



Michel Sorel (Columbia University)  
for the MiniBooNE Collaboration  
NFWG Seminar, CERN, August 2002

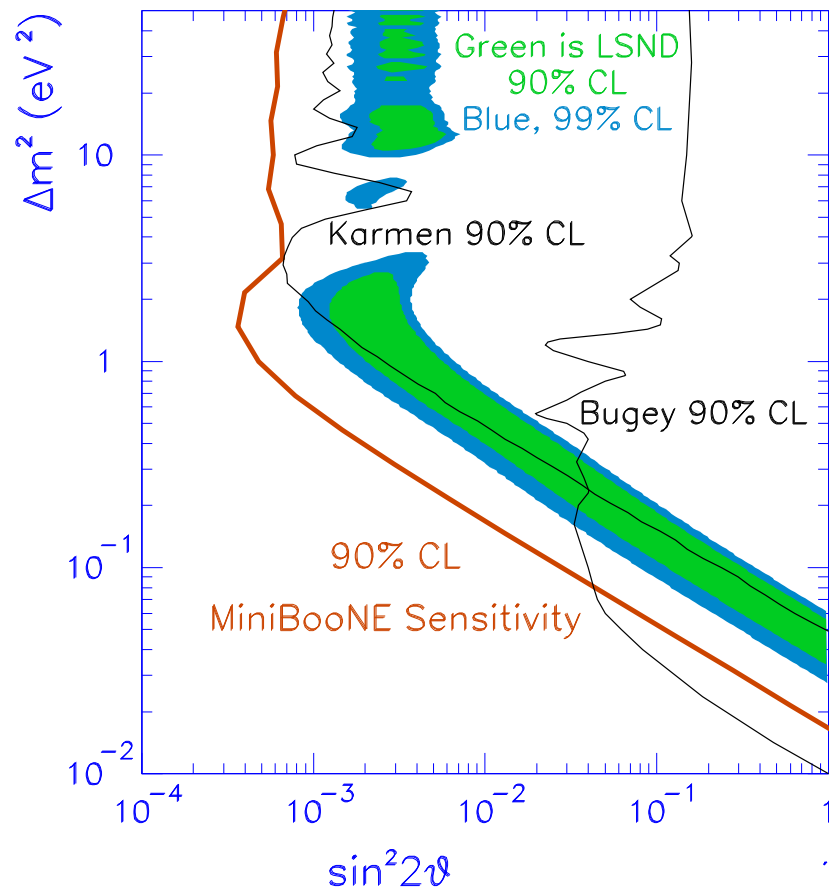
**MINIBOONE**  
ONE COOL HORN

# Outline

- Introduction: MiniBooNE and the BooNE beam
- MiniBooNE horn: physics motivations
- Design of the horn, striplines, power supply, horn cooling
- Highlights of horn construction and assembly
- Horn testing at the test facility
- Horn installation at the target hall
- Horn changeover (if needed...) and radioactive horn handling

# The MiniBooNE Experiment

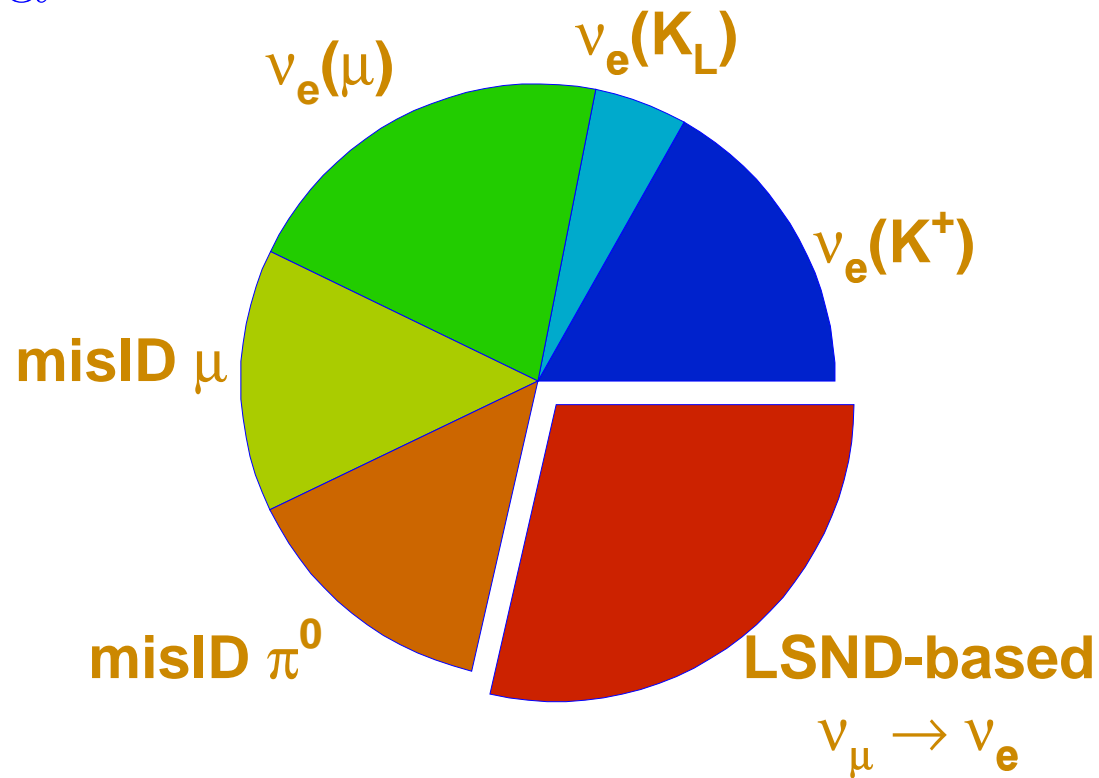
- MiniBooNE: Fermilab experiment to search for  $\nu_\mu \rightarrow \nu_e$  oscillations
- MiniBooNE will address in a **definite** and **independent** way the evidence for neutrino oscillations seen by the LSND Experiment



- **definite**: same  $L_\nu/E_\nu$  ratio as for LSND and enough statistics to cover the LSND region at the  $5\sigma$  level
- **independent**:  $E_\nu = 0.3 - 1.5$  GeV and  $L_\nu = 540$  m are both a factor of 10 larger than LSND, resulting in very different backgrounds to the oscillation search and systematics for the  $\nu$  flux and particle ID

# The $\nu_\mu \rightarrow \nu_e$ Oscillation Search

- Before any energy cuts:



# The $\nu_\mu \rightarrow \nu_e$ Oscillation Search (cont'd)

- Approximate number of expected events:



LSND-based  $\nu_\mu \rightarrow \nu_e$ : 1,000



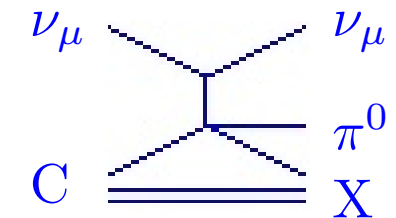
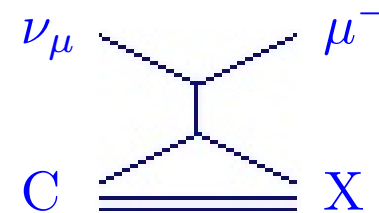
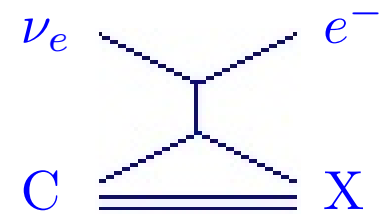
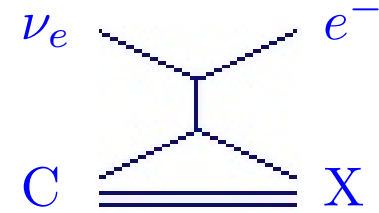
Intrinsic  $\nu_e$  bgr: 1,500



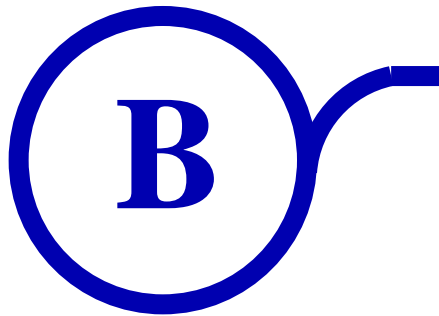
$\mu$  mis-ID bgr: 500



$\pi^0$  mis-ID bgr: 500



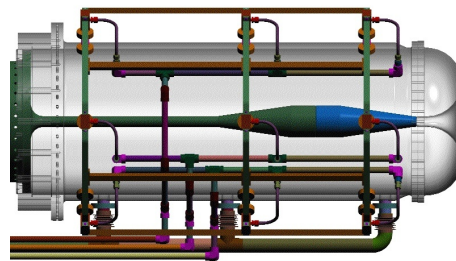
# The BooNE Beam



## Primary Beam:

high-intensity 8 GeV proton source from FNAL Booster.

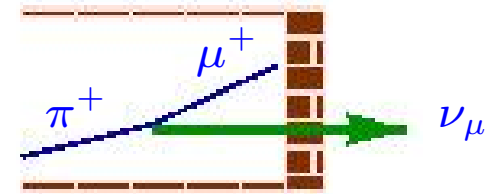
MiniBooNE requires  $10^{21}$  protons on target  $\Leftrightarrow$  2 years of running



## Secondary Beam:

protons strike a 71 cm beryllium target, producing secondary  $\pi^\pm$ 's,  $K^\pm$ 's.

Magnetic focusing of secondary beam from horn surrounding the target



## Neutrino Beam:

$\pi^+ \rightarrow \mu^+ \nu_\mu$  in the 25/50 m decay channel.

After absorber, almost pure  $\nu_\mu$  beam pointing towards the detector

# BooNE beam: physics-driven requirements

- Beamline is optimized to:
  1. maximize the  $\nu_\mu$  flux at 0.5-1 GeV
  2. minimize the  $\nu_\mu$  flux above 1 GeV
  3. minimize the  $\nu_e$  flux
  4. understand well the systematics of the  $\nu_e$  flux
- Without any magnetic focusing device, it would take MiniBooNE  $\sim 15$  years of running in order to reach the desired sensitivity!!
- Ideally, the magnetic focusing system should produce a nearly-parallel pion beam in the decay region with the right energy to produce 0.5-1 GeV neutrinos

# People involved in the MiniBooNE horn project

- K. Anderson
- L. Bartoszek (Bartoszek Engineering)
- L. Bartelson
- L. Bugel
- C. Jensen
- I. Kourbanis (project manager)
- H. Le
- B. Markel (Markel & Associates)
- J. Misek
- F. Nezrick
- H. Pfeffer
- R. Reilly
- D. Schmitz
- D. Snee
- M. Sorel
- R. Stefanski
- E. Zimmerman



# MiniBooNE Horn Design: Unique Requirements

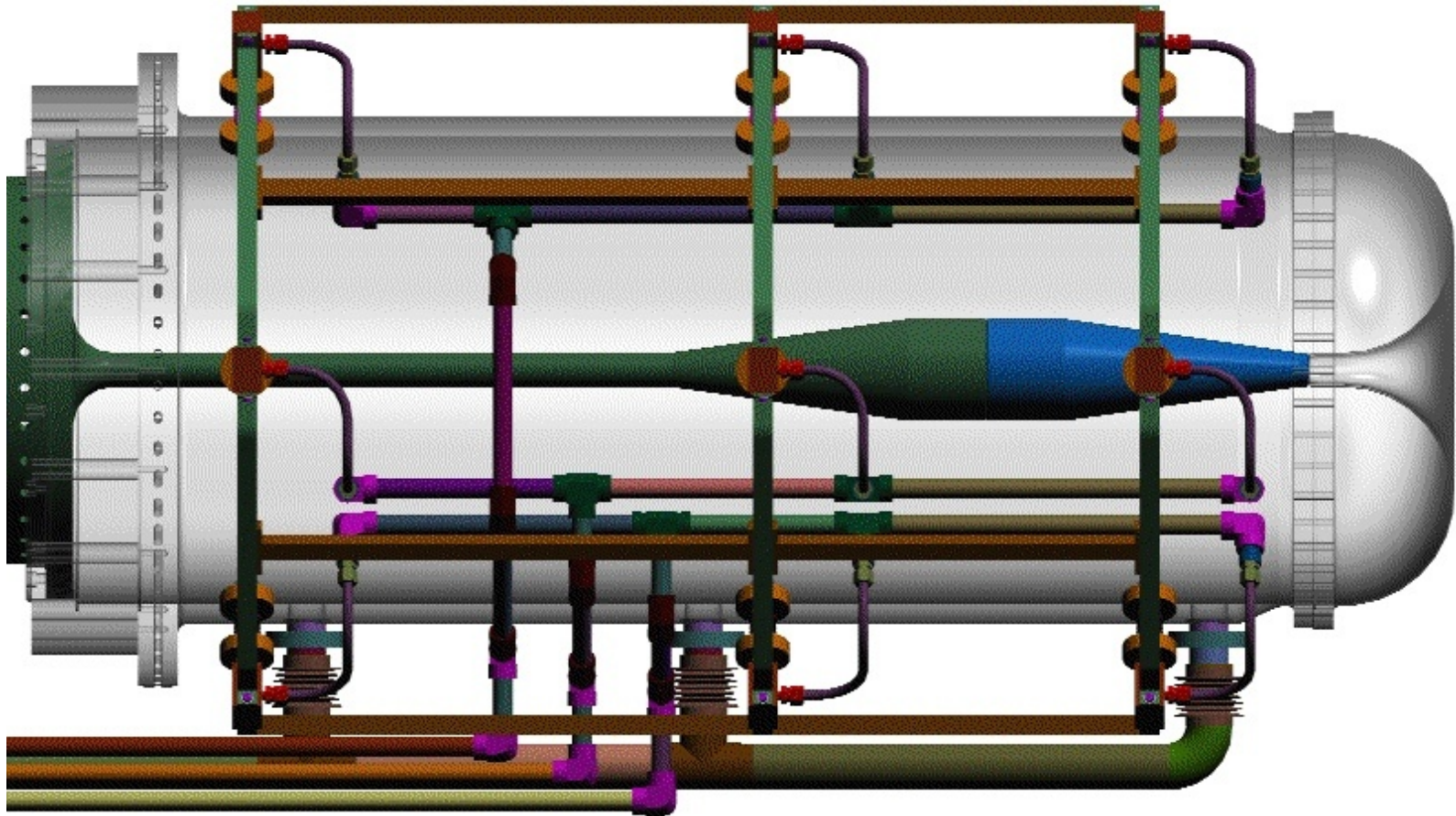
- Physics-driven requirements for the magnetic focusing system:
  1. large angular acceptance for  $\pi^\pm$
  2. large momentum acceptance for low-energy  $\pi^\pm$
  3. sign selection: focus either  $\pi^+$  or  $\pi^-$ , by inverting the power supply polarity

⇒ horn appears to be the best choice
- Additional requirements:
  1. very high repetition rate, up to 15 Hz
  2. design life of  $2 \cdot 10^8$  current pulse cycles, to keep the number of horns needed to do the experiment to two at the most
  3. material with high electrical conductivity and low residual radioactivation

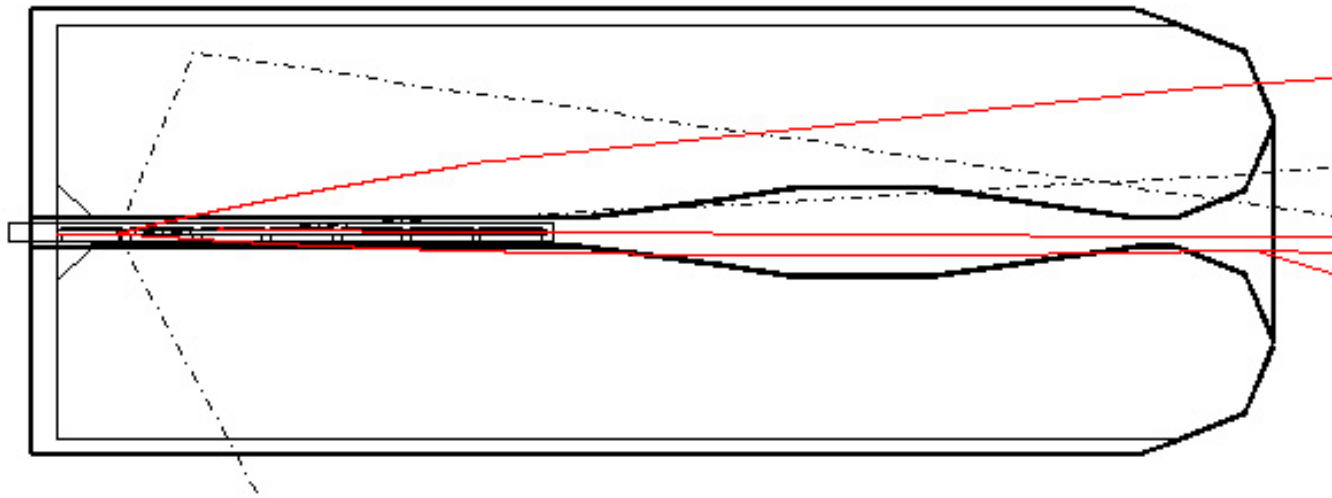
# MiniBooNE Horn Characteristics

- A horn contains a toroidal magnetic field in the volume between two coaxial conductors
- Current flows along the inner conductor and back along the outer conductor.
- In MiniBooNE, the inner conductor is of conical shape, with a radius varying between 2.2 and 6.54 cm. The outer conductor is of cylindrical shape, with a radius of 30 cm. The horn material is Al alloy 6061-T6.
- The horn is 1.85 m long
- The horn is excited by a 143  $\mu s$  long, half-sinusoidal current pulse. The peak current is 170 kA.
- The horn operates at an average rep rate of 5 Hz. The total average power deposited in the horn is 2.4 kW.
- The horn is cooled by spraying water on the inner conductor ( $\sim$  1 liter per second)

## 3-D Model of the Horn

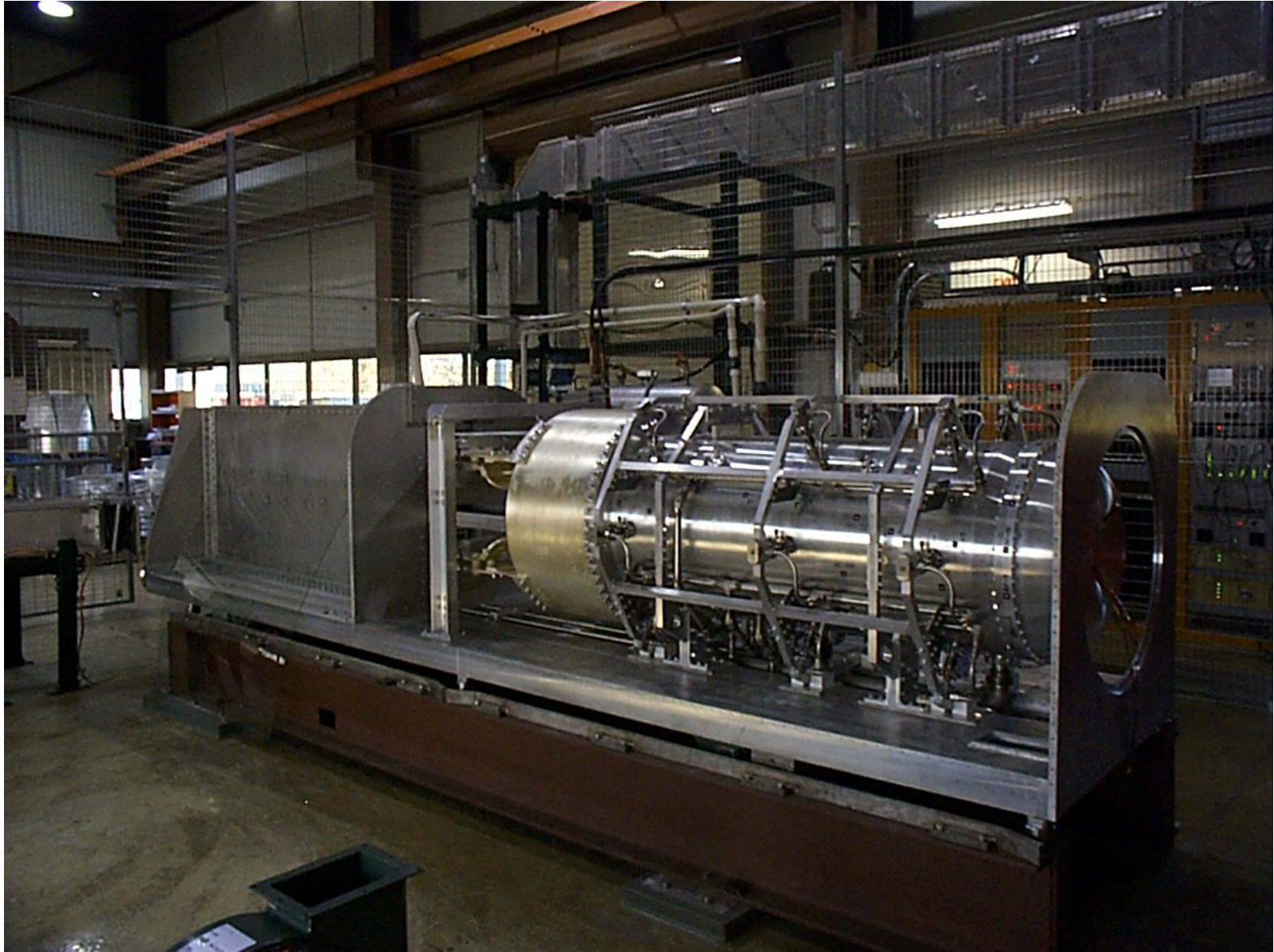


# Particle Trajectories in the Horn

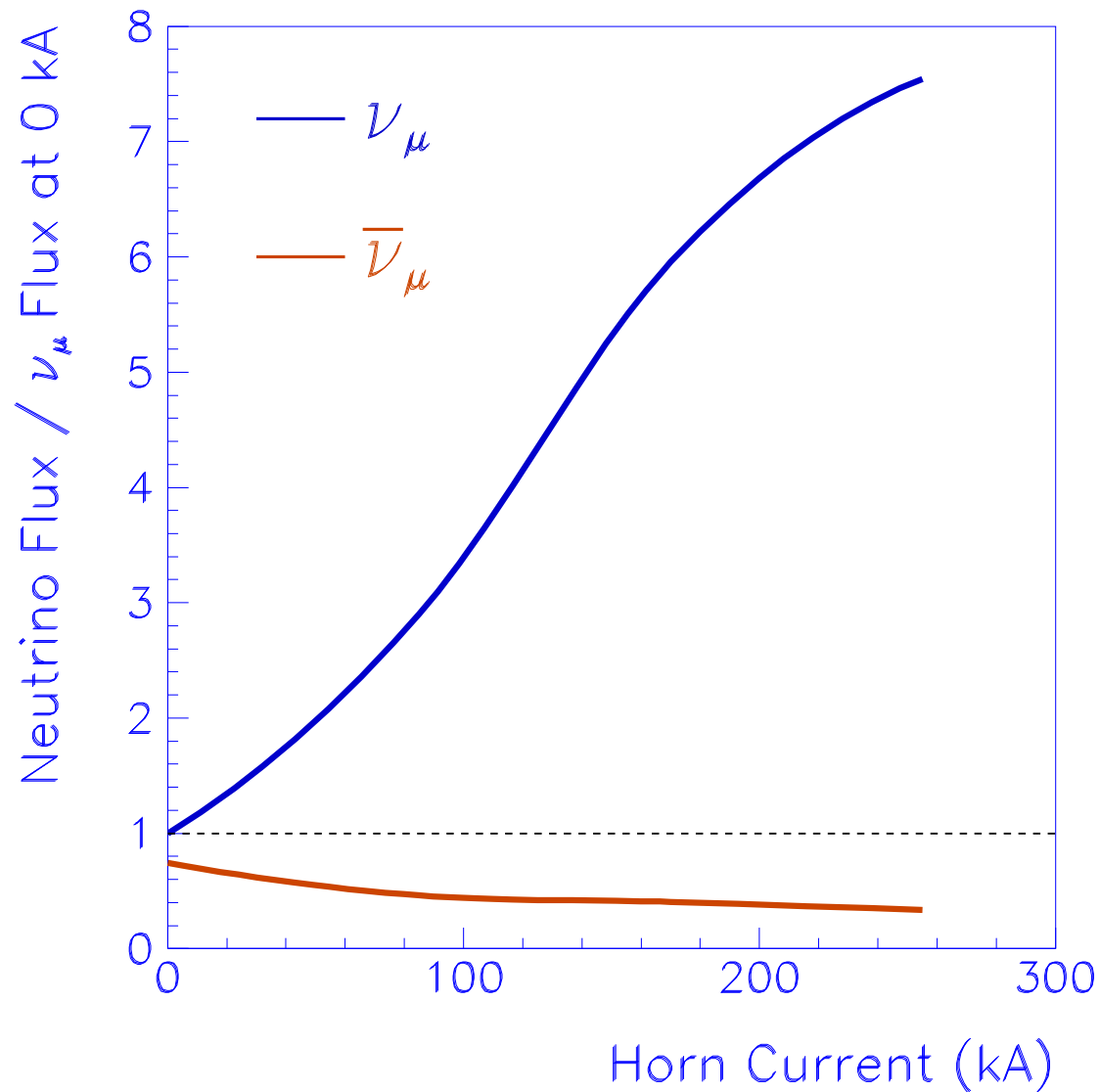


- Red tracks: charged particles
- Black tracks: neutral particles

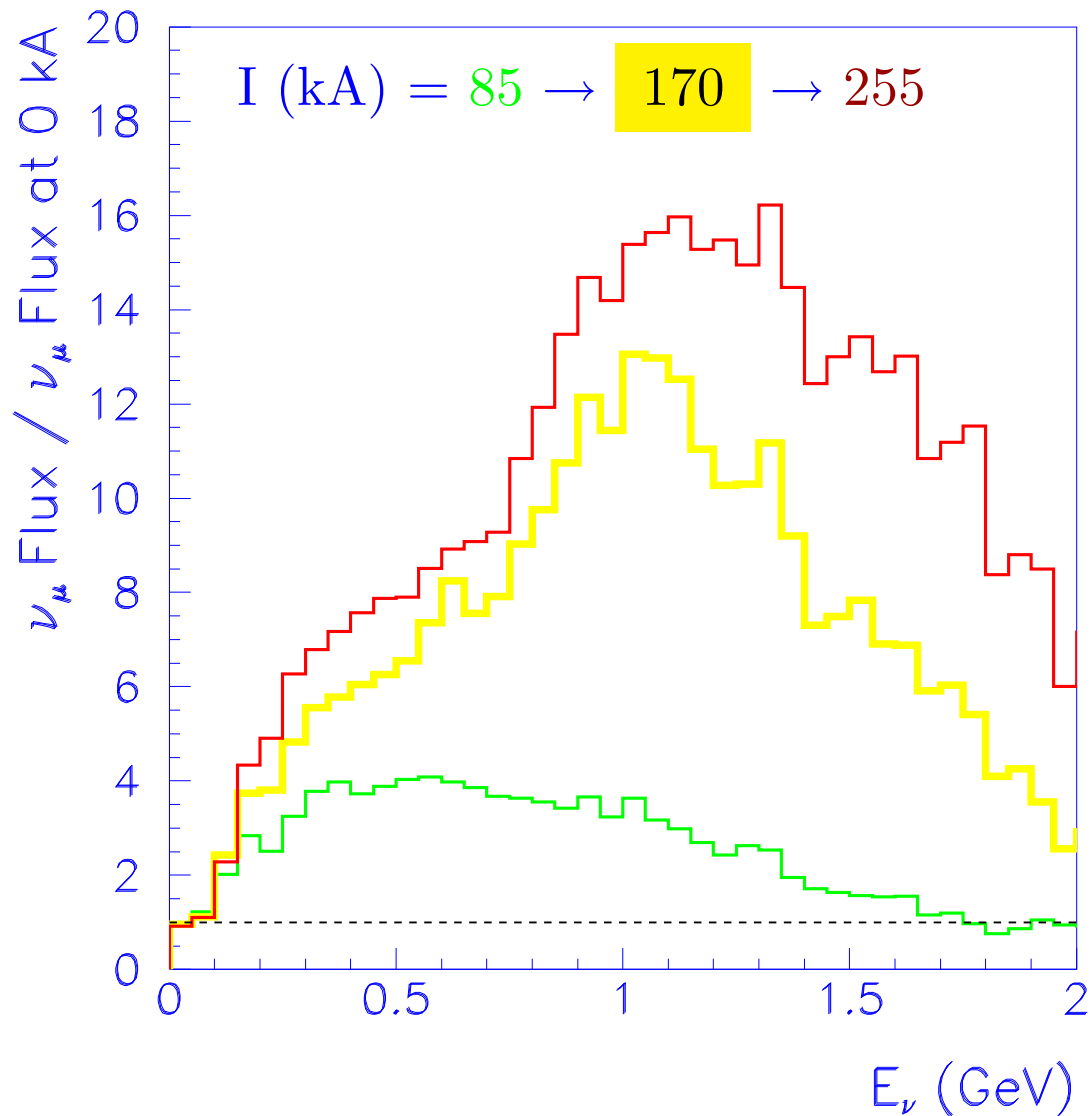
# Horn Module Overview



# Simulated Neutrino Flux at the MiniBooNE Detector: horn focusing factor and sign selection

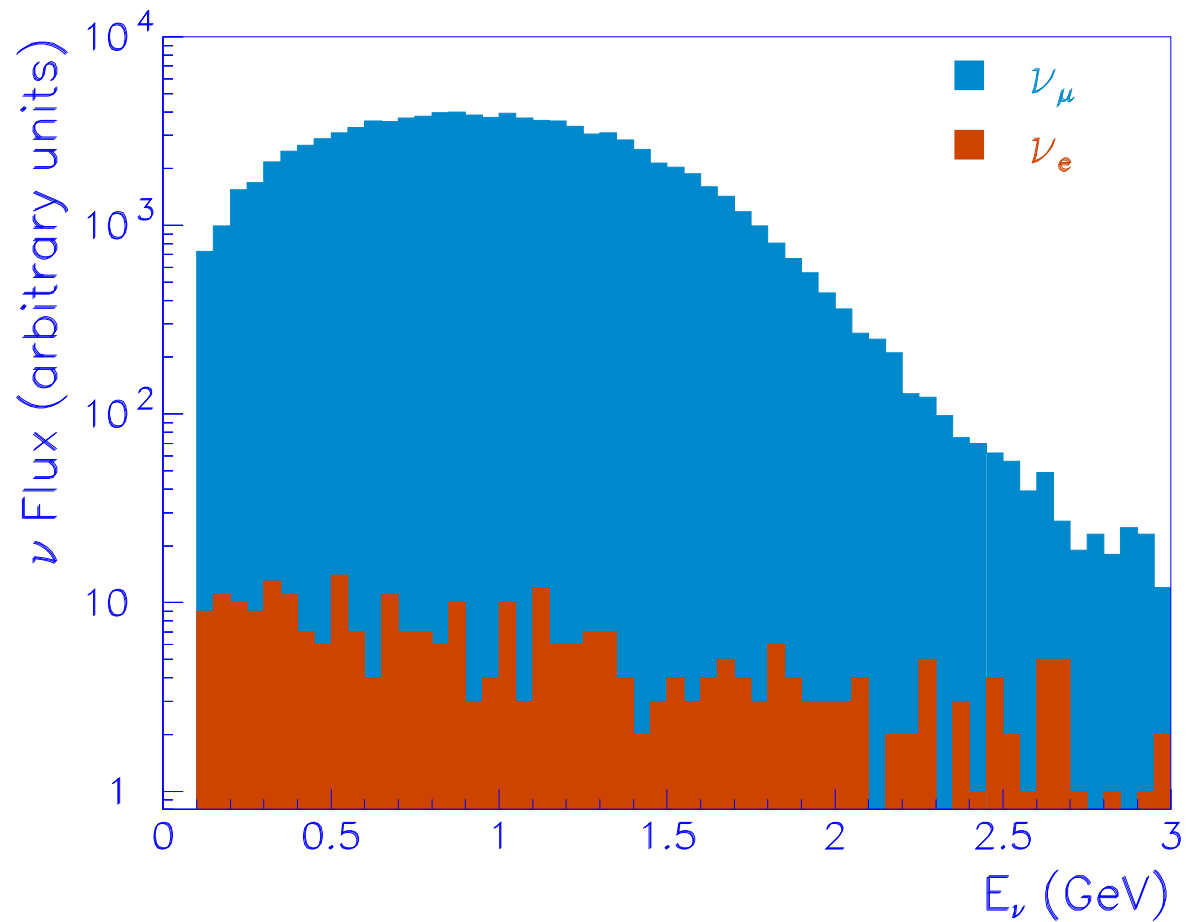


# Simulated Neutrino Flux at the MiniBooNE Detector: Neutrino Energy and Horn Current



# Neutrino Fluxes at the Detector with a 170 kA Horn

- 0.3-1.5 GeV  $\nu_\mu$  flux with very low (0.3%)  $\nu_e$  contamination:

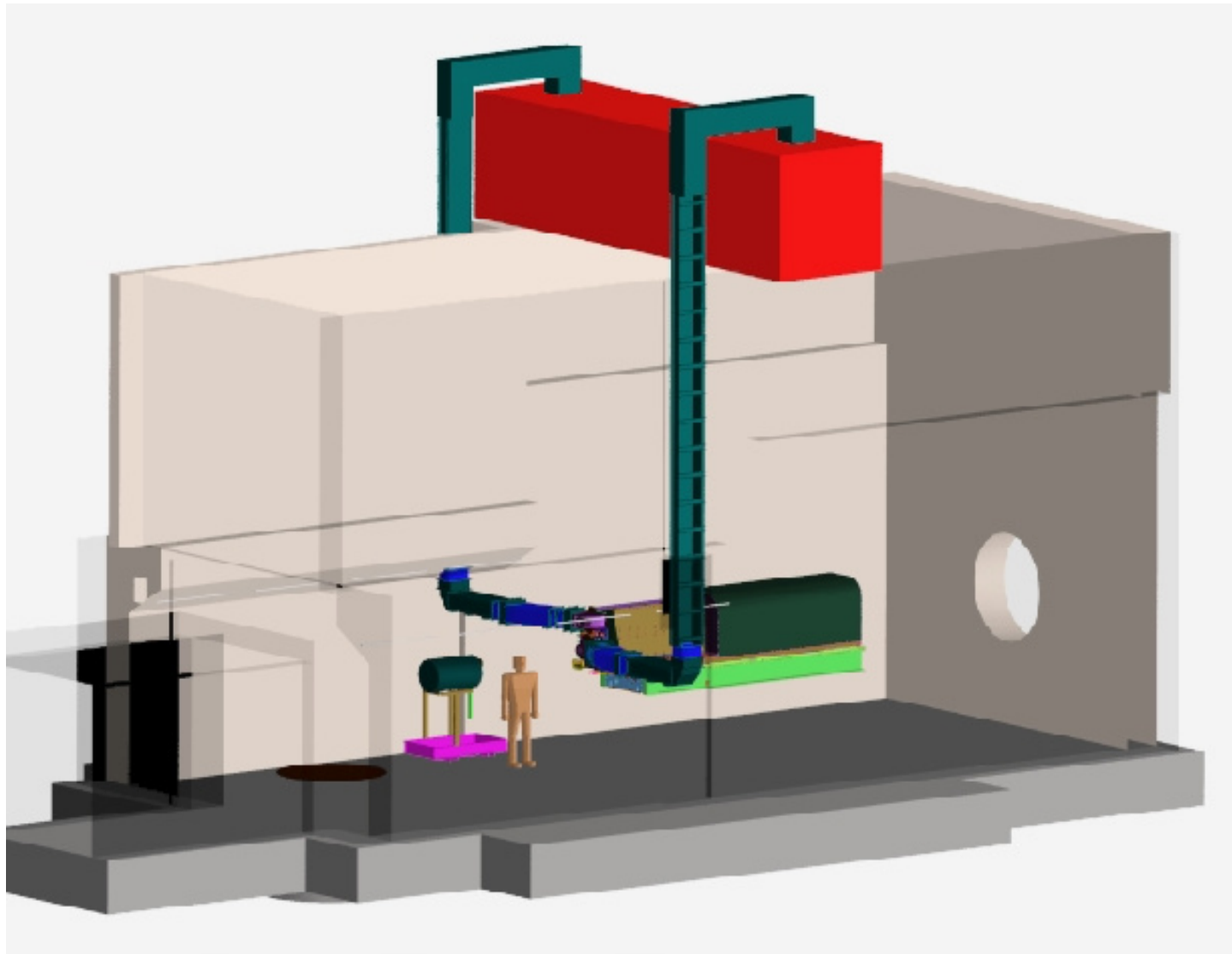




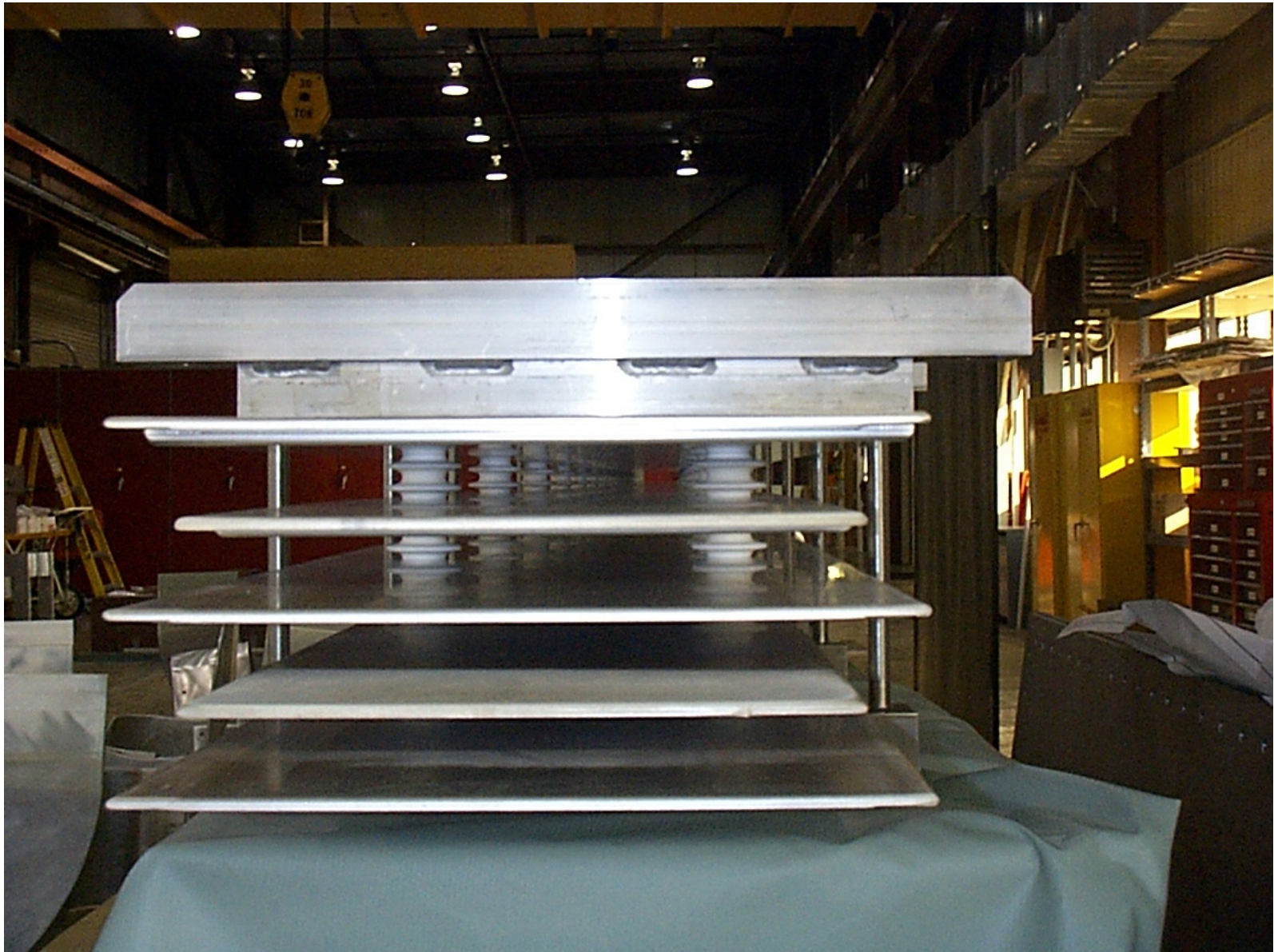
# Horn Striplines

- Striplines: current transmission lines between the power supply and the horn.
- MiniBooNE striplines are air-cooled aluminum plates.
- Two 20 m long striplines, each with a long and a short section
- Balanced design, that is with an odd number of conductors per stripline, and with adjacent plates seeing opposite current flows. This is to minimize forces.
- The plates spacing is 2.5 cm. Fluted alumina insulators with a 5.0 cm creepage length were used to separate the conductors.
- The striplines were corona tested
- Flat design made to minimize the striplines inductance

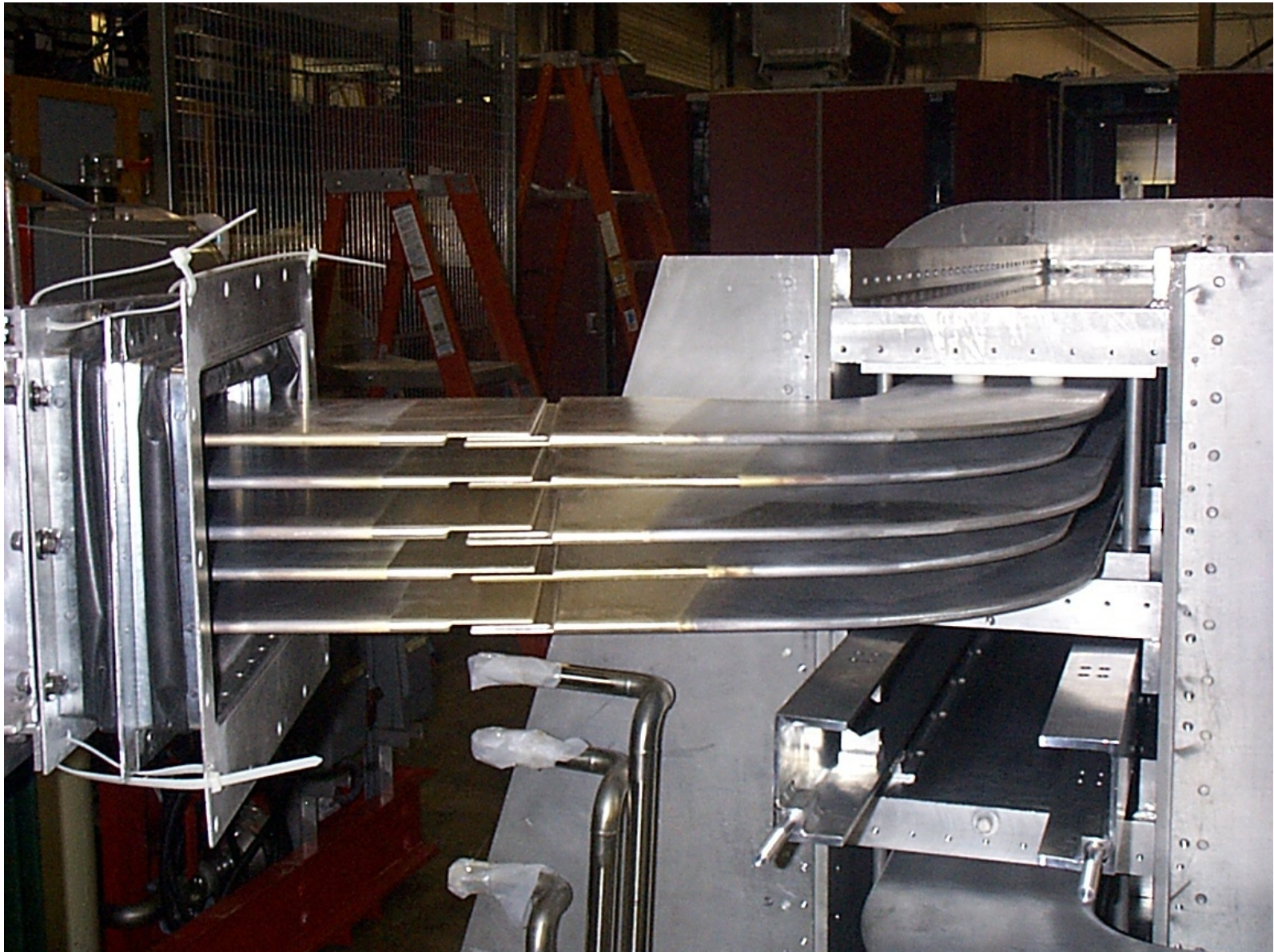
# Striplines connecting the power supply to the horn



## View of a Stripline



## View of a Stripline Joint

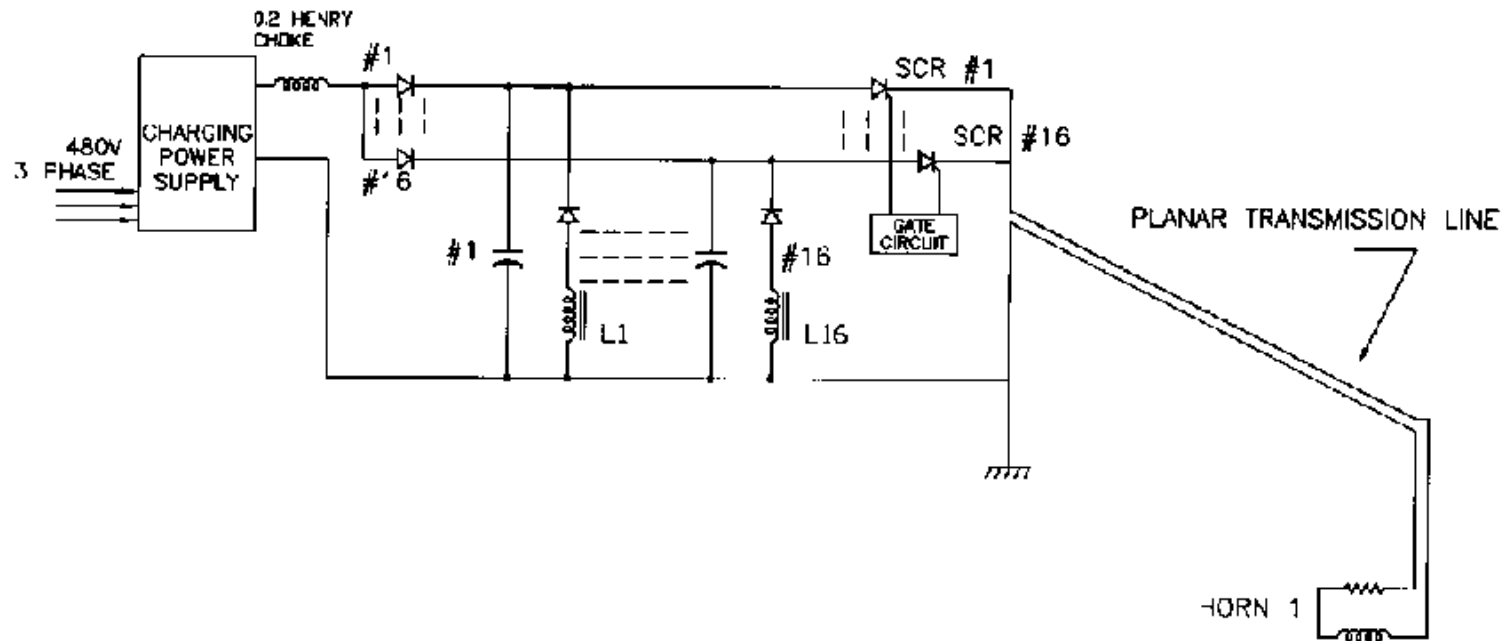


# Horn Power Supply

- Energy is stored in a capacitor bank ( $1,344 \mu F$ ) and switched via silicon controlled rectifier (SCR) switches into the horn load
- A short current pulse width of  $143 \mu s$  was chosen to keep the power supply operating voltage under 10 kV and to reduce excessive heating of the horn
- The system is divided into 16 parallel capacitors, each with its own SCR switch
- The system has a separate circuit for energy recovery
- Circuit parameters for 170 kA, 5 Hz operation:

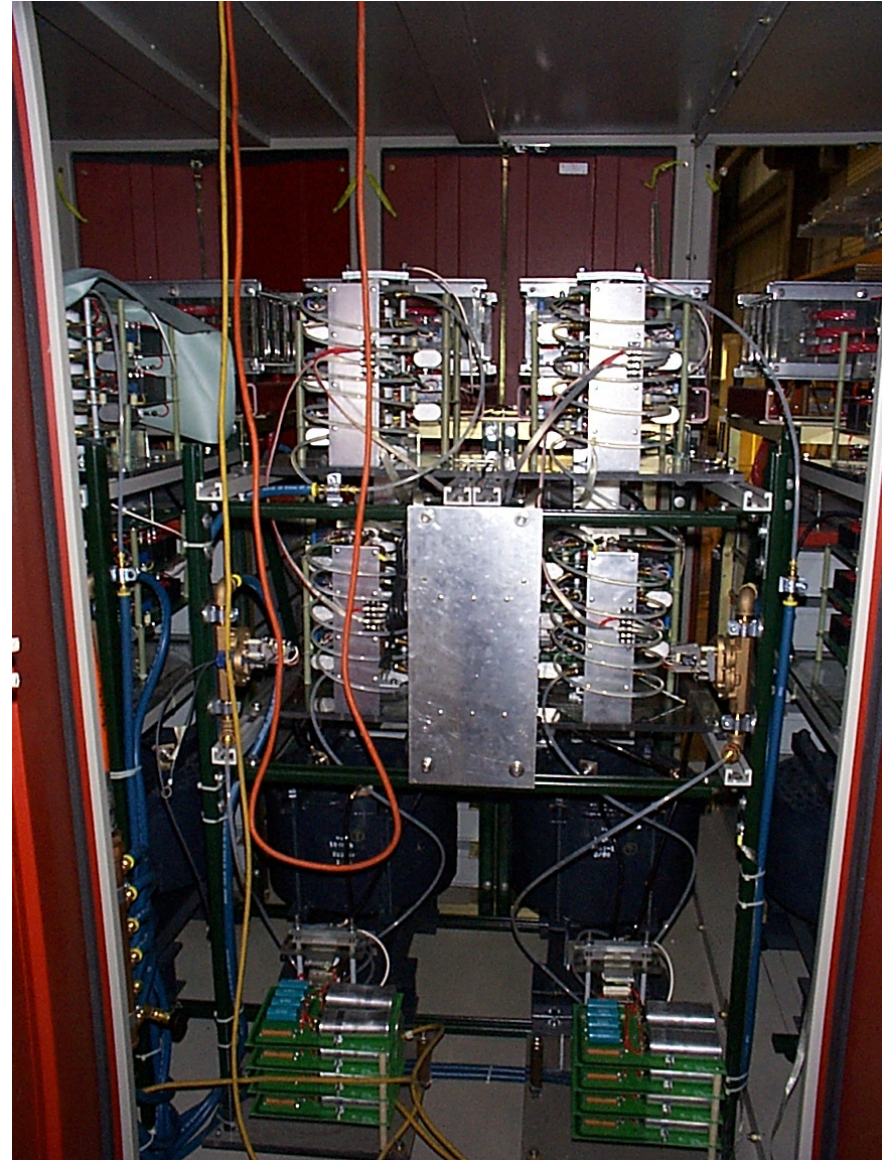
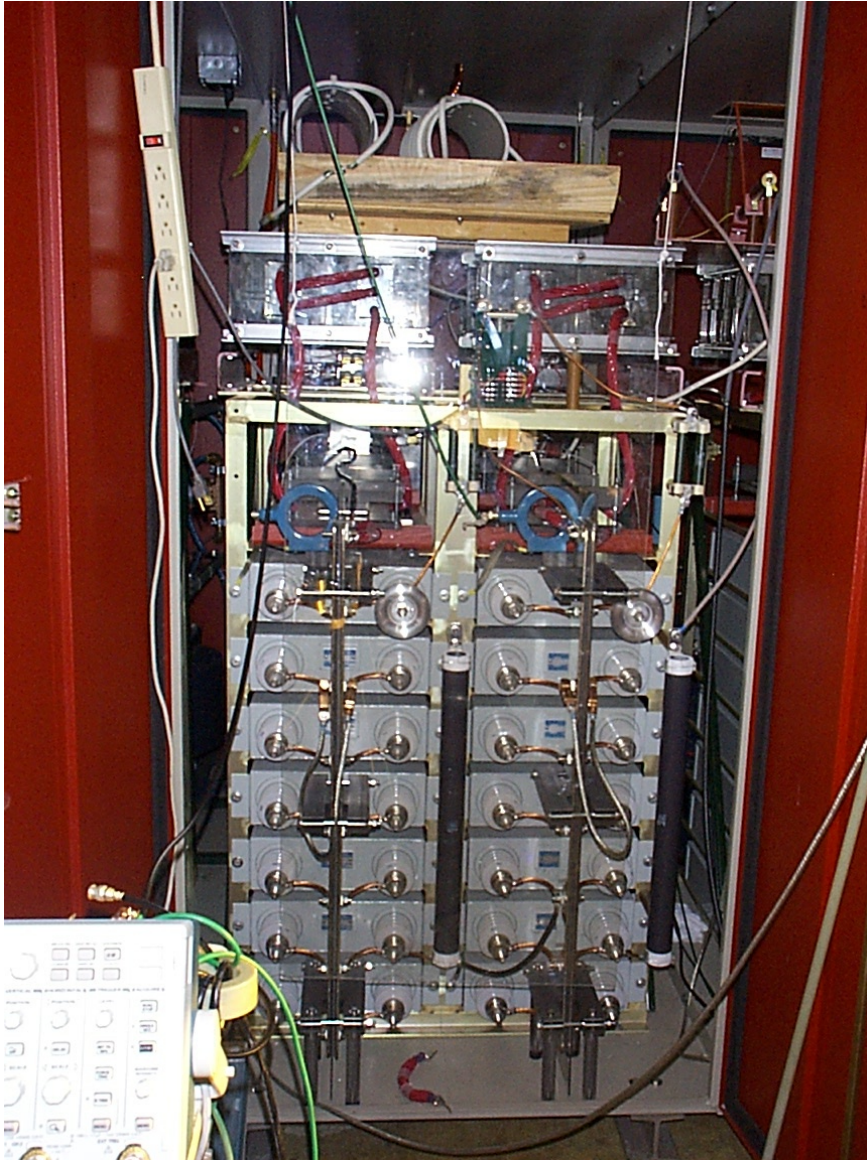
Component	Inductance	Resistance	Power
Horn	$0.70 \mu H$	$0.24 m\Omega$	$2.4 kW$
Stripline (20 meters)	$0.26 \mu H$	$0.50 m\Omega$	$5.0 kW$
Capacitor Bank plus losses	$0.37 \mu H$	$3.0 m\Omega$	$30 kW$
Total	$1.33 \mu H$	$3.74 m\Omega$	$37.4 kW$

# Power Supply Schematic and Mode of Operation



1. The capacitor bank is initially charged to 6 kV, appropriate to deliver 170 kA output current
2. Upon command from the SCR switch, the stored energy is switched into the horn load
3. After the discharge, the capacitor bank has reversed its polarity
4. To recover this energy, the capacitor bank is allowed to “ring” through a separate inductor via diodes, after which the capacitor bank polarity is in the forward direction
5. The energy lost from the capacitor bank is replaced by the charging power supply in time for the next discharge cycle to begin

# Power Supply View



# Horn Construction and Assembly Highlights

- Forged horn outer conductor
- Horn water cooling: the water spraying system is vibration isolated from the outer conductor, and has its own support structure
- Solid twist transitions, to connect the flat striplines to the cylindrically symmetric horn
- The horn inner conductor was welded at Fermilab using a programmable TIG welding machine



## Outer Conductor after Forging



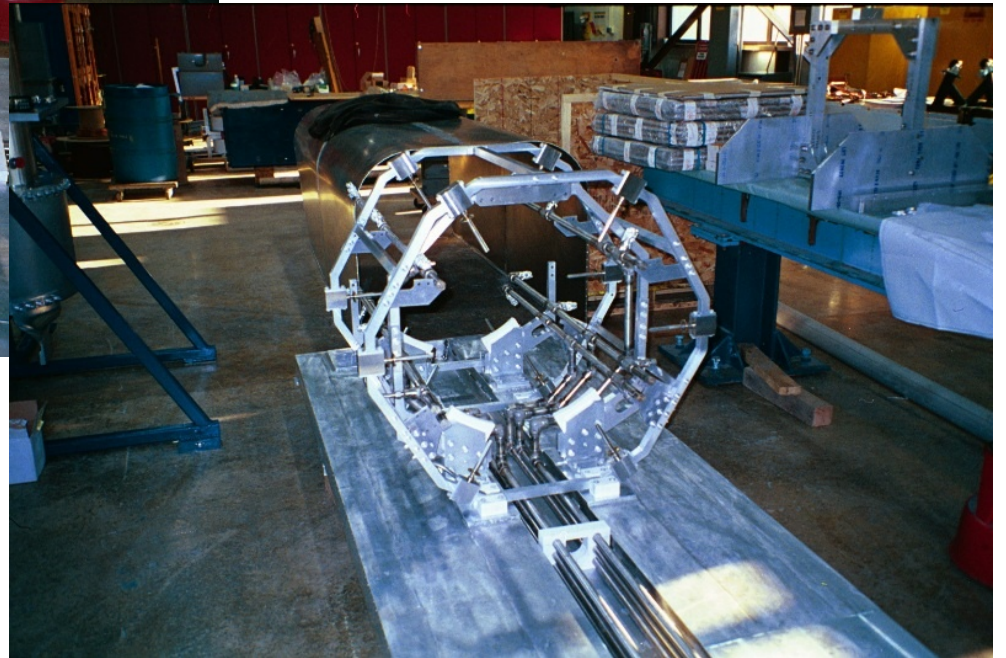
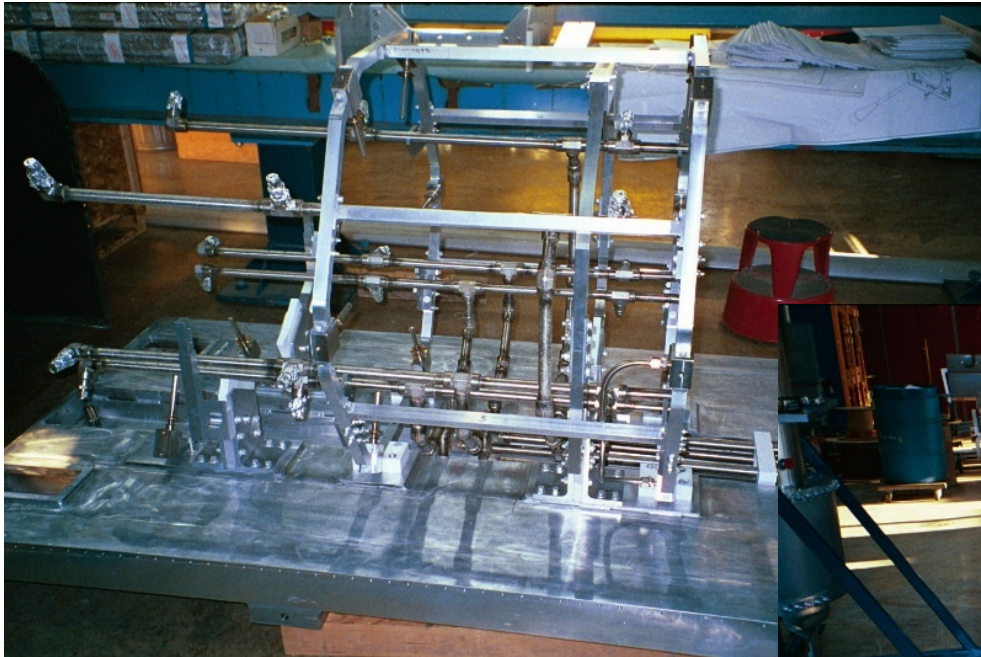
# Outer Conductor after Machining



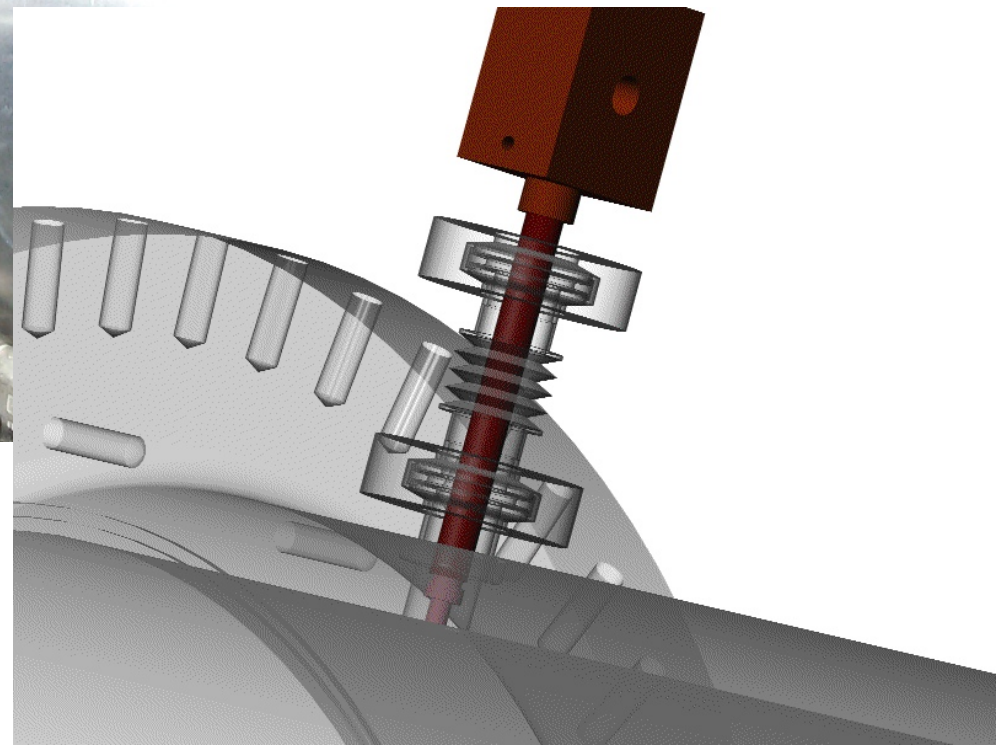
# Outer Conductor after Welding



# Horn Cooling: Support Structure and Water Manifolds



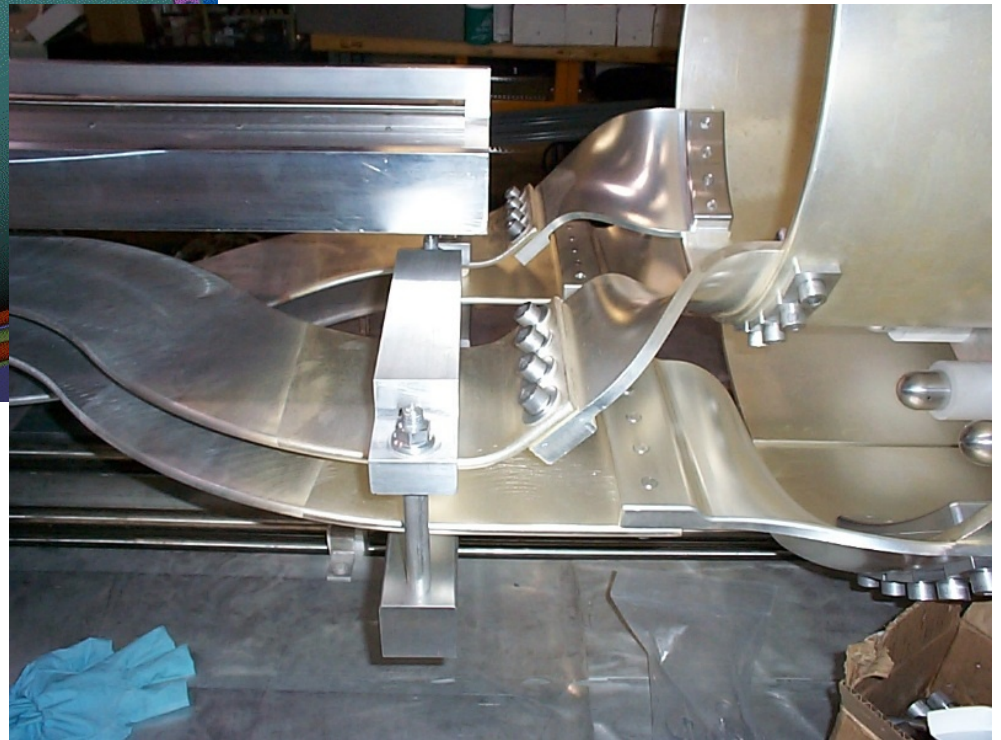
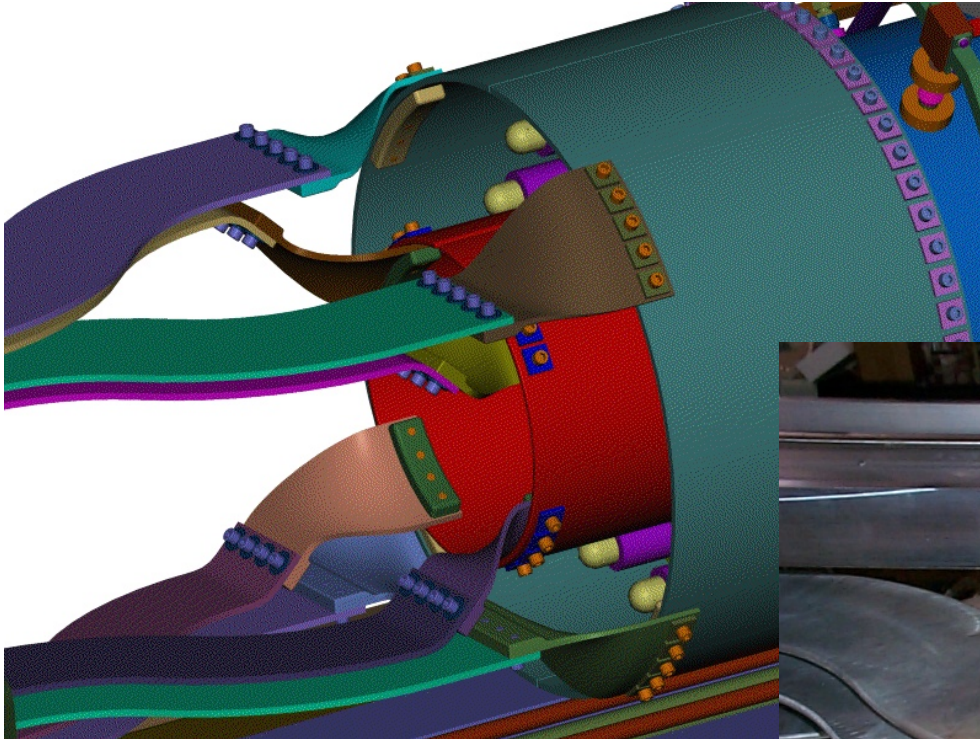
# Horn Cooling: Details of a Vibration Isolation Bellows and Nozzle



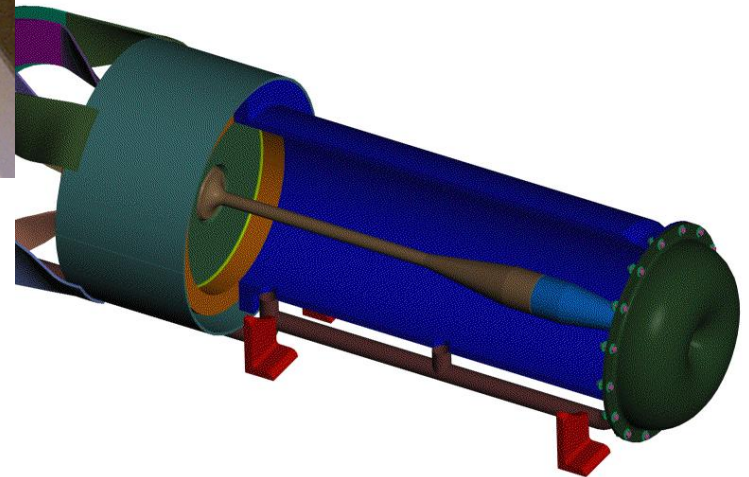
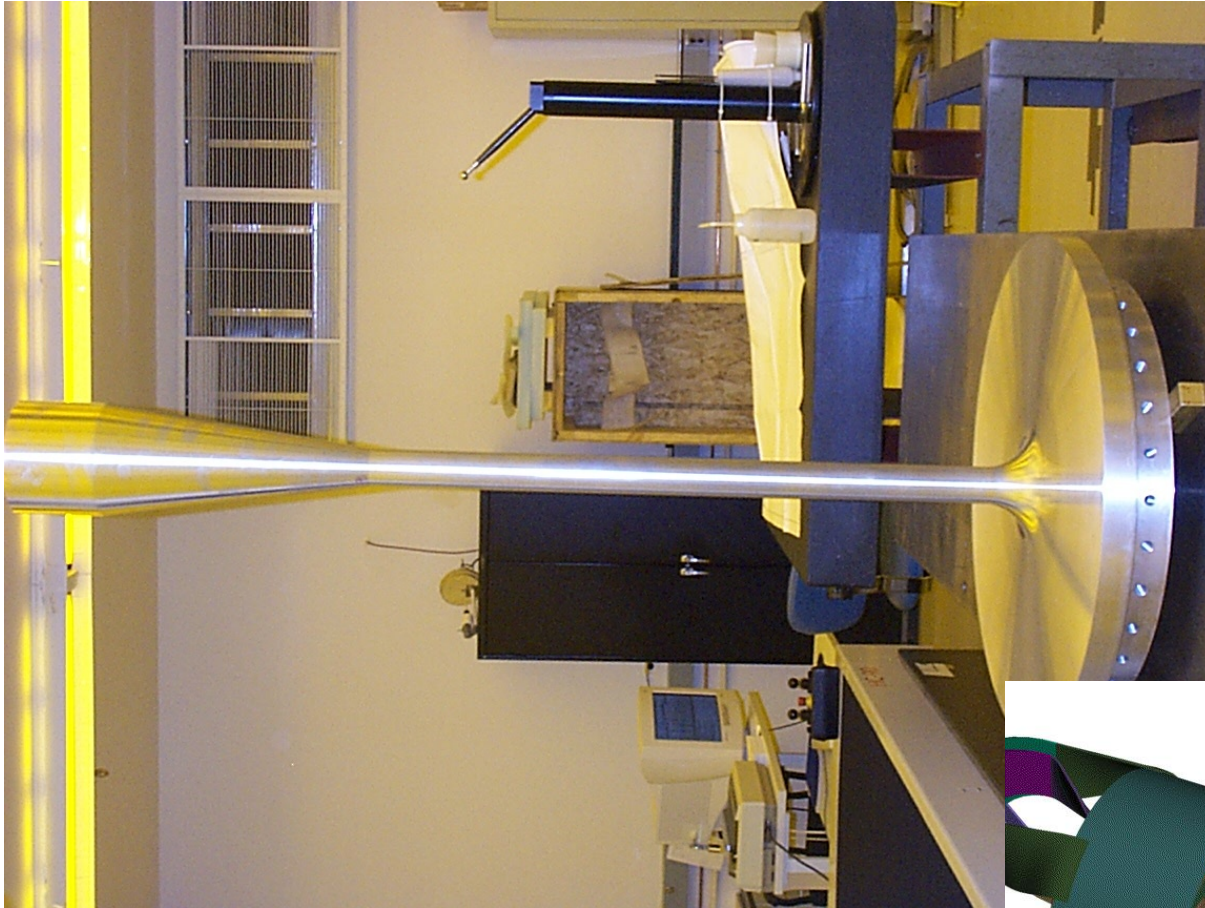
# Outer Conductor with Cooling System



# Twist Transitions

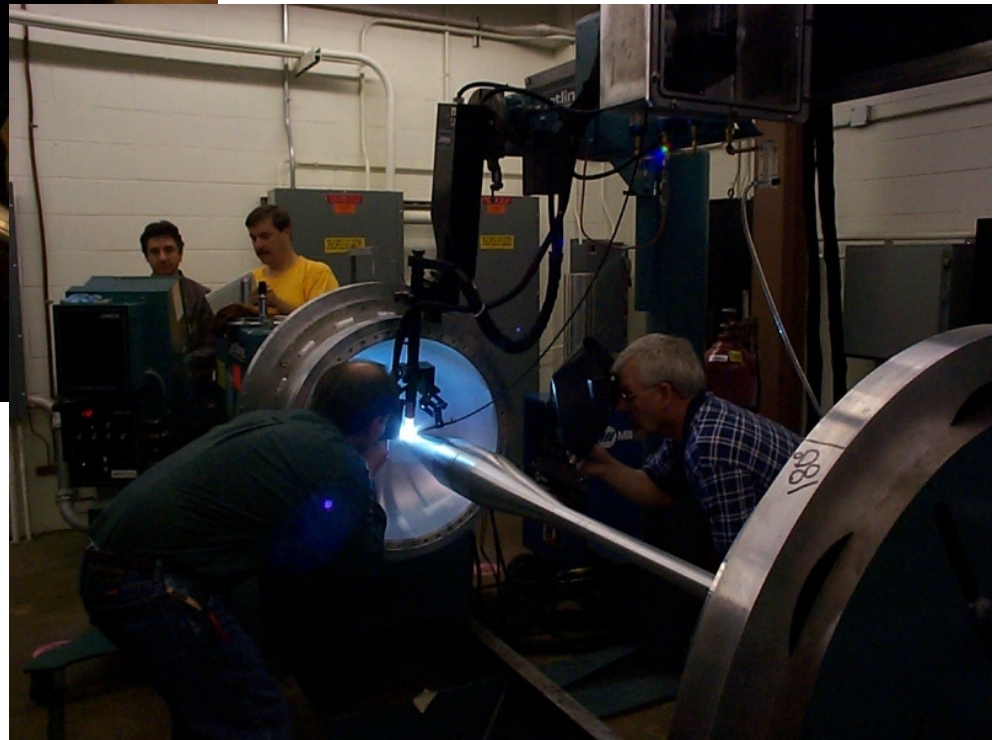
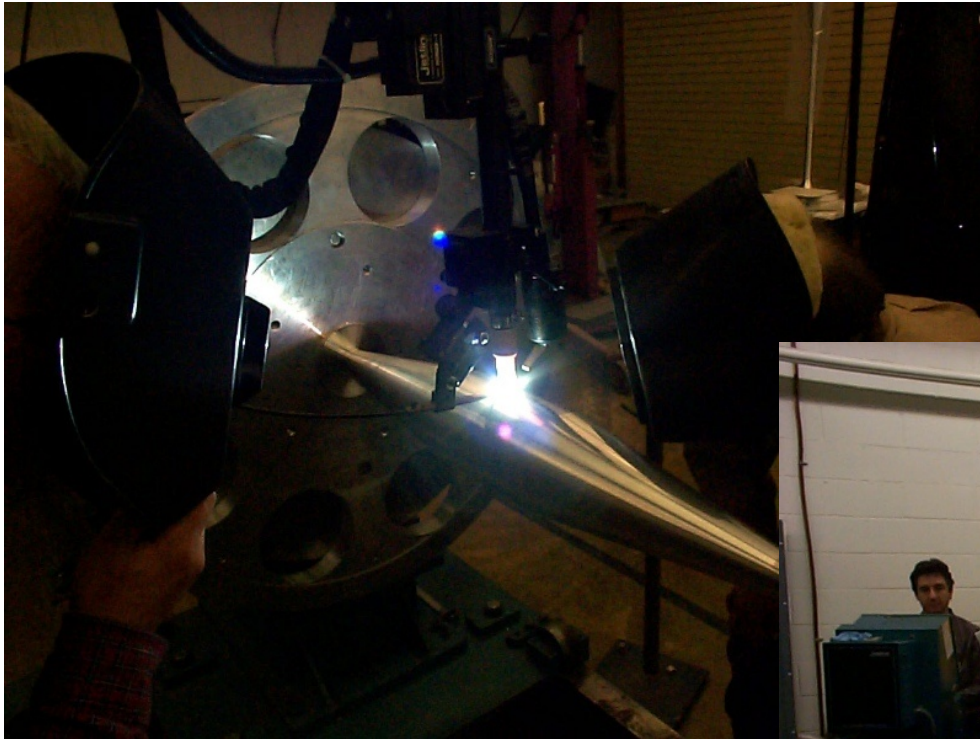


# Inner Conductor before Welding





# Inner Conductor Welds



# Radiography of Large Weld



# Inserting the Inner into the Outer Conductor



# Horn testing

- We tested the MiniBooNE horn system at the MI-8 Test Area between Jul-01 and Feb-02
- What we tested/measured:
  1. Power supply operation
  2. Horn water cooling
  3. Horn magnetic field
  4. Horn vibrations and mechanical stresses
  5. Long-term operation

# Overview of MI-8 Horn Test Area



# Current and Voltage Profiles



## HORN MONITORING SYSTEM

Date

07/31/2001

Write

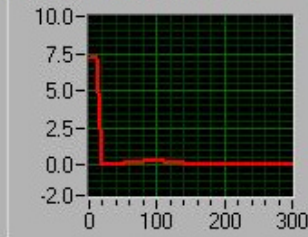
Outside Range

Time

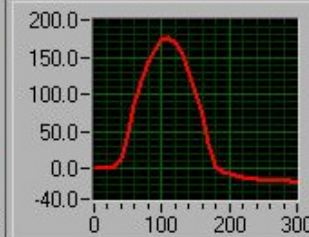
11:44:27 AM



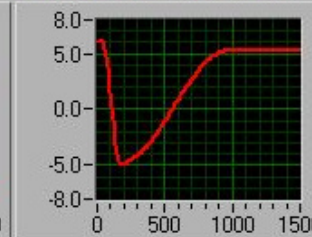
POWER SPLY TRG (V)



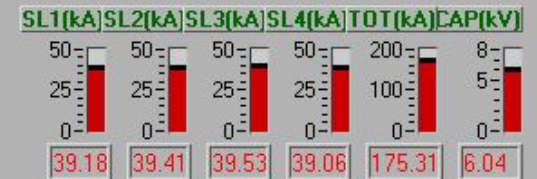
HORN CURRENT (kA)



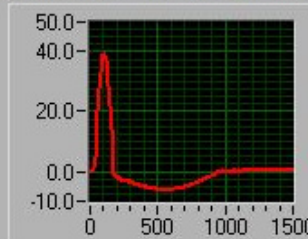
CAP BANK VOLTAGE (kV)



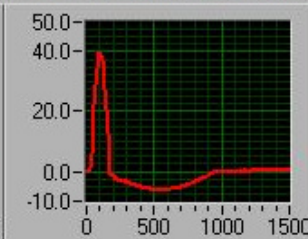
### PEAK VALUES



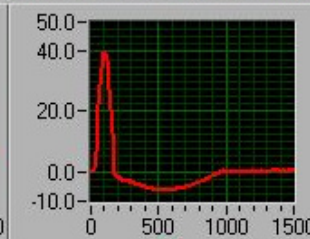
STRIPLINE 1 CURRENT (kA)



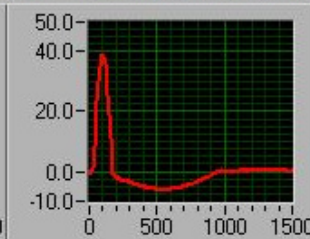
STRIPLINE 2 CURRENT (A)



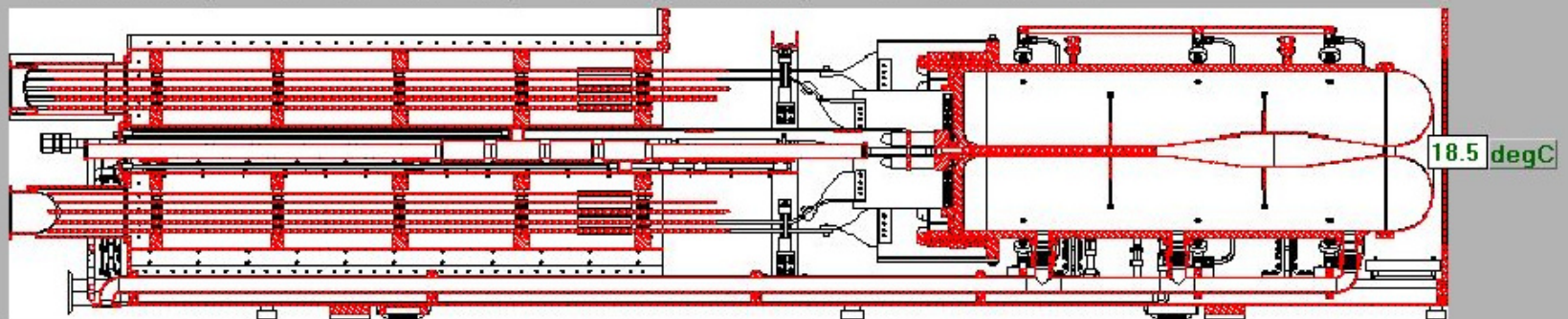
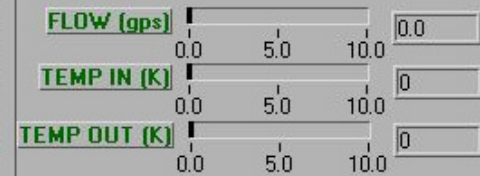
STRIPLINE 3 CURRENT (kA)



STRIPLINE 4 CURRENT (kA)



### WATER COOLING

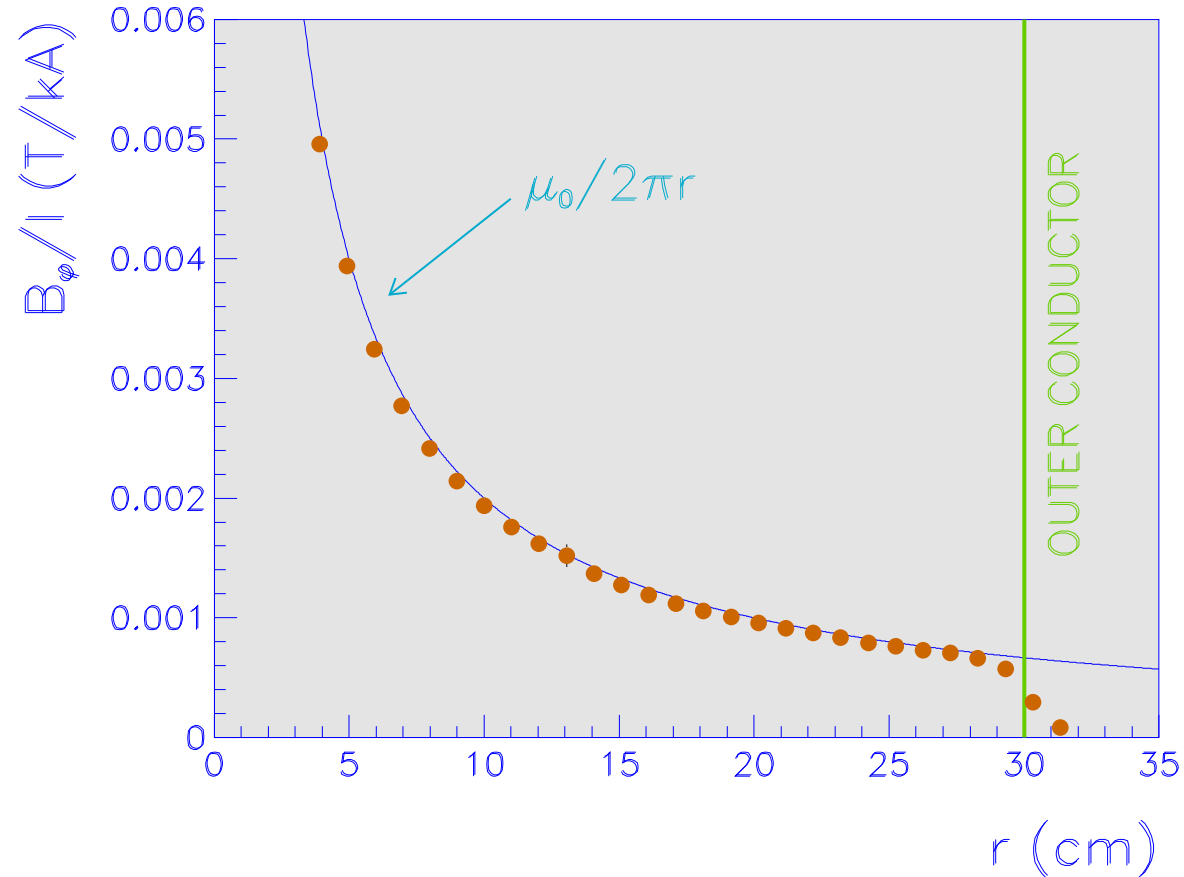


# Horn Magnetic Field Measurement



- Used coils inserted from water ports to map the azimuthal component of the the field
- 300 different positions between the inner and the outer conductor were mapped

# Horn Magnetic Field: Radial Dependence

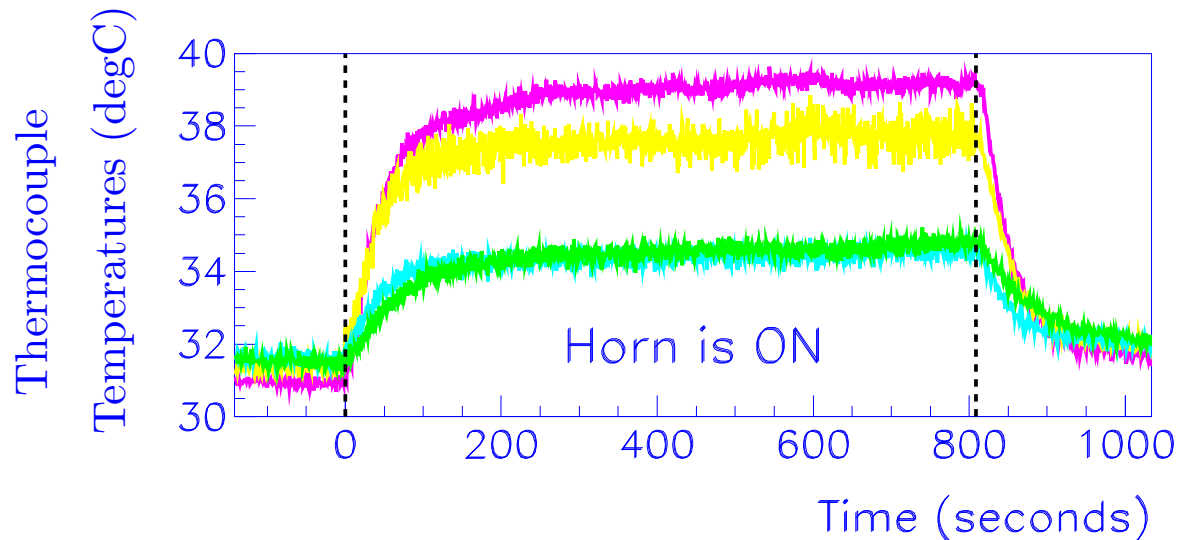


- $B_\phi$ : measured magnetic field (azimuthal component)
- I: horn current
- r: radial distance from the horn axis

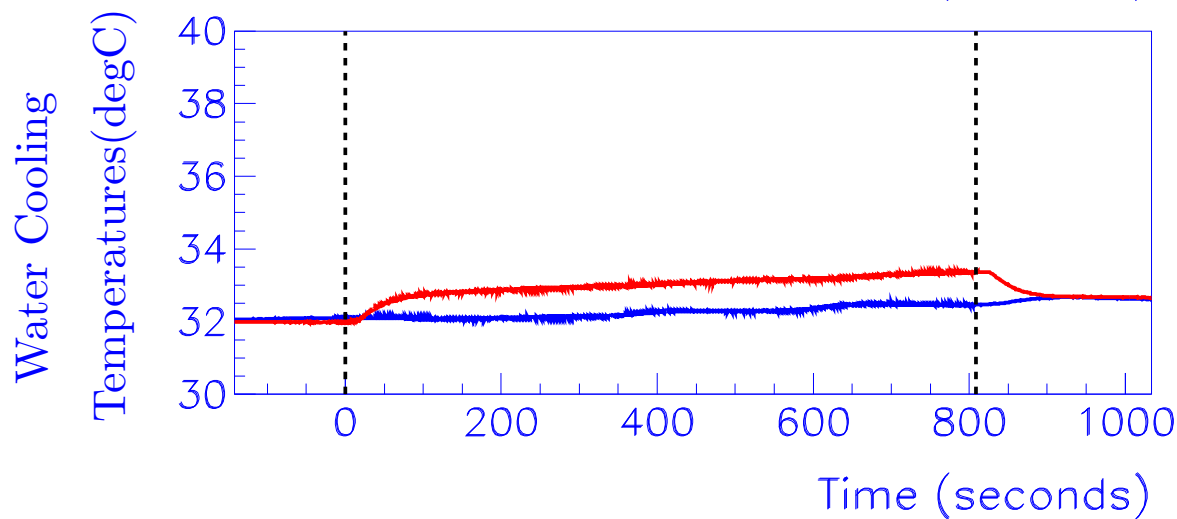
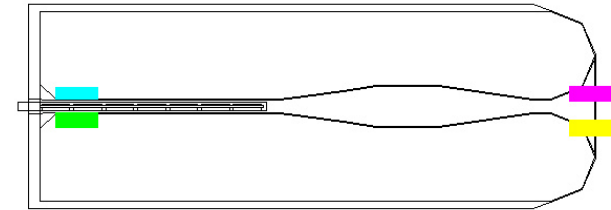


# Horn Temperature Measurements

- There is a clear correlation between the inner conductor temperature (unavailable at run time) and the return temperature of the water cooling system (available):



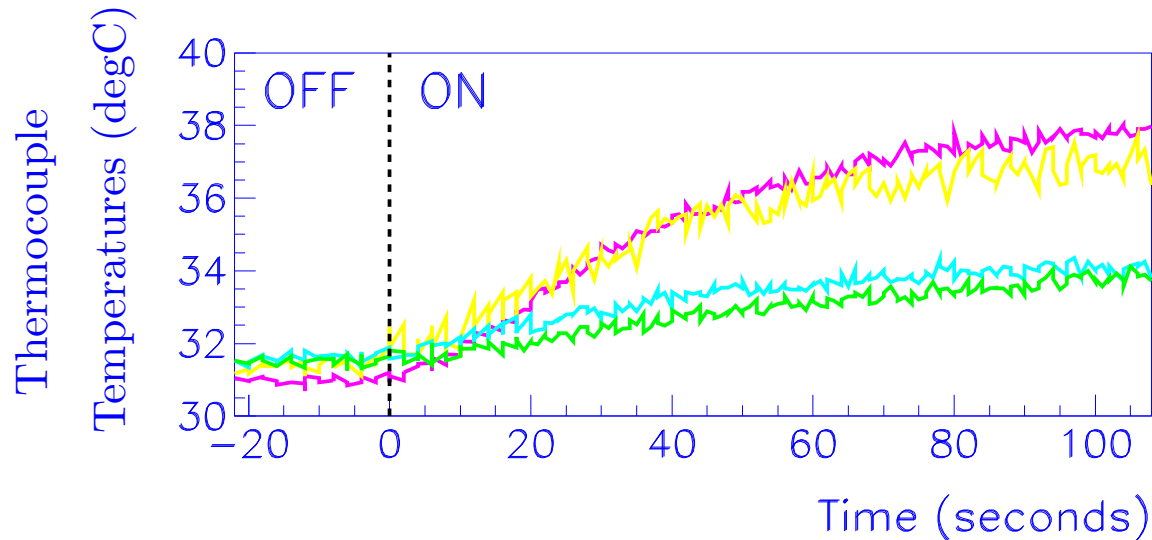
Thermocouple locations:



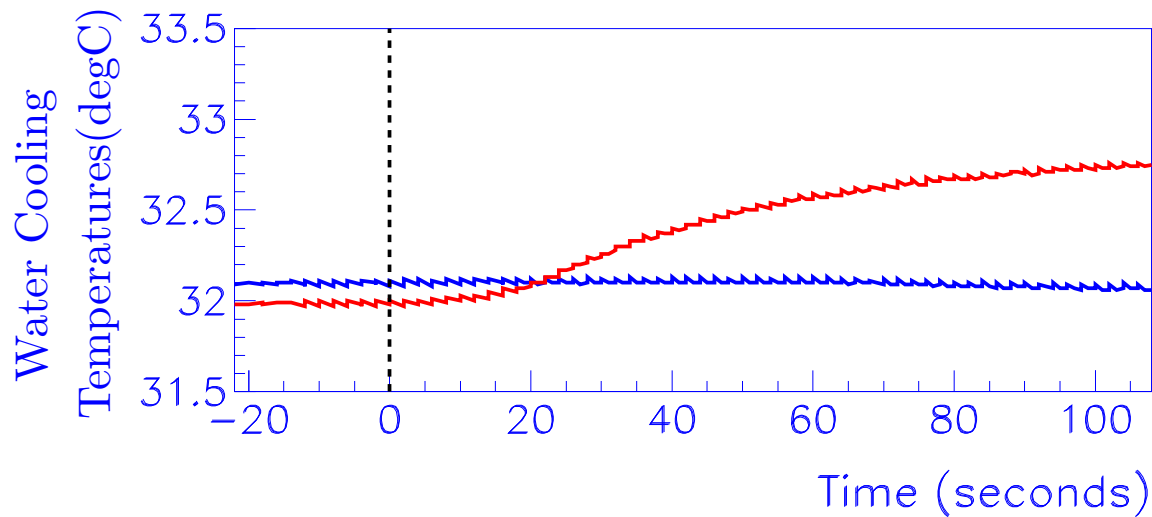
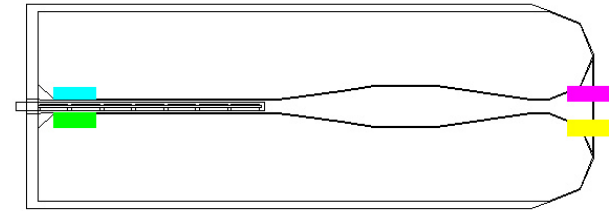
Water Cooling Temperatures:  
Supply, Return

# Horn Temperature Measurements (cont'd)

- We should be able to detect any excessive horn heating via the water cooling temperatures within a few seconds:



Thermocouple locations:



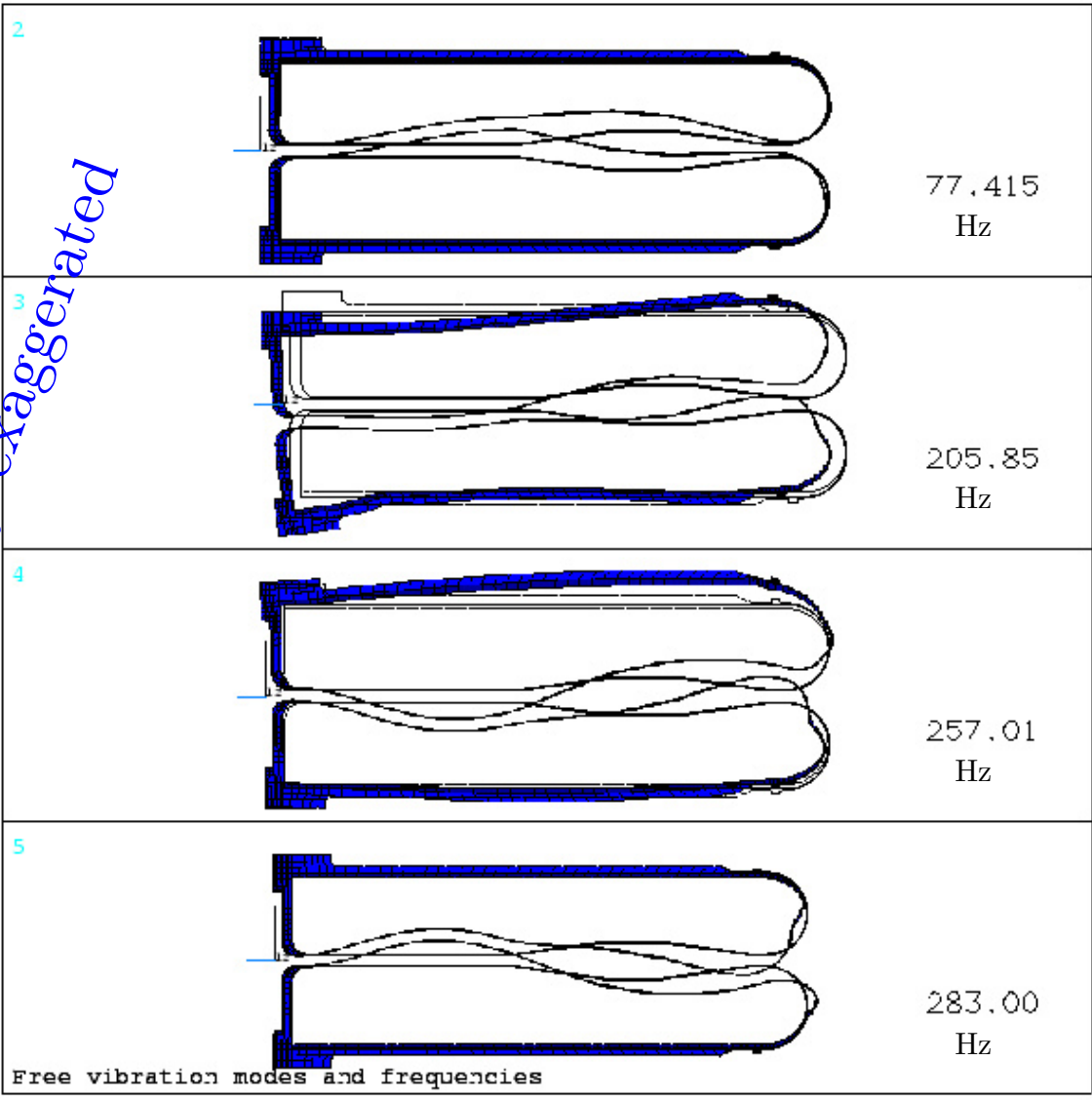
Water Cooling Temperatures:  
Supply, Return

# The Horn Vibration Spectrum and the Fourier Spectrum of the Current Pulse

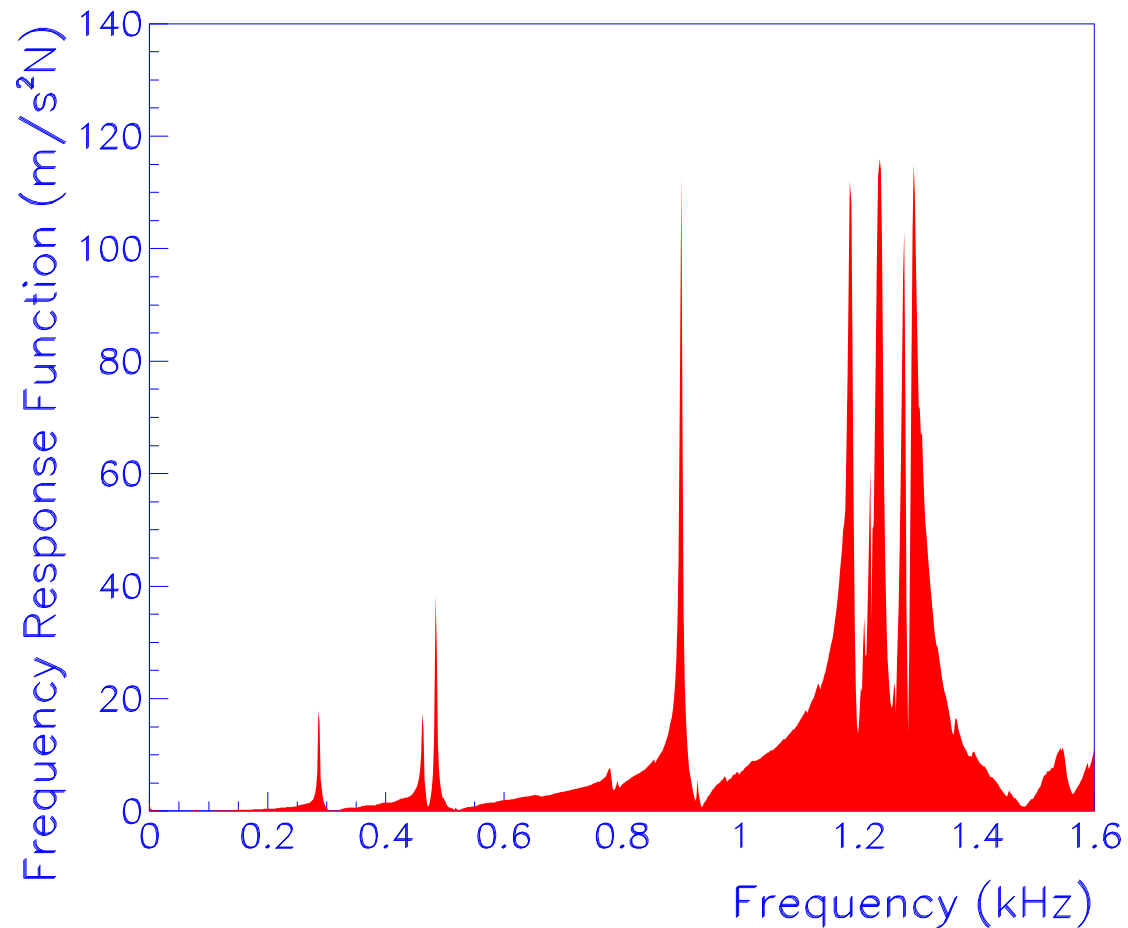
- The pulsing of the horn causes vibrations of the horn's mechanical structure
- The 143  $\mu\text{s}$ -long pulse repeats 10 times, 1/15 sec between each pulse, then the horn is off until 2 seconds from the first pulse in train
- A Fourier analysis of this current pattern shows that the MiniBooNE horn has significant frequency components out to  $\sim 5$  kHz
- Concern: frequencies propagating in the horn might match the natural frequencies of the structure and induce mechanical resonances that overstress the horn
- The natural frequency of the inner conductor should not be close to any of the first multiples of 15 Hz

# First Four Normal Modes of Horn from Finite Element Analysis

*Deflections greatly exaggerated*



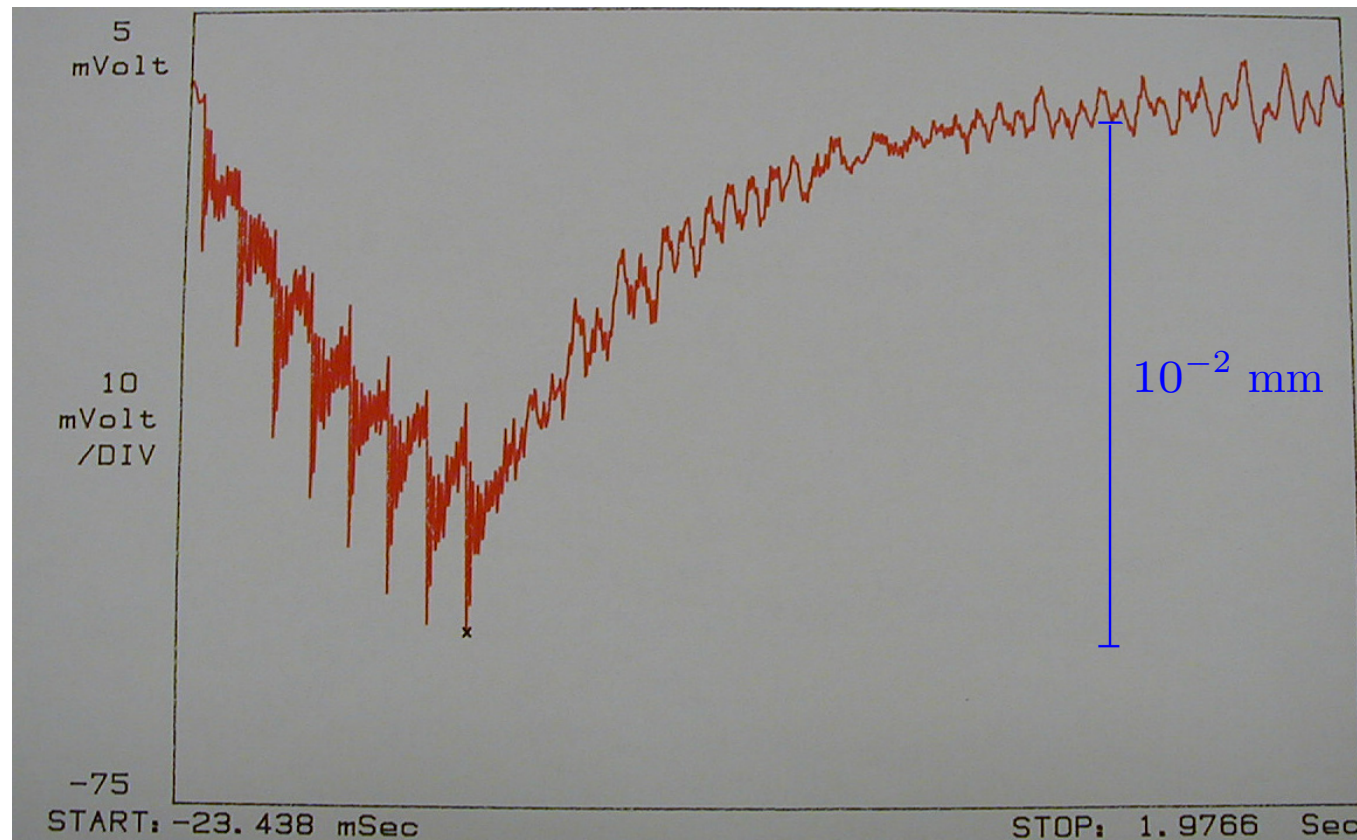
# Measurement: Vibrations in the Frequency Domain



- Conclusion: normal modes do not match any of the lowest harmonics
- Vibrations will be monitored continuously by analyzing the horn sound

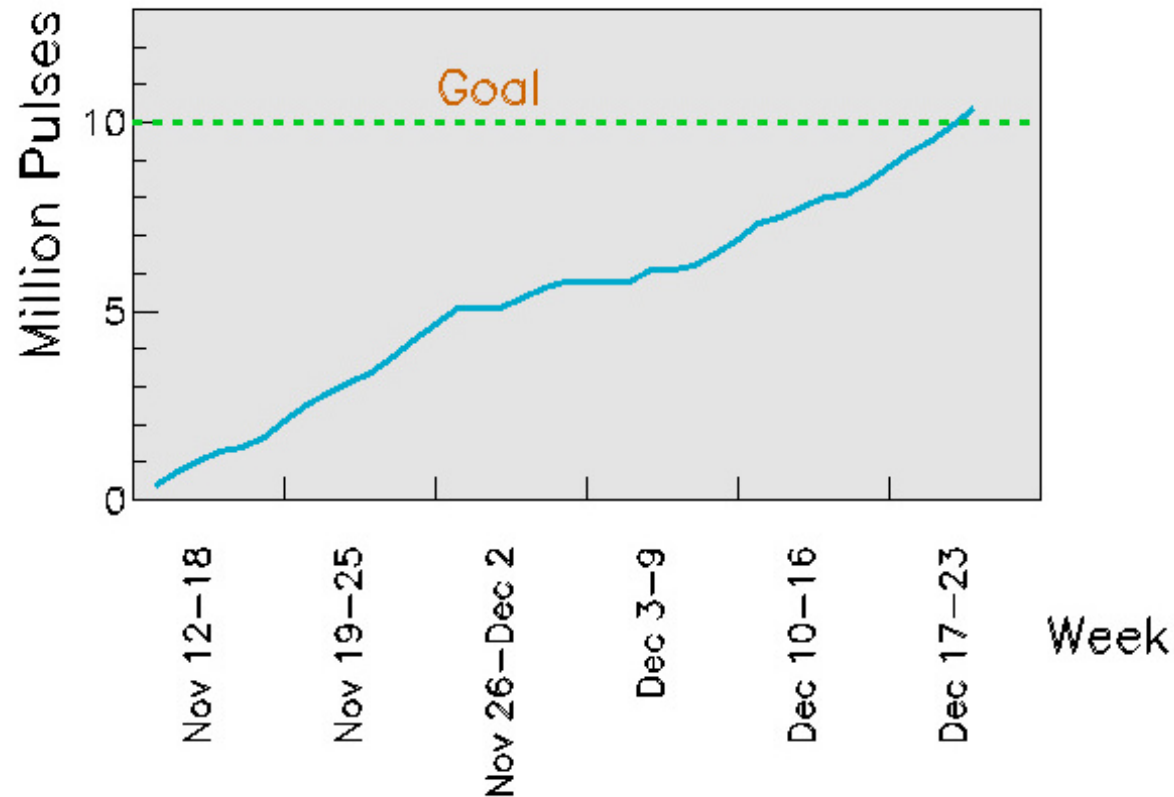
# Measurement: Vibrations in the Time Domain and Thermal Expansion

- This measurement is for a burst of 8 current pulses at 100 kA
- Vibrations die before the next pulse in the train arrives
- We also measured the longitudinal thermal expansion of the horn:  $\sim 10^{-2}$  mm with no water cooling



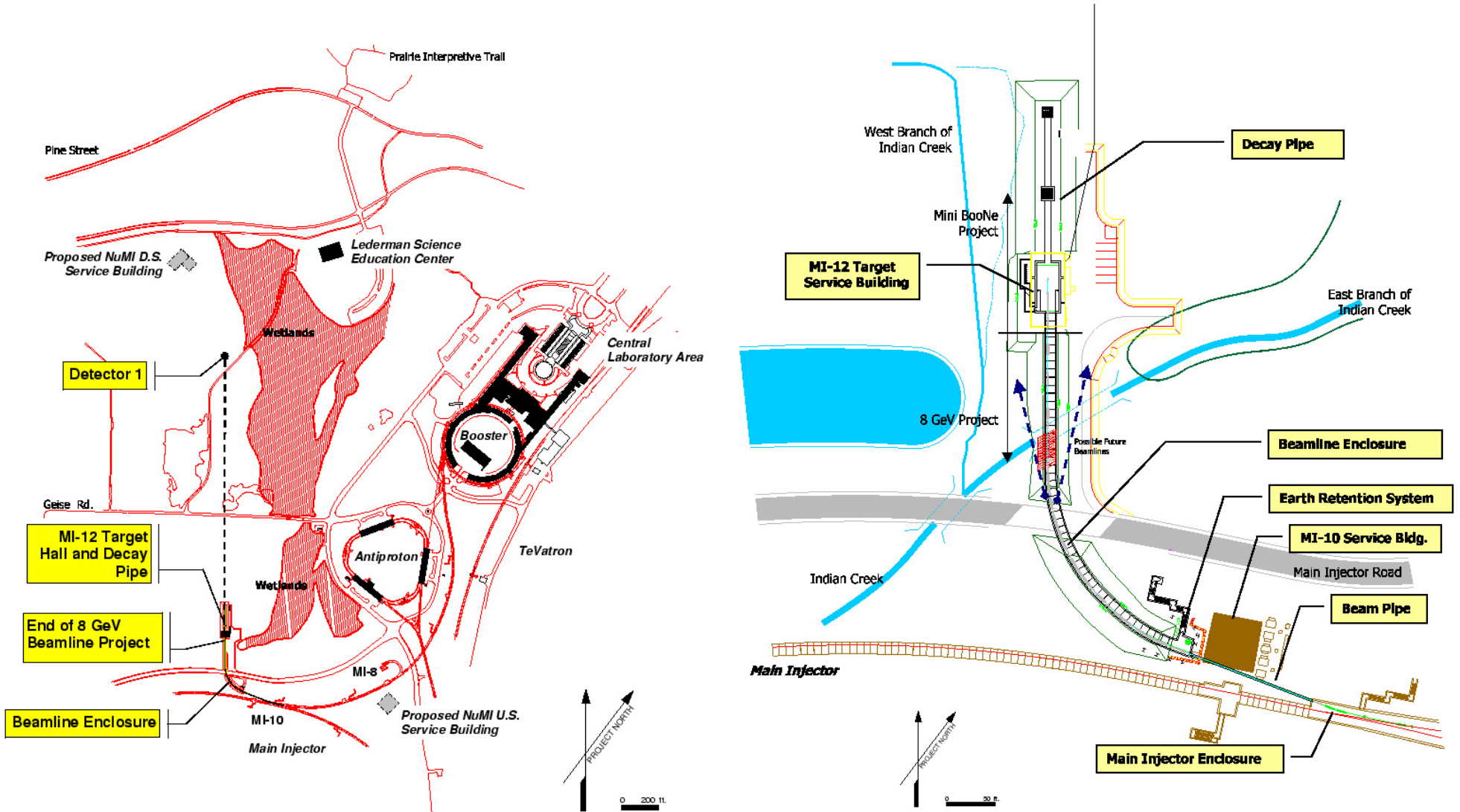
# Horn Endurance Test

- The horn was successfully tested for 6 weeks of almost continuous operation
- The total number of current pulses through the horn during testing was about 10 millions, or 5% of its design lifetime
- With 10 million pulses, the MiniBooNE horn is already the horn with the longest lifetime ever built



# Target Hall

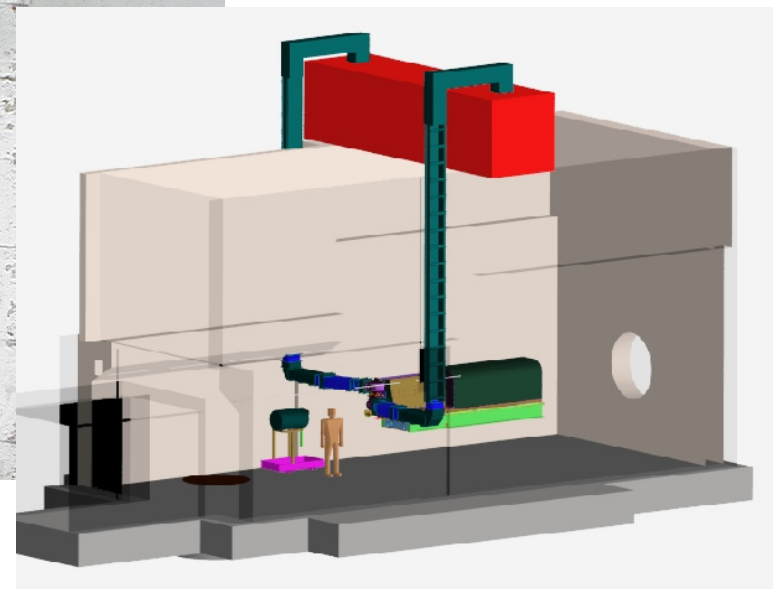
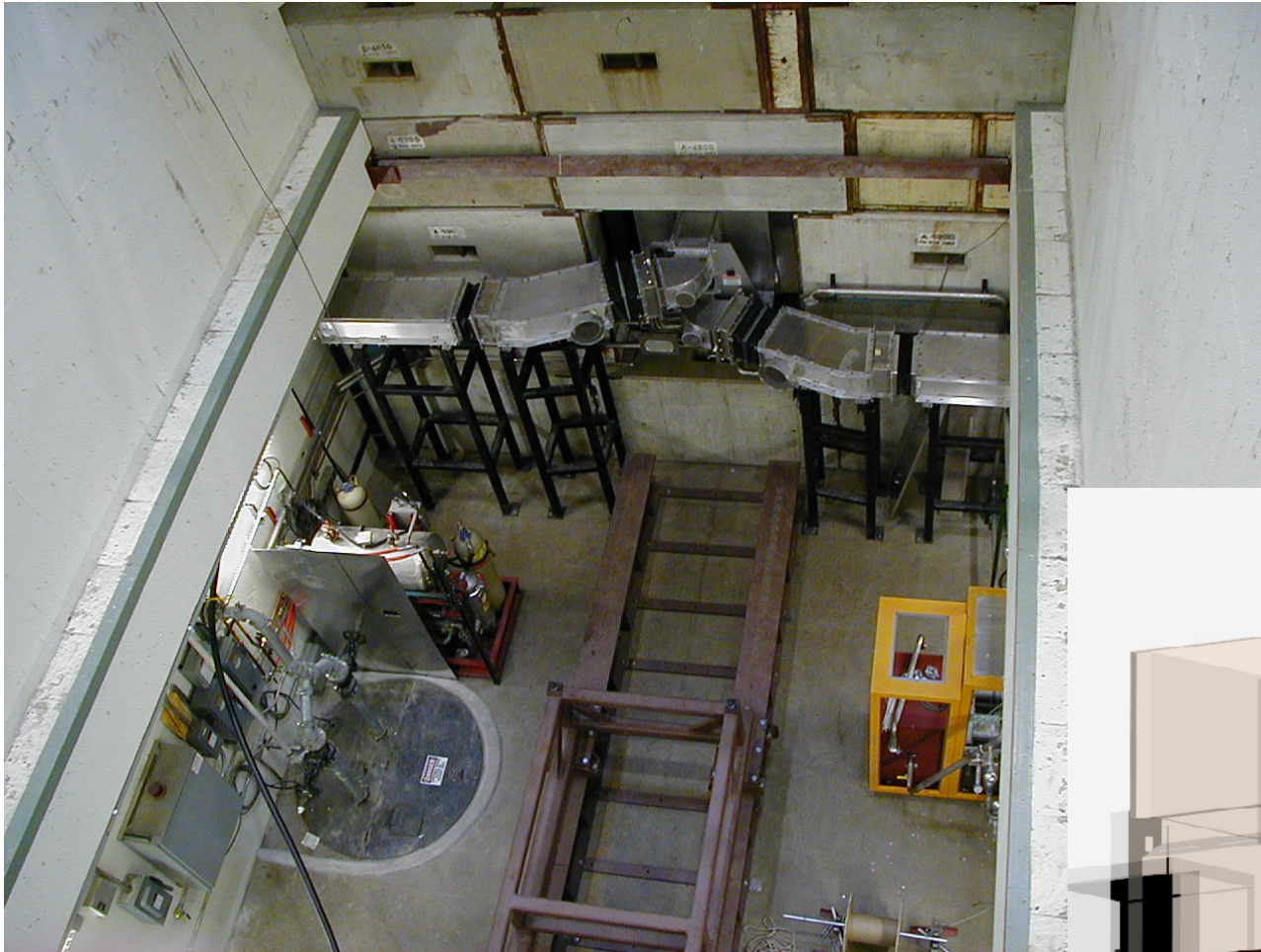
- In March, we started the move the horn to its final destination, the MI-12 target hall:





# Horn in Target Hall

- As of June, the horn system is entirely assembled in the target hall:



# Horn Changeover

- The horn module is expected to be highly radioactive (30 rad/hr at 60 cm), the major concern being 1.2 MeV photons from  $^{22}\text{Na}$
- In order to deal with a horn failure scenario:
  1. A spare horn is being built now
  2. A detailed procedure outlining all the steps for a horn changeover has been written, reviewed, and tested during a “dry run” in June
- In order to reduce the radiation exposure for a horn changeover to under 100 mrem/hr, the shielding requirement is 12 cm of steel on all sides
- Because of the crane lifting capacity, two separate coffins (an inner and an outer) will be used
- Two main goals of radioactive horn handling procedure:
  1. Allow for a *short*-term handling of the shielded radioactive horn
  2. Coffins themselves should provide the shielding necessary for safe personnel operation during horn removal

# Inner and Outer Coffins

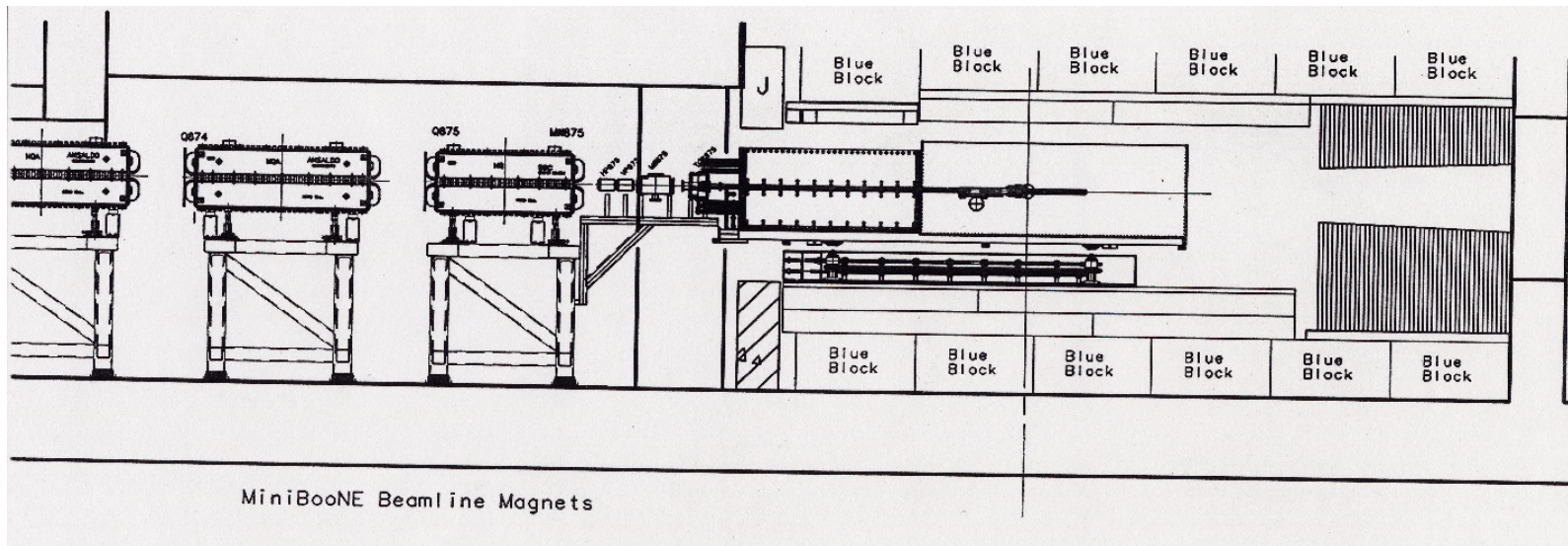
- The inner coffin has 4 cm thick walls except from the top cover and the front door (13 cm thick)
- The outer coffin has 9 cm thick walls and is open at the top and the front
- Total weight of two coffins: 40 tons



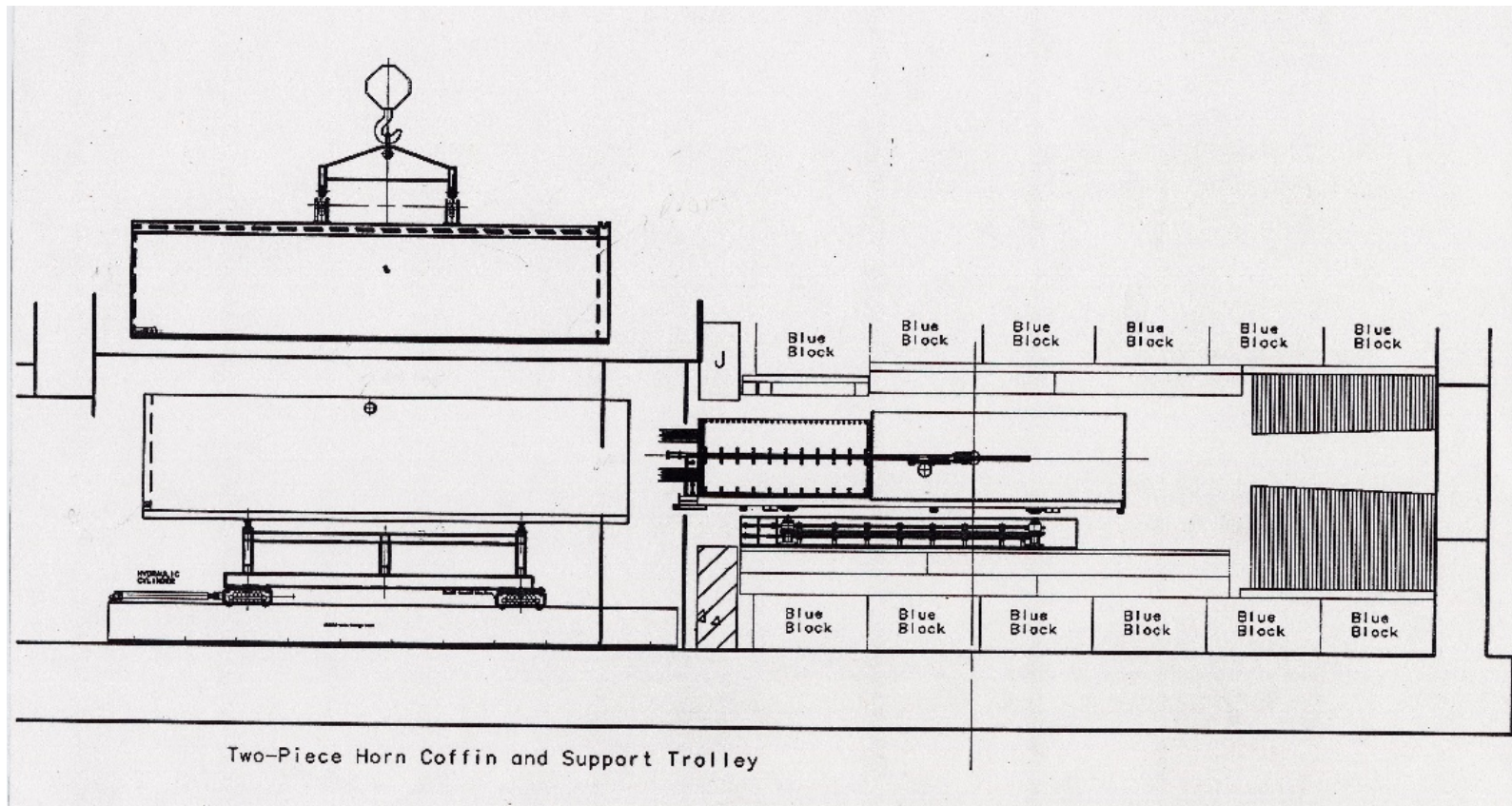
## Horn Changeover (cont'd)

- The radioactive horn module will be stored inside the two coffins in a controlled area
- Four coffins (two inner and two outer coffins) will be needed for a changeover
- Exposure time by personnel in high radiation area (100 mrem/hr) is very short during the changeover process (5-10 mins, for disconnecting the striplines and the water cooling piping)
- Total estimated time for a changeover is 2 weeks
- The next slides show the steps we will follow during a horn changeover

# Step 1: Initial Configuration

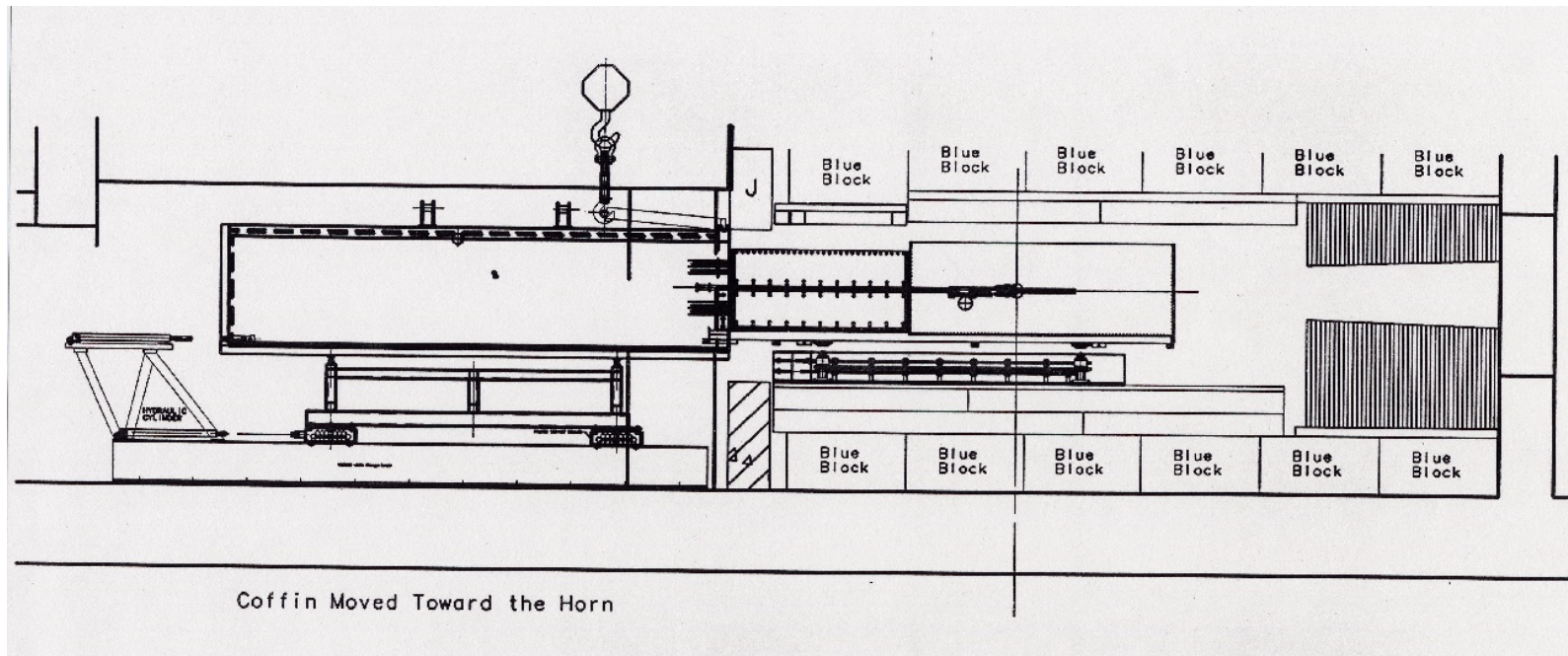


## Step 2: Lower Inner and Outer Coffins





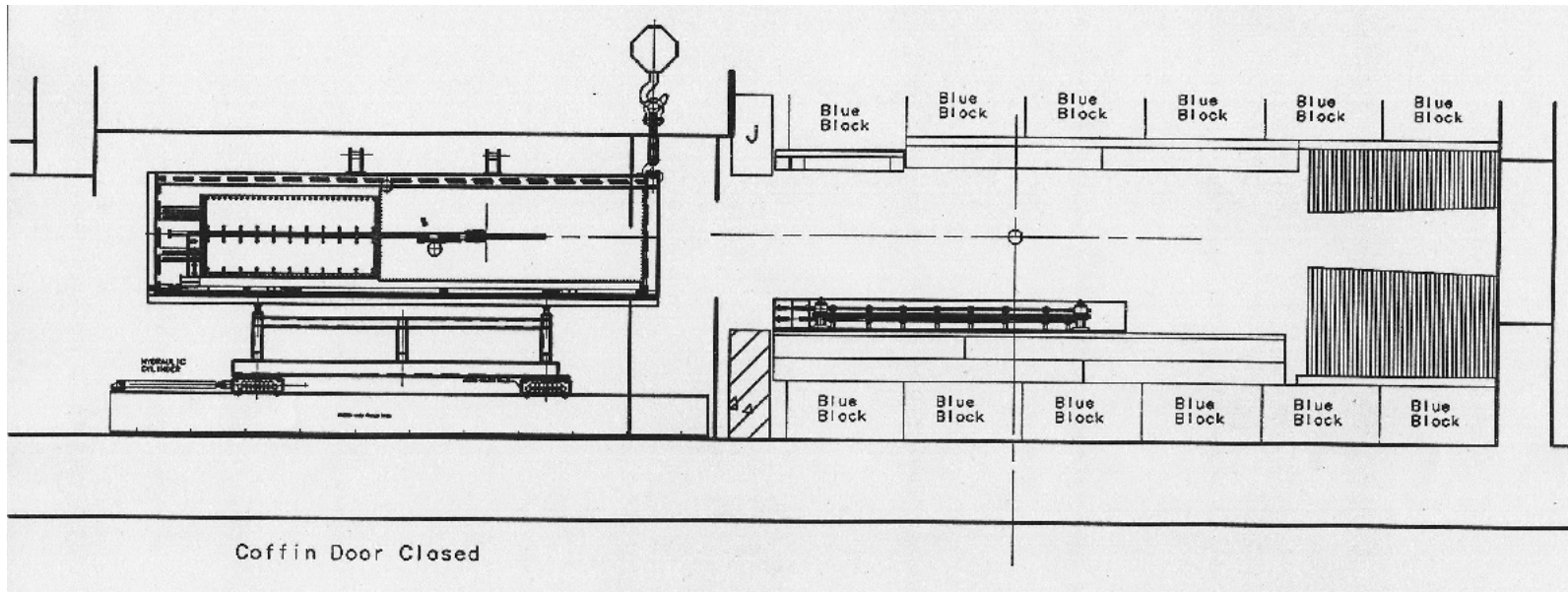
# Step 4: Position the Coffins next to the Horn Module







# Step 6: Close Inner Coffin Door



# Conclusions

- The horn will give MiniBooNE an order of magnitude increase in statistics for the neutrino oscillation search
- The MiniBooNE horn has been built, assembled, and positioned into the target hall
- The extensive horn testing performed has not shown any major problems with the horn design
- The horn design should allow MiniBooNE to complete its run with a maximum of two horns
- A detailed plan exists for an eventual horn changeover
- Final horn testing is currently going on
- The MiniBooNE detector is ready and taking cosmic-ray data
- The start-up of MiniBooNE beam data is scheduled for the end of August