MI, Recycler, and NuMI Modifications

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The NOvA program

- The NuMI Off-axis ν_e Appearance experiment, NOvA, will search for evidence of muon-to-electron neutrino oscillation by comparing the composition of the NuMI beamline at the source and in an underground laboratory in Minnesota.
- Neutrinos are neutral particles that switch among three flavors: electron, muon and tau. Scientists have observed electron neutrinos from the sun changing to muon and tau neutrinos. They have seen muon neutrinos produced by cosmic rays oscillate to tau neutrinos. With the NOvA experiment, scientists are searching for a third type of neutrino oscillation: muon-to-electron.
- Using two detectors, a 222-metric-ton near detector and a 15-metric-kiloton far detector, NOvA will search for evidence that muon neutrinos can change into electron neutrinos during the 810 km trip. The experiment will examine how many muon neutrinos, ν_μ, leaving the near detector at Fermilab appear as electron neutrinos, ν_e, at the far detector.

From the P5 report,
http://www.er.doe.gov/hep/files/pdfs/P5_Report%2006022008.pdf

Neutrinos Have Mass!

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U^\dagger \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U^*_{\beta j} e^{-i\frac{m_j^2 L}{2E}} U_{\alpha j} \right|^2$$

- $\nu_e, \nu_\mu, \nu_\tau \leftrightarrow \nu_1, \nu_2, \nu_3$
  - Flavor States: creation and detection
  - Mass States: propagation

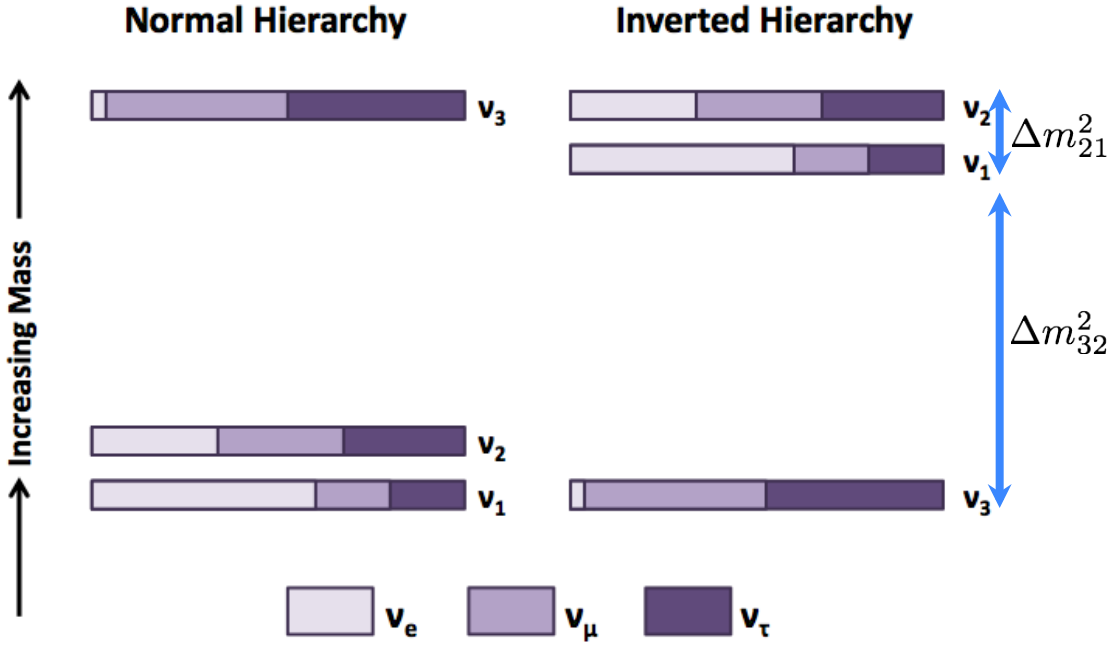
- A neutrino created as one flavor can later be detected as another flavor, depending on
  - distance traveled (L)
  - neutrino energy (E)
- For NOvA, optimized at E~2 GeV

From P. Vahle FNAL Users Meeting June 2011
Nova Docdb 6008

NOvA's place

Several major areas of research:

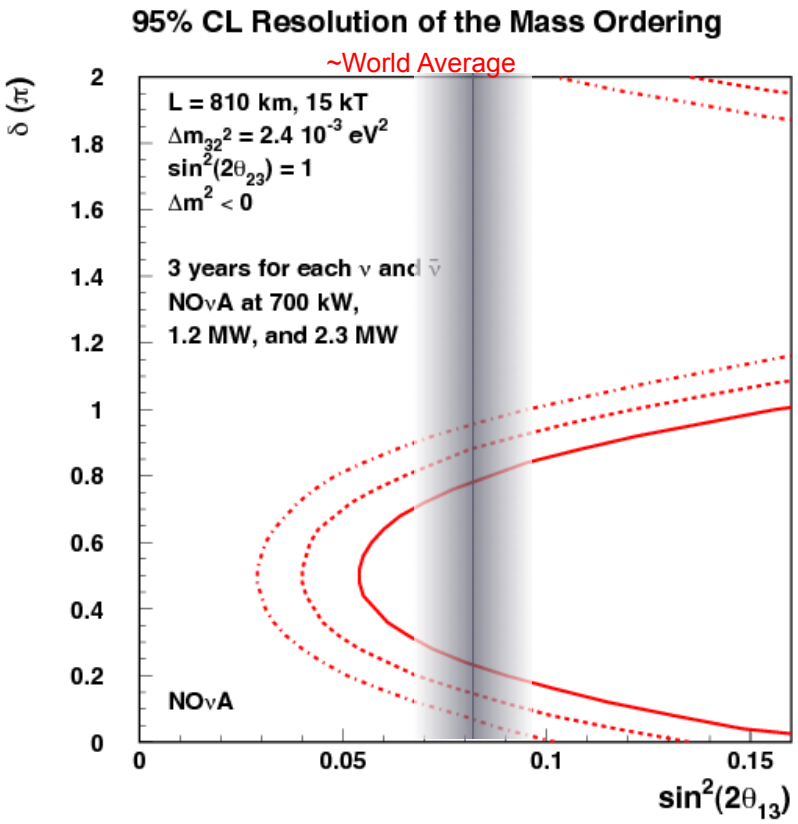
- Precision measurements of mixing parameters (θ_{12}, θ_{23}, , Δm^2_{21} Δm^2_{32})
- Is θ_{13} non-zero? YES!!!!
- smaller than other angles!
- Is there a CP violation phase?
- What is the mass hierarchy?
- Existence of sterile neutrinos?

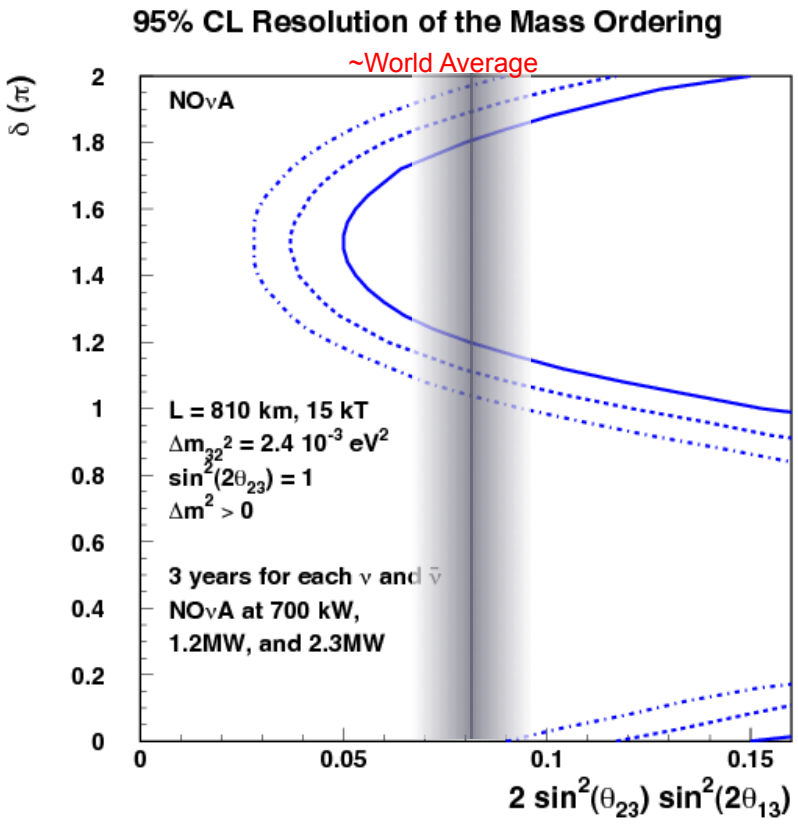


$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From R. Toner Harvard March 2012
Nova Docdb 7196

Mass Hierarchy and δ_{CP}





If $\sin^2(2\theta_{13})$ is below a certain value, we will not be able to measure it definitively
Plot: if $\sin^2(2\theta_{13})$ is to the right of the curve, NOvA can measure the hierarchy alone
Note the curves: 6 years at 700 kW is the solid curve: 3.6e21 total protons!

From R. Toner Harvard March 2012
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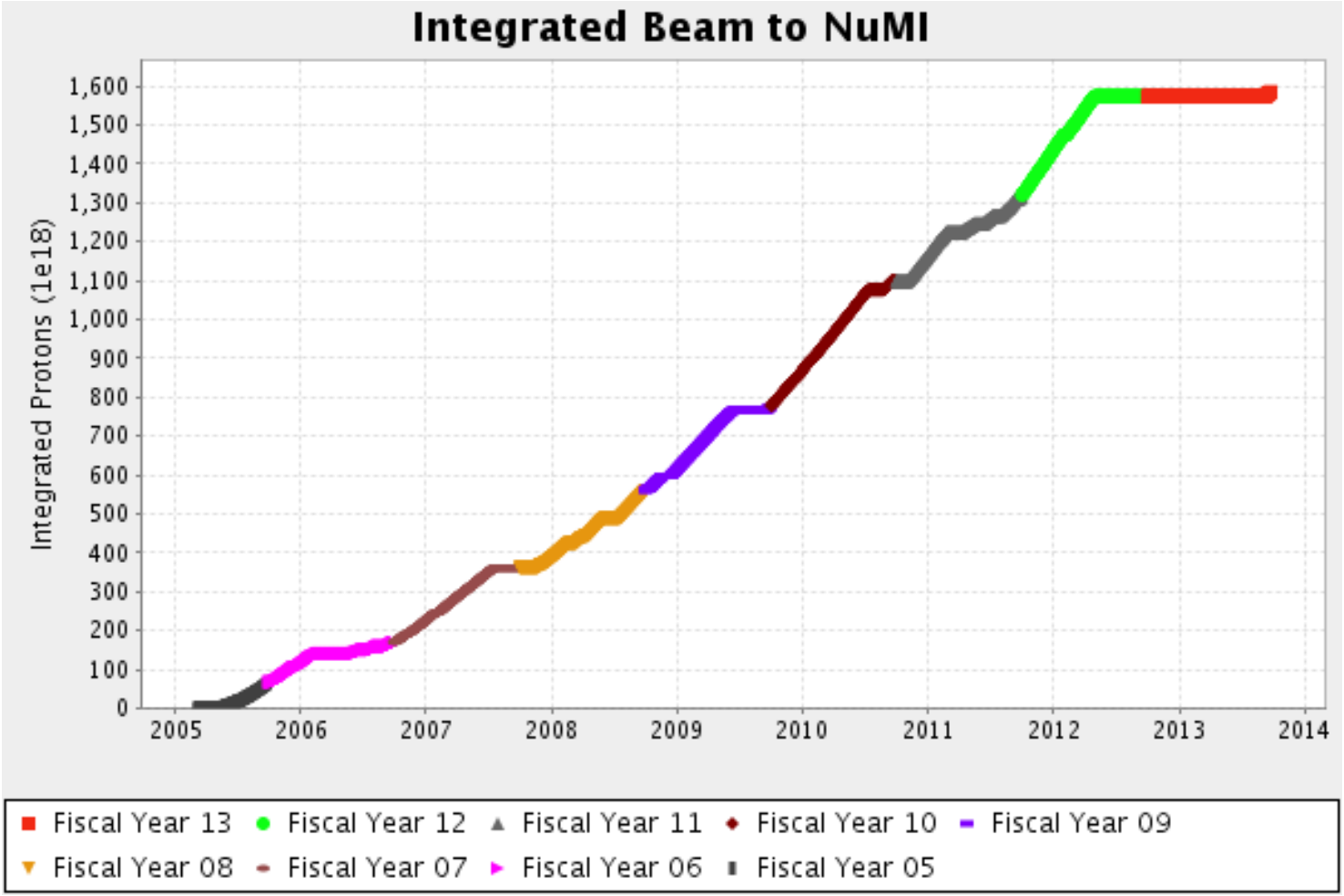
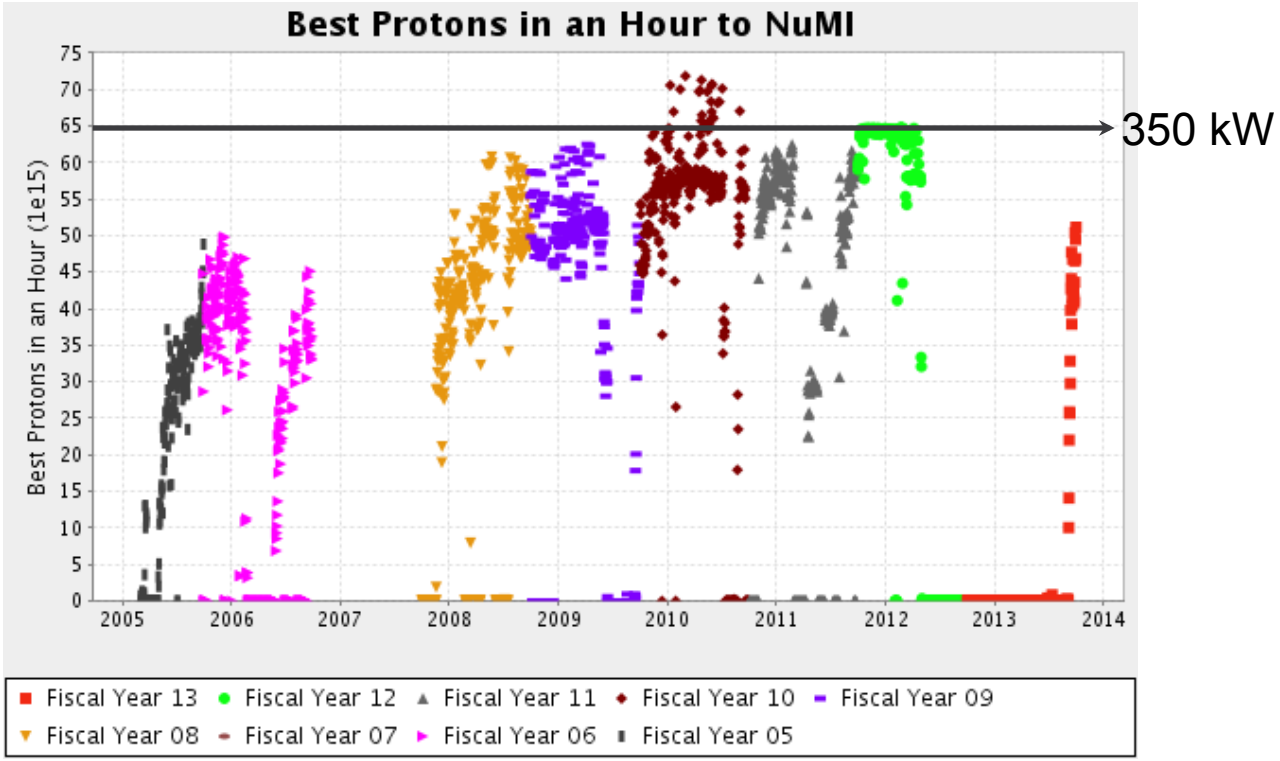
Accelerator Performance for NuMI

- Started delivering protons to NuMI in 2005
  - ~1.55e21 in 7 years: NOvA goal is 3.6e21 in 6 years



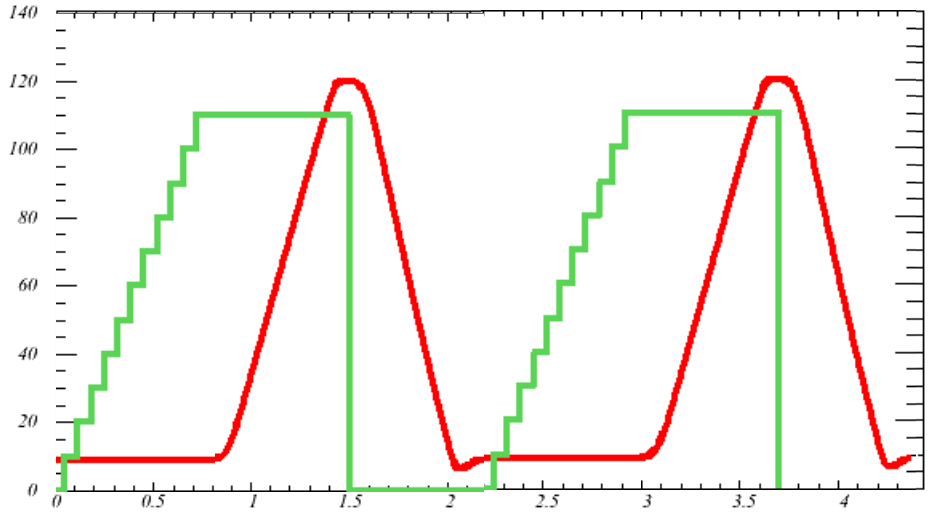
Accelerator Performance for NuMI

- Power = # Protons * Energy / time
  - 1e15/hour @ 120 GeV = 5.33 kW
  - 3.7e13/2.2 sec @ 120 GeV = 323 kW



350 kW on target

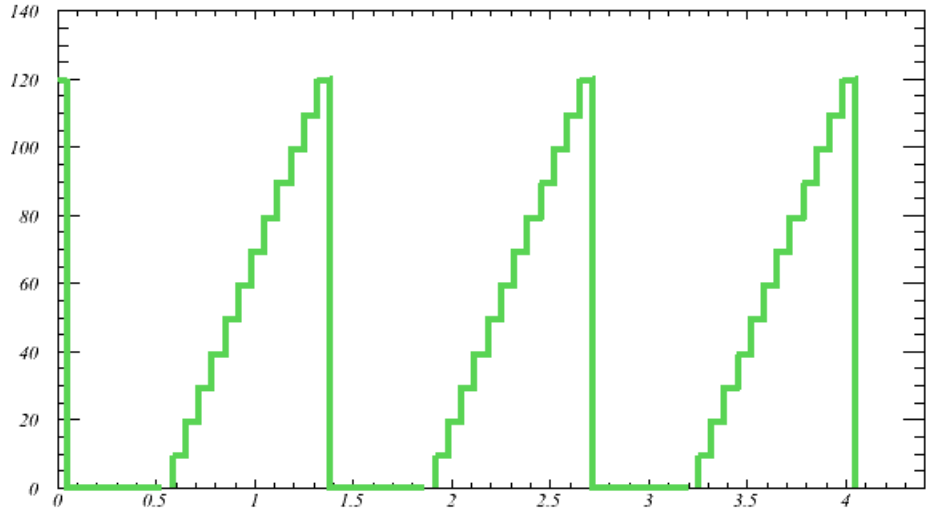
- Previous operation:
  - H- linac at ~35 mA
  - Charge exchange injection into Booster 10-11 turns: 4.3e12
  - 9 pulses (at 15 Hz) into Main Injector with RF slip stacking
  - Ramp at 204 GeV/s and extract to NuMI target
  - 3.7e13 / 2.2 sec cycle 323 kW



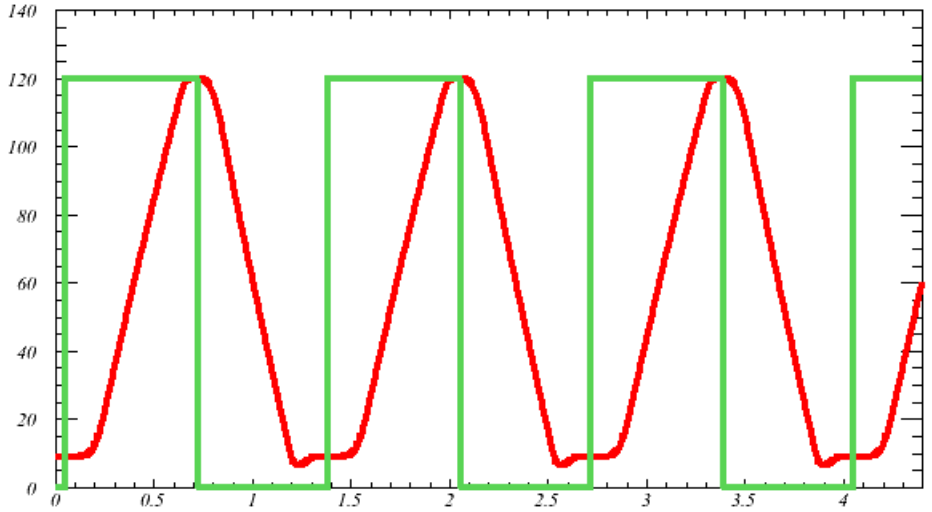
Increasing Beam Power

- Move slip-stacking to recycler
- 11 batch -> 12 batch
- Increase Main Injector ramp rate (204 GeV/s -> 240 GeV/s)
- 330 (380) -> 700kW with only ~10% increase in per-pulse intensity
- Peak intensity 10% just more frequent

Decrease the cycle time?



Recycler



Main Injector

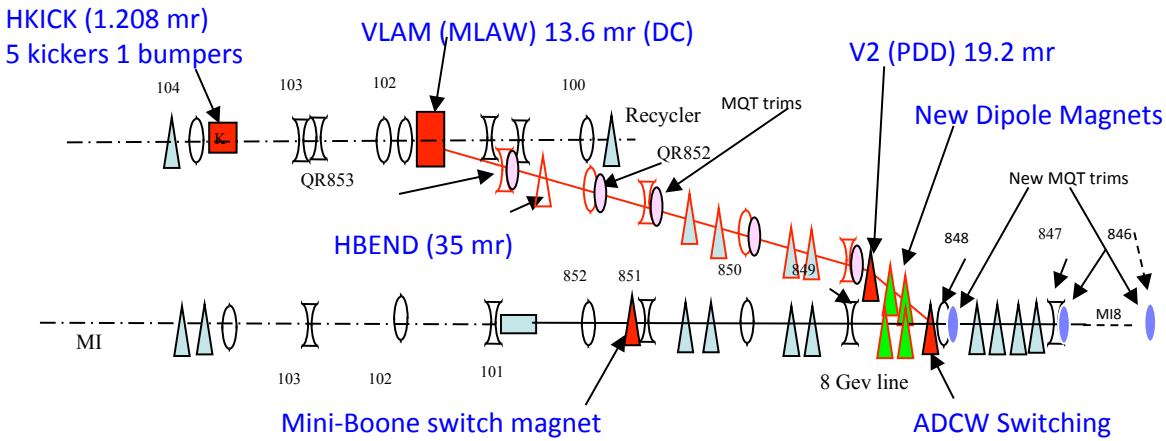
P. Adamson, NuFact11
Nova-doc 6363

Accelerator and NuMI Upgrades

- ANU is part of NOvA (MIE project in OHEP)
  - Convert the Recycler to a proton accumulation ring
    - Two new transfer lines: injection and extraction
    - Two new 53 MHz RF cavities: for slip stacking
    - Upgrades to abort kickers: to handle full turn
    - New instrumentation
  - Increase the MI ramp rate to 240 GeV/sec
    - Upgrades to main power systems (QD bus)
    - Increase #RF cavities from 18 to 20
  - Upgrade the target hall to handle 700 kW
    - Adjustments to better tune the ν energy spectrum for the physics
    - Experiment is placed off axis
  - Decommission and remove antiproton and collider equipment
    - Transfer lines: RR->MI and MI->RR, MI->TeV
    - Stochastic and Electron Cooling
    - RF Coalescing cavities

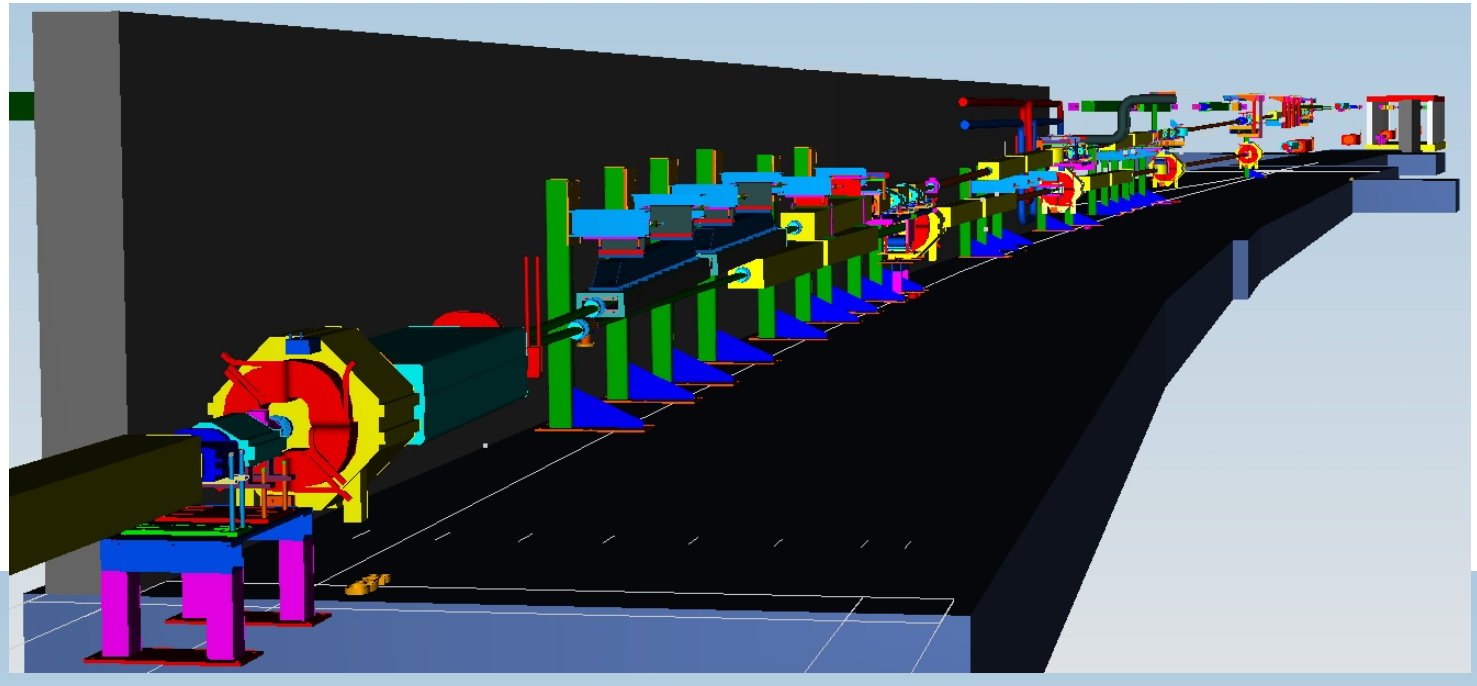
Injection Line

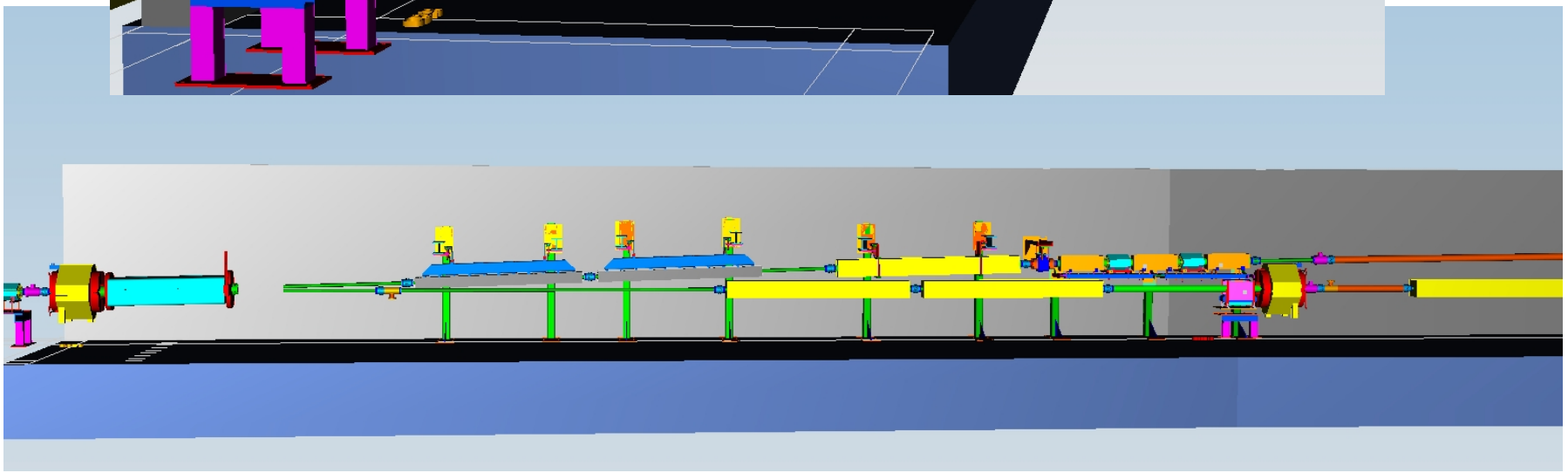
- Preserve Booster Neutrino Beam, Capability to inject into MI
  - Vertical switch magnet in the transfer line from Booster to MI



  - Switched dipole at 849
  - ADCW (wide-gap modification of old ADC magnet)
  - Strontium Ferrite permanent magnet dipoles like rest of MI-8
  - Two Samarium Cobalt dipoles (space constraints)
  - Strontium Ferrite recycler quads, powered quad trims for lattice matching

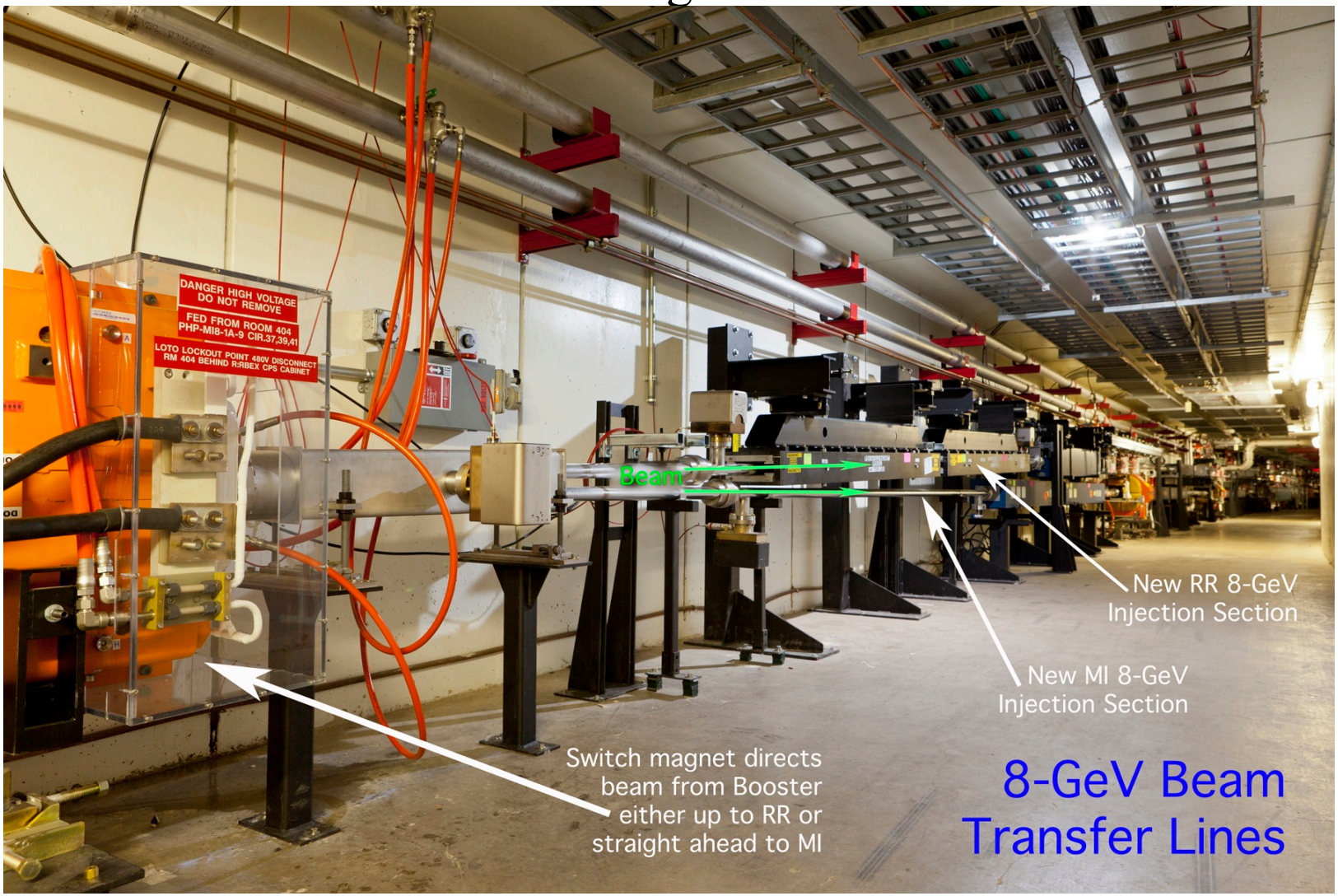
3d models of the transfer lines





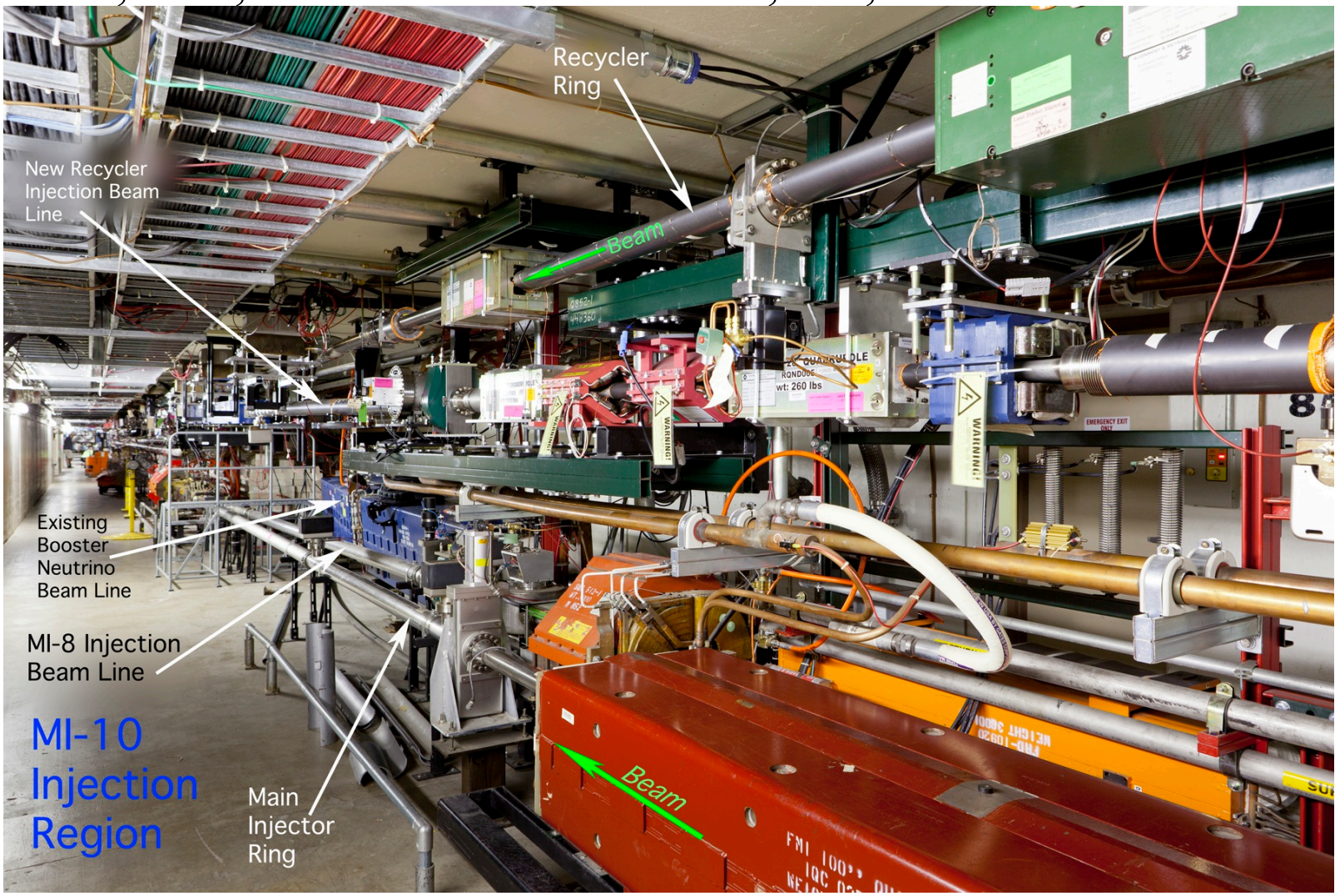
Upstream end of injection line

- Starts at the vertical switch magnet



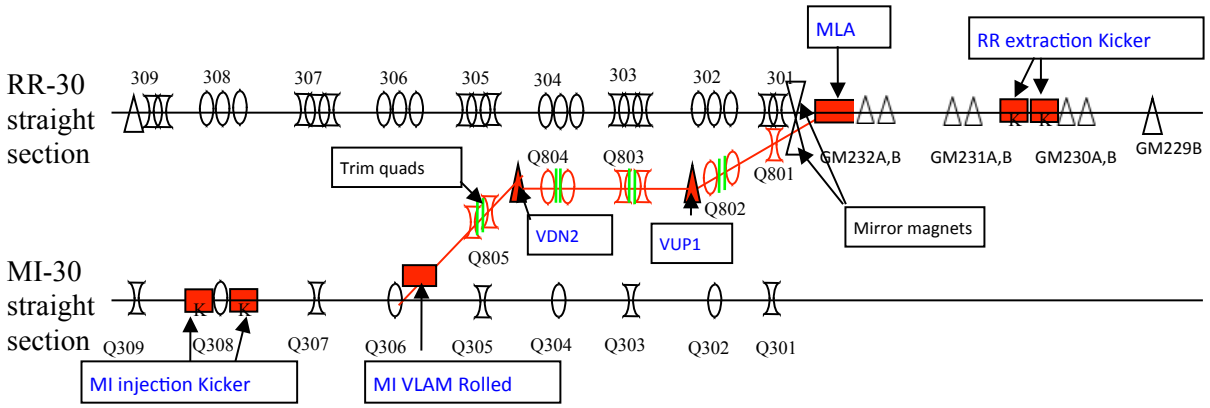
MI8 MI Crossover area

- RR8, MI8, Booster Neutrino Beam, RR, & MI



Extraction Line & RR 30

- Recycler 30 straight: location of electron cooling insert (removed)
- Rebuild to FODO lattice to look like rest of Recycler
- Extraction line from RR to MI



RR30 ECool area

- Major Decommissioning:
  - Removed electron cooling
  - Rebuilt shield wall
  - Rebuilt to look like the rest of the Recycler
  - Transfer line into Main Injector

Rebuilt shield wall

Electron beam lines from Pelletron to Recycler

~12 tons hand stacked concrete blocks

similar stack on other side of steel wall

Before

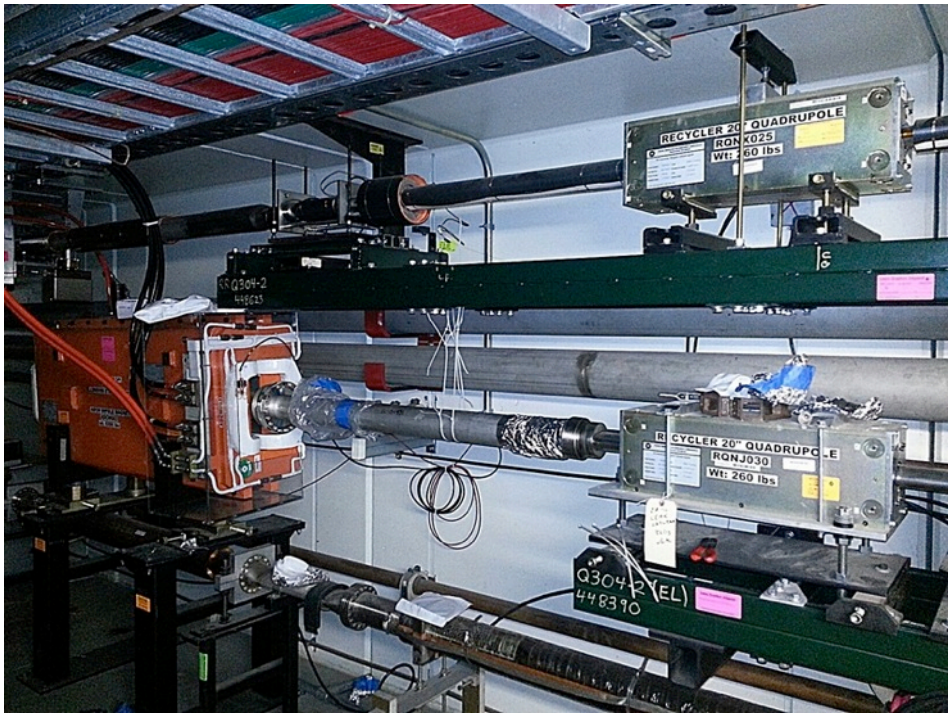
During

After

Extraction Line installation

- Mirror magnets at start of the transfer line
- During installation, lead shielding on MI magnets for ALARA

- Recycler, transfer line and Main Injector
  - Down bend (VDN2) is the orange magnet on the left

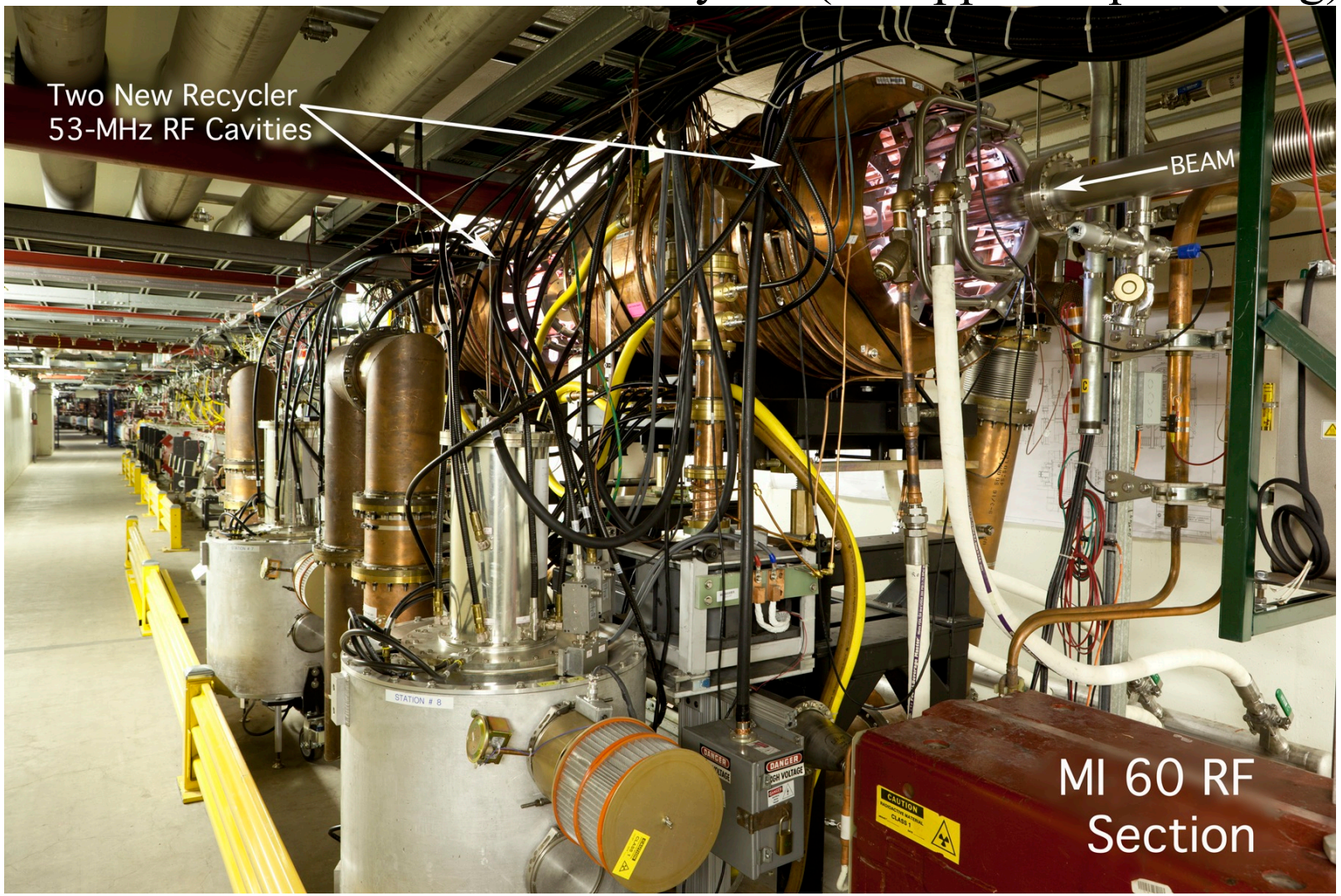


Abort region upgrades

- Cleanly abort unwanted beam from Recycler
  - Gap clearing kicker: 1.6 μsec to clear the injection gap
  - Full turn abort: 11 μsec to clear the ring

RR RF Upgrades

- 2 New 53 MHz cavities for Recycler (to support slip stacking)



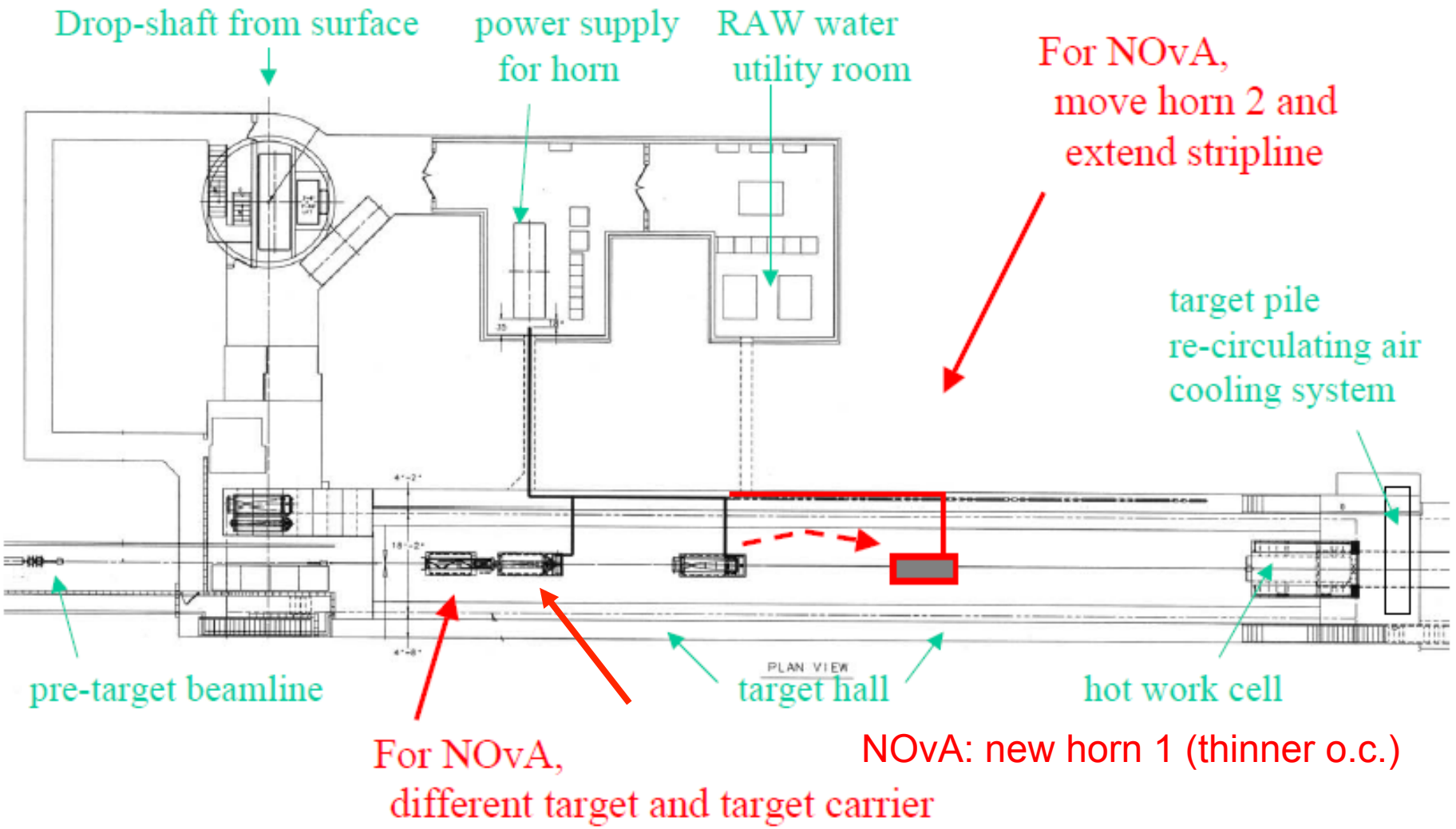
MI RF Upgrades

- 2 Additional 53 MHz cavities for Main Injector (18-> 20)
  - ion pump flipped up -> new cavity location

NuMI Beamline Changes

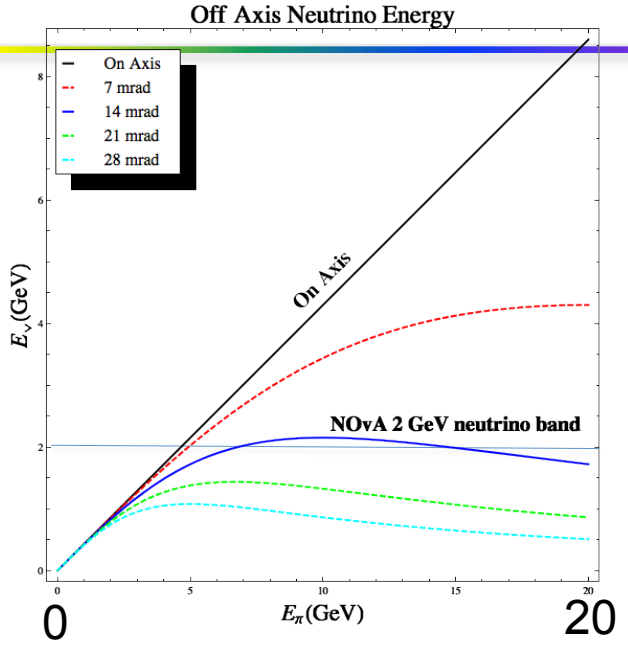
- Upgraded diagnostics: better understanding of beam
  - 12 new wire profile monitors
- Swapped magnets:
  - functionally identical but with better cooling
  - needed more cooling given the increase in frequency
- Upgrades to the power supplies
  - to handle the increase in frequency

Target Hall Upgrades

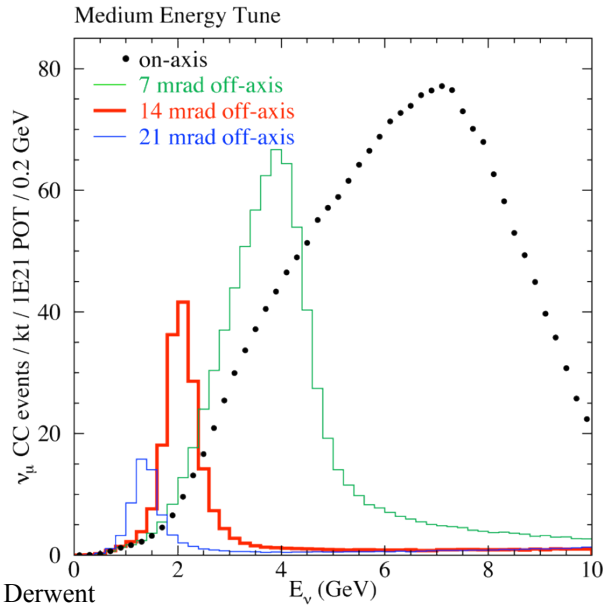


Off-axis neutrino beam

$$E_\nu = \frac{\left(1 - \frac{m_\mu^2}{m_{\pi,K}^2}\right) E_{\pi,K}}{1 + \gamma^2\theta^2}$$

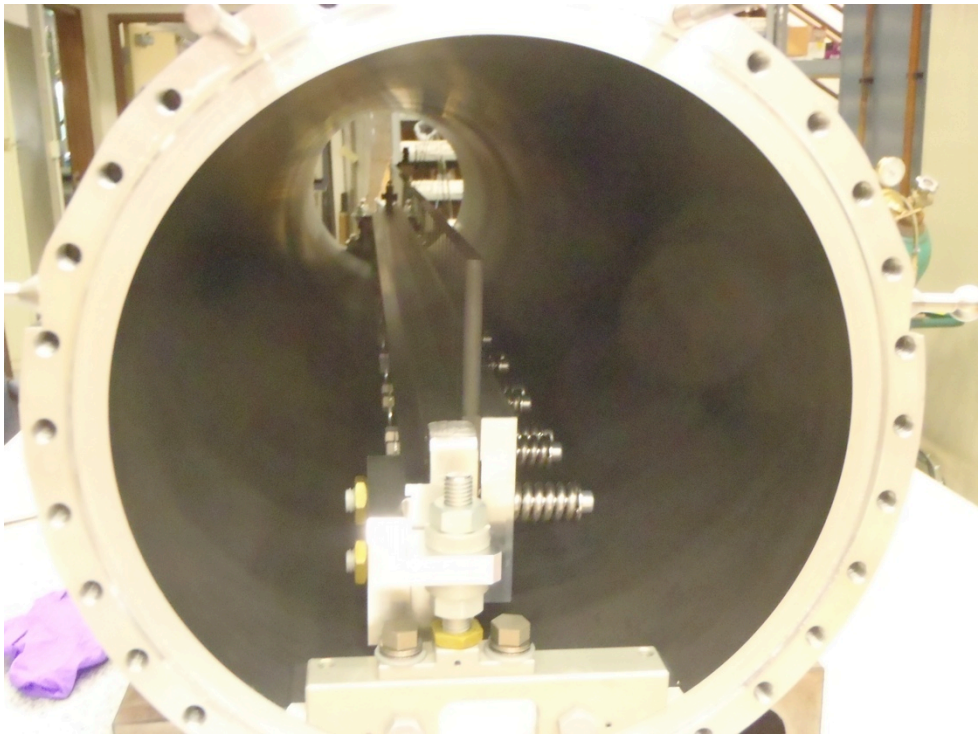


- Off-axis, neutrino energy driven by angle
- Adjust focusing to optimize flux
- Lower total flux, greater flux in energy band of interest



NOνA target

- NuMI target (top) must fit inside horn 1
- Geometry constrains design. NOνA target (right) upstream of horn 1 (neutrino energy from off-axis angle)
- Physics requirements allowed for changes in the design
  - mechanically more robust



Summary

- Series of upgrades to increase the protons on target
  - Use of the Recycler as proton accumulator
    - new transfer lines
    - 2 new RF cavities
  - Upgrades to MI to increase frequency
    - vertical quad bus supply
    - 2 additional RF cavities
  - Upgrades to NuMI Beamline to handle increased frequency
    - new power supplies and magnets
    - improved diagnostics
  - Changes in target station
    - physics requirements
    - handle increased power
- Goals:
  - 6e20 protons on target / year
  - peak power 700 kW