless transition to new horn design with minimal downtime
  - Horns designed as wear parts and are expected to be replaced (next horn always under construction)
- Full conceptual design in 2016, new horn ready to use in 2019
- Need to study sensitivity reach with upgraded flux



# Backup

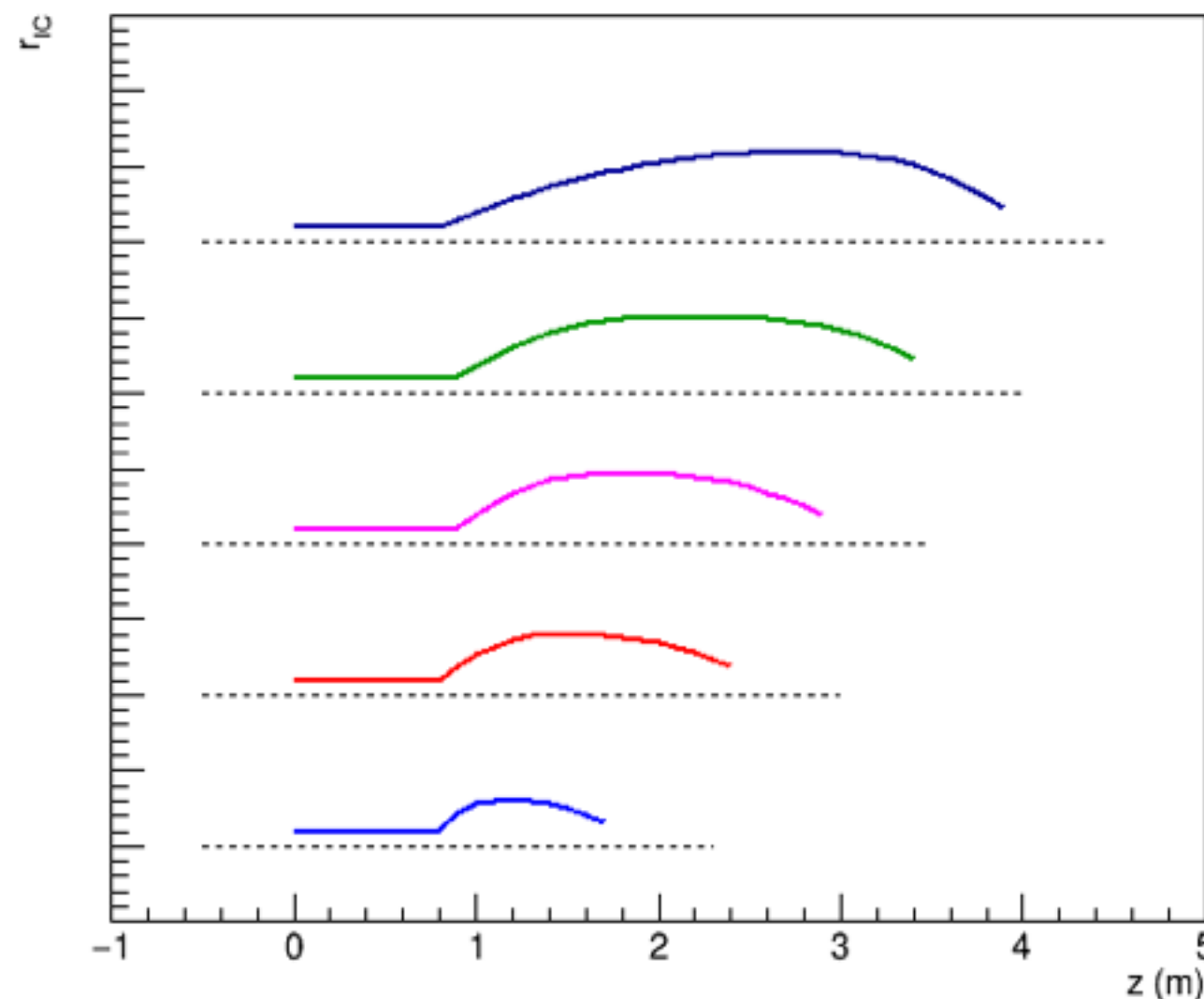
# BNB reoptimization

- Reoptimize beamline for SBN program, maximize physics reach of the Liquid argon based program
- Iterative process
  - Cross dependency between optimization parameters
  - Went through few physics reoptimizations and engineering checks
- Converging toward conceptual design



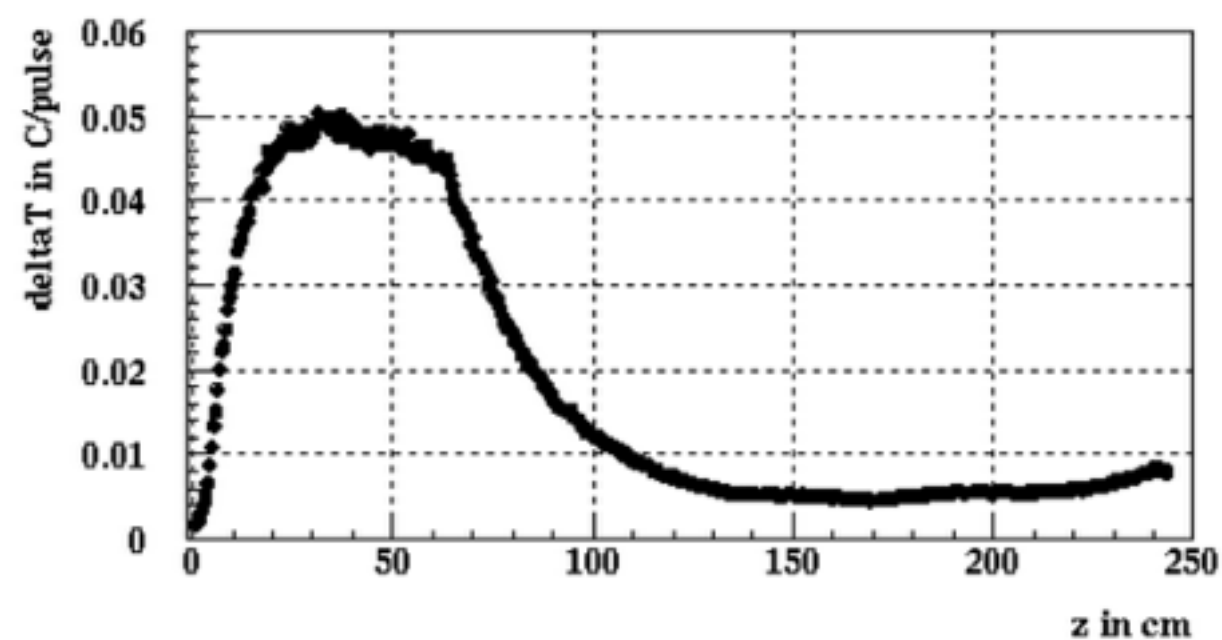
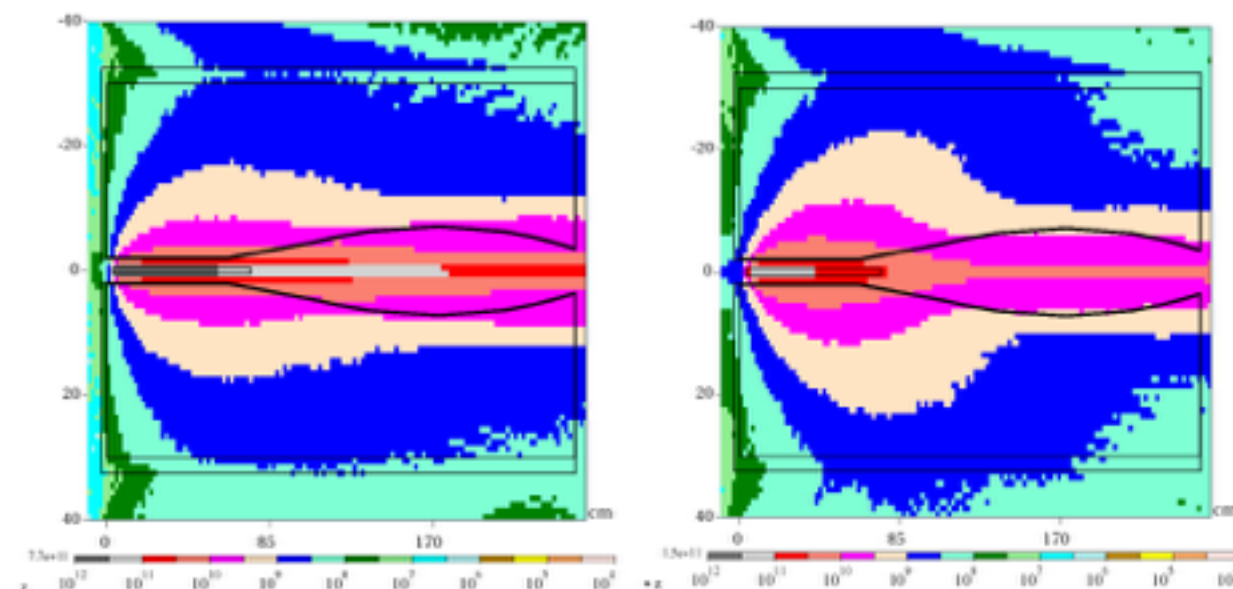
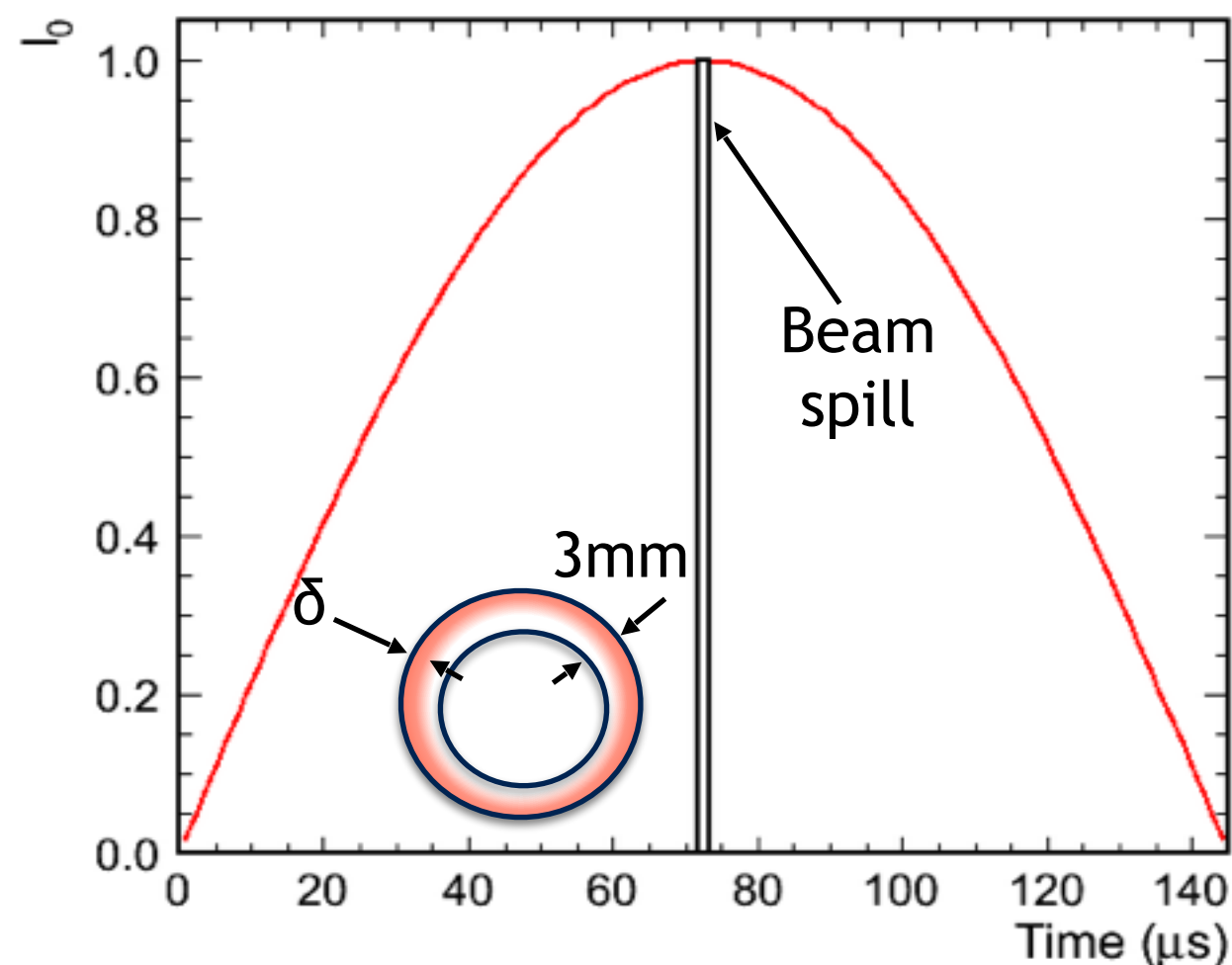
# Optimization

- Fast MC used for fitting
  - Genetic algorithm
  - 7 inner conductor shape parameters, horn current
- Optimized for most neutrino events
- Regenerate neutrino fluxes with full BNB MC with optimized horn to calculate real gain
  - Real beamline geometry
  - HARP pion production cross sections



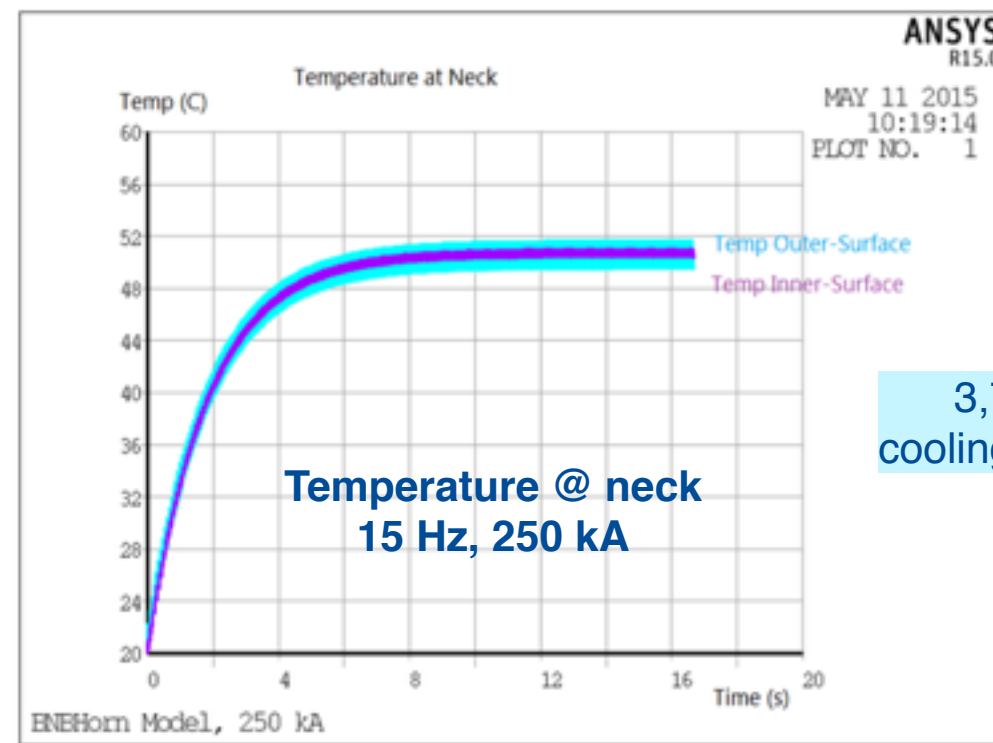
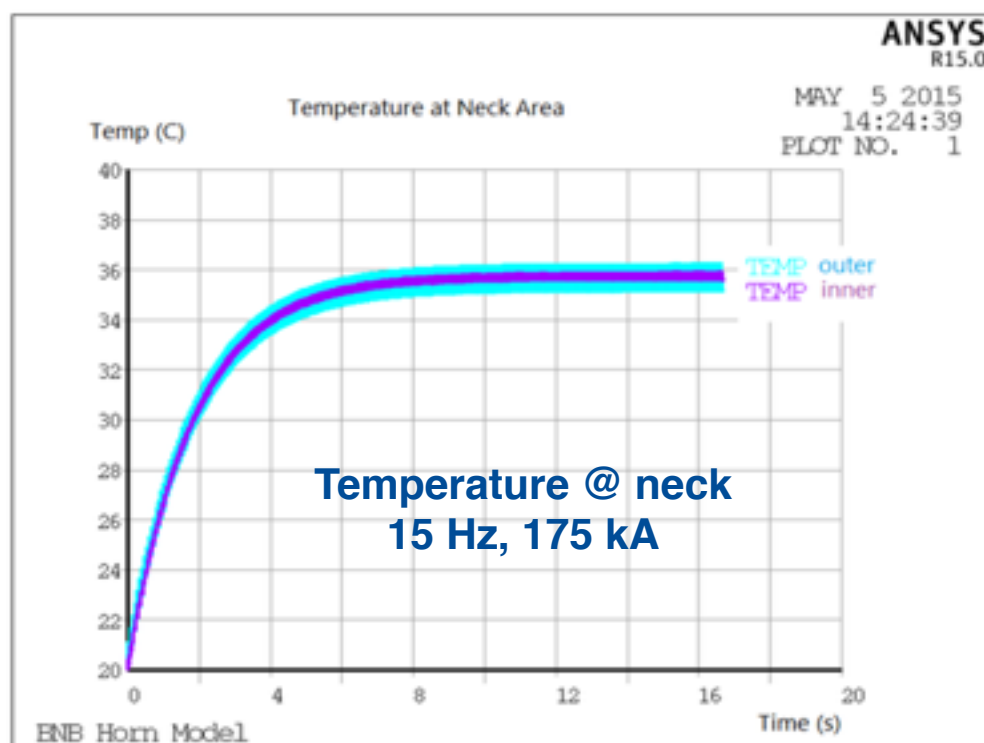
# Heat load

- Main contribution from Joule heating
- Beam heating contributes less than 10% at 175kA
- Skin depth is  $\delta=1.4\text{mm}$  for BNB horn

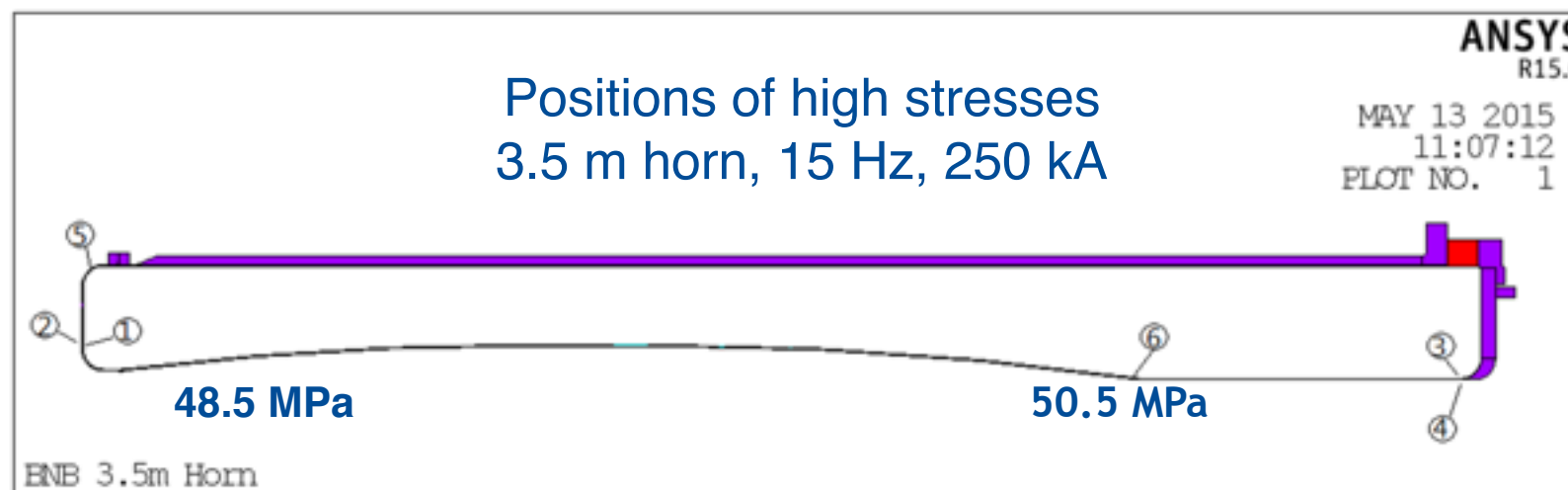




# FE analysis

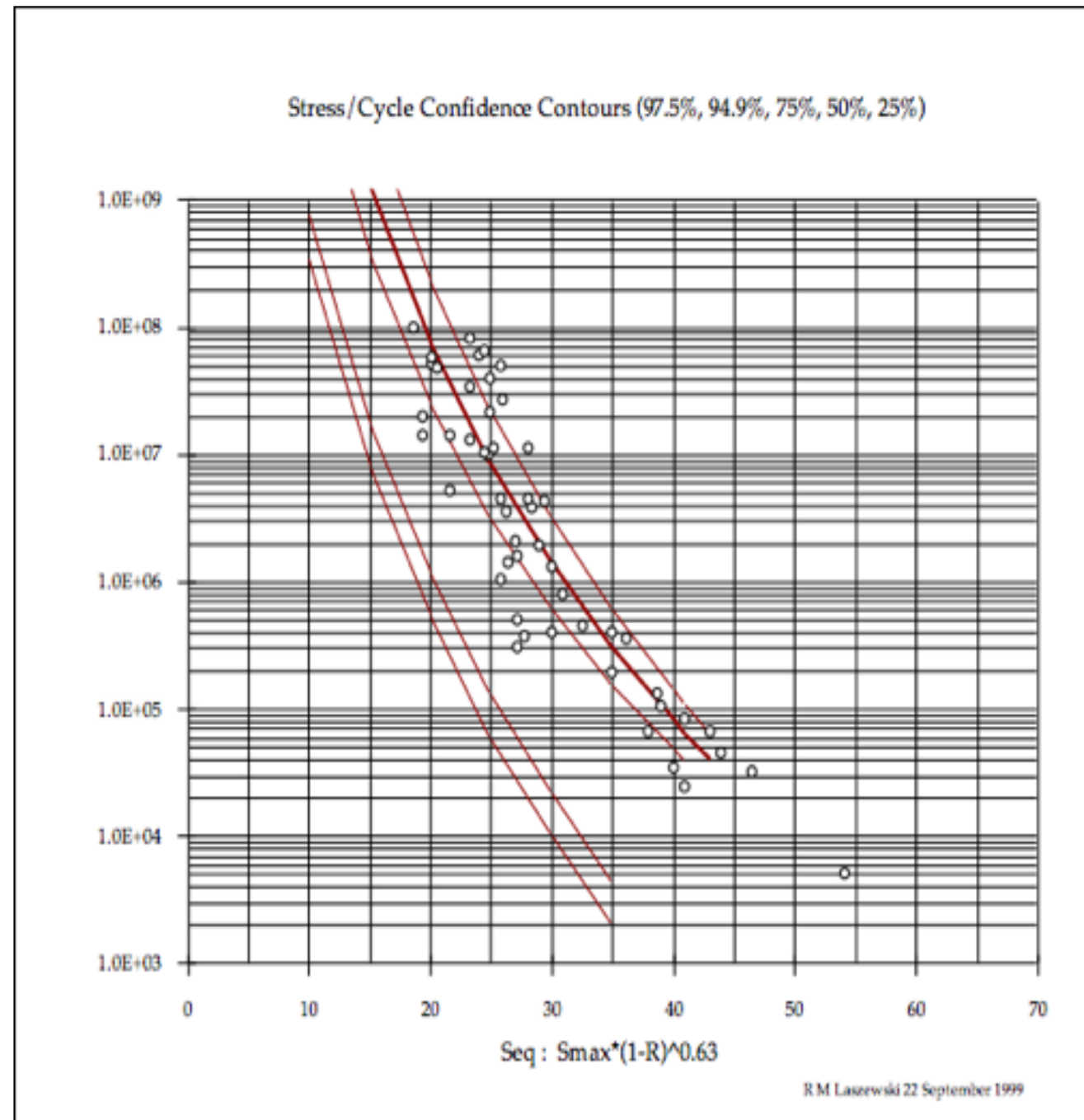


3,750 W/m<sup>2</sup> C  
cooling film coefficient



- Identify high stress points, use full stress history for each element in fatigue analysis

# Allowable stress

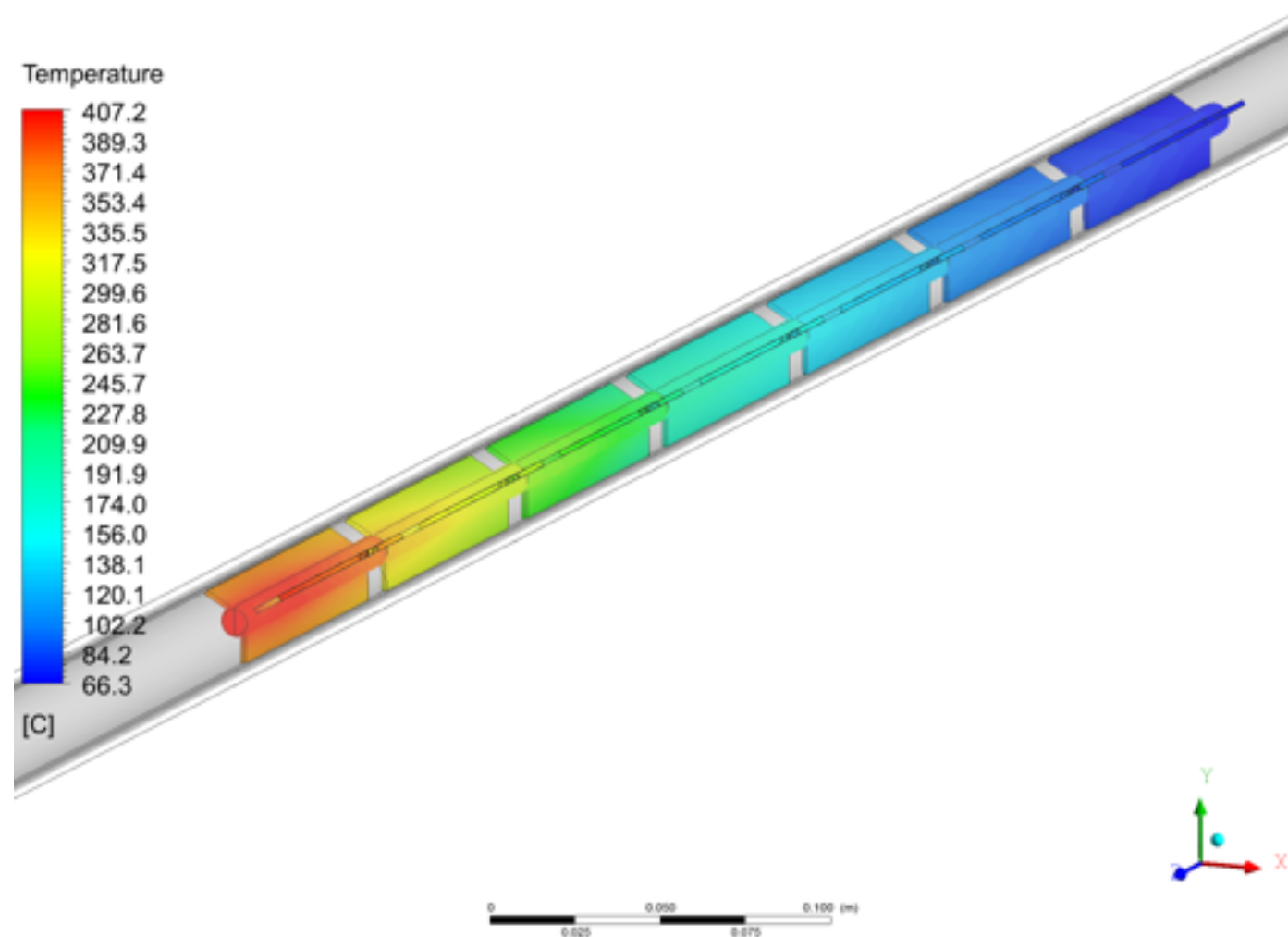


# Radiological limits

	Limit	Reason
Booster & 8 GeV Line up to cell 803	1.8e17/hr	Overburden
8 GeV Line (cell 803 to cell 850)	2.84e17/hr	Overburden
8 GeV Line (cell 850 to BNB target station)	1.62e17/hr	Dose at stripline penetration
BNB Target Station	7.5e20/year	Groundwater

- 1.62e17POT/hr assuming 4.5e12 protons per pulse corresponds to maximum average rate of 10Hz

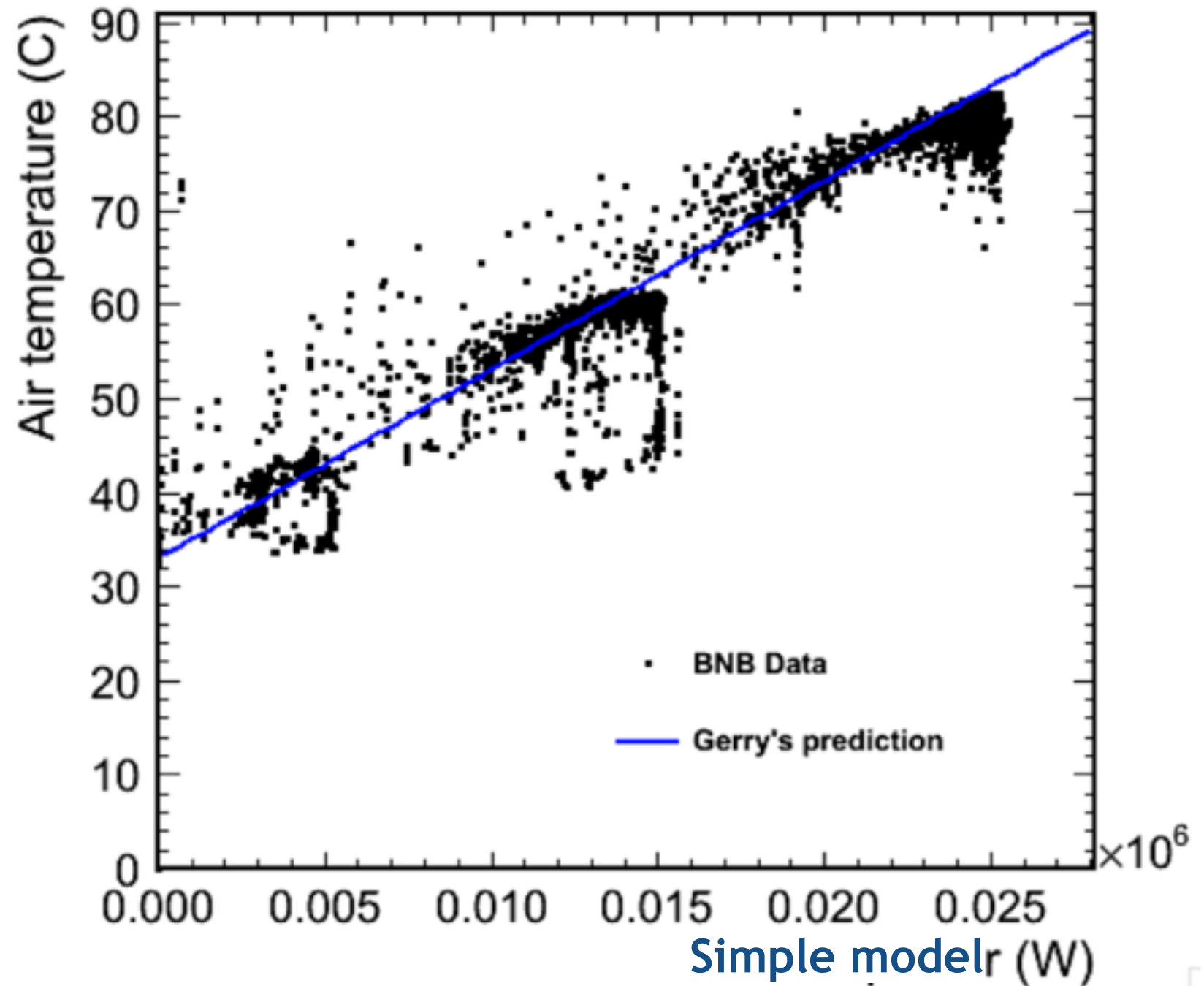
# Target temperature





# Target cooling

- Air cooled
- Simple heat transfer model taking into account energy deposition ( $\sim 600\text{W}@5\text{Hz}/5\text{e}12$ ) and air flow describes observed data well



# Resources

- Bartoszek Engineering - Larry Bartoszek
  - Horn Design
- Fermilab:
  - AD: Keith Gollwitzer, Tom Kobilarcik, Valerie Lebedev, Craig Moore, Sergei Striganov
  - AD - engineering: Salman Tariq, Howie Pfeffer, Dan Wolff
  - ND: Steve Brice, Cat James, Doug Jensen, Paul Lebrun, Byron Lundberg, Alberto Marchionni, Peter Wilson, Zarko Pavlovic
  - PPD - engineering: Zhijing Tang, Erik Voirin
  - BNB expertise, MARS modeling, neutrino flux optimization, power supply refurbishment, FE analysis, instrumentation upgrades
- University of Chicago - Joseph Zennamo
  - SBN sensitivity
- Yale - Corey Adams
  - SBN sensitivity

# Cost

- Estimated cost based on experience with BNB/NuMI horns \$6.5M
  - \$1.5M horn power supply
    - Includes new components and labor
  - \$5M reoptimized and redesigned horn
    - Includes design of horn and stripline, procurement, fabrication, and installation