MINIBOONE

ONE COOL HORN

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for the MiniBooNE Collaboration

NFWG Seminar, CERN, August 2002

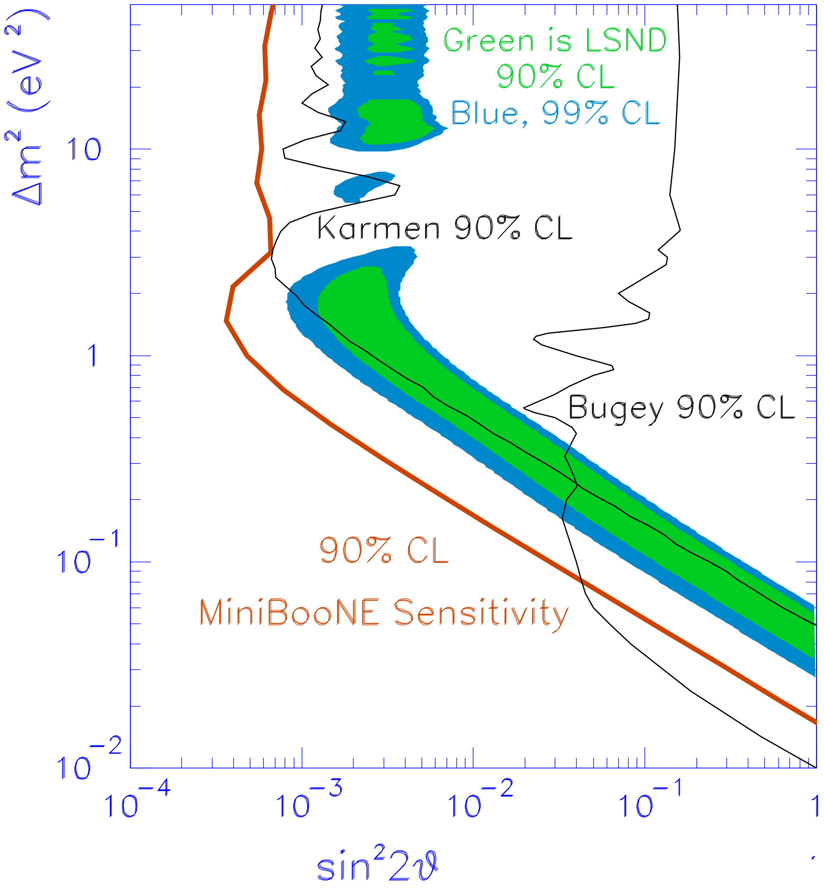
Outline

- 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 $\nu_\mu \longrightarrow \nu_e$ oscillations

- MiniBooNE will address in a definite and independent way the evidence for neutrino oscillations seen by the LSND Experiment

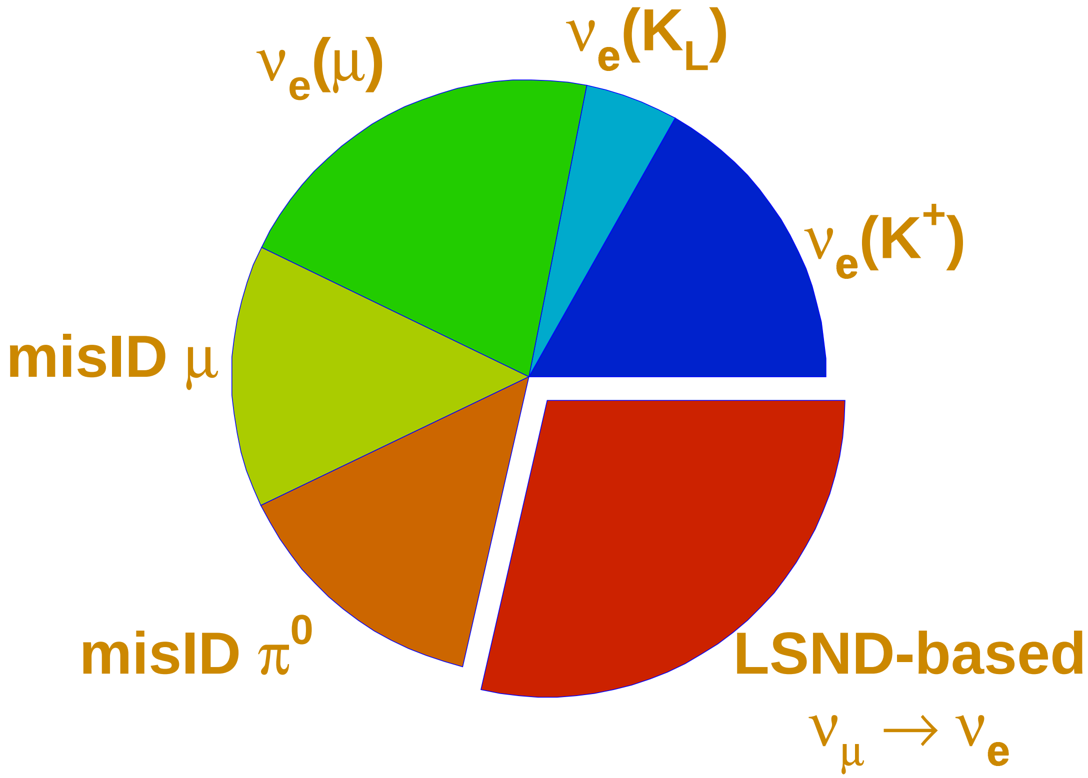


- definite: same L_ν/E_ν ratio as for LSND and enough statistics to cover the LSND region at the 5σ level

- 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 ν flux and particle ID

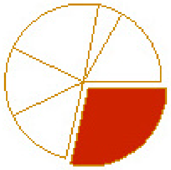
The $\nu_\mu \rightarrow \nu_e$ Oscillation Search

- Before any energy cuts:

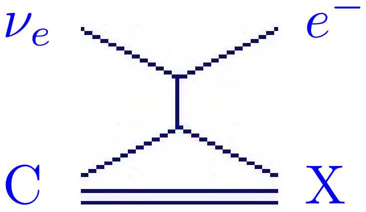


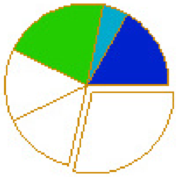
The $\nu_\mu \rightarrow \nu_e$ Oscillation Search (cont'd)

- Approximate number of expected events:

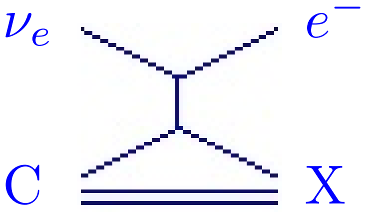


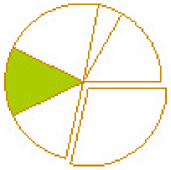
LSND-based $\nu_\mu \rightarrow \nu_e$: 1,000



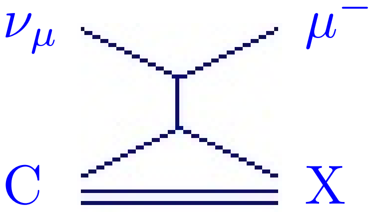


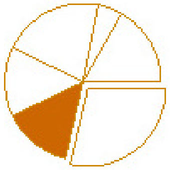
Intrinsic ν_e bgr: 1,500



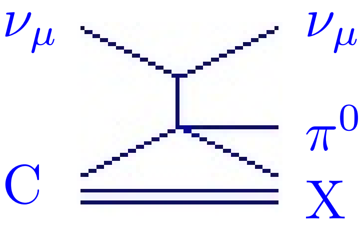


μ mis-ID bgr: 500



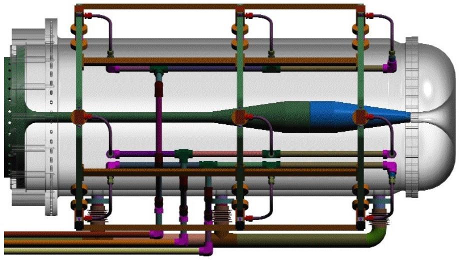


π^0 mis-ID bgr: 500

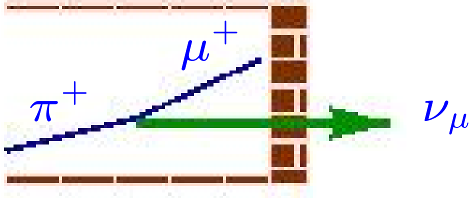


The BooNE Beam

Primary Beam:
high-intensity 8 GeV proton source from FNAL Booster.
MiniBooNE requires 10^{21} protons on target ⇔ 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:
$\pi^+ \longrightarrow \mu^+ \; \nu_\mu$ in the 25/50 m decay channel.
After absorber, almost pure ν_μ beam pointing towards the detector

BooNE beam: physics-driven requirements

- Beamline is optimized to:

1. maximize the ν_μ flux at 0.5-1 GeV
2. minimize the ν_μ flux above 1 GeV
3. minimize the ν_e flux
4. understand well the systematics of the ν_e flux

- Without any magnetic focusing device, it would take MiniBooNE ∼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 π^{+} or π^{-}, by inverting the power supply polarity

$\Rightarrow$ horn appears to be the best choice

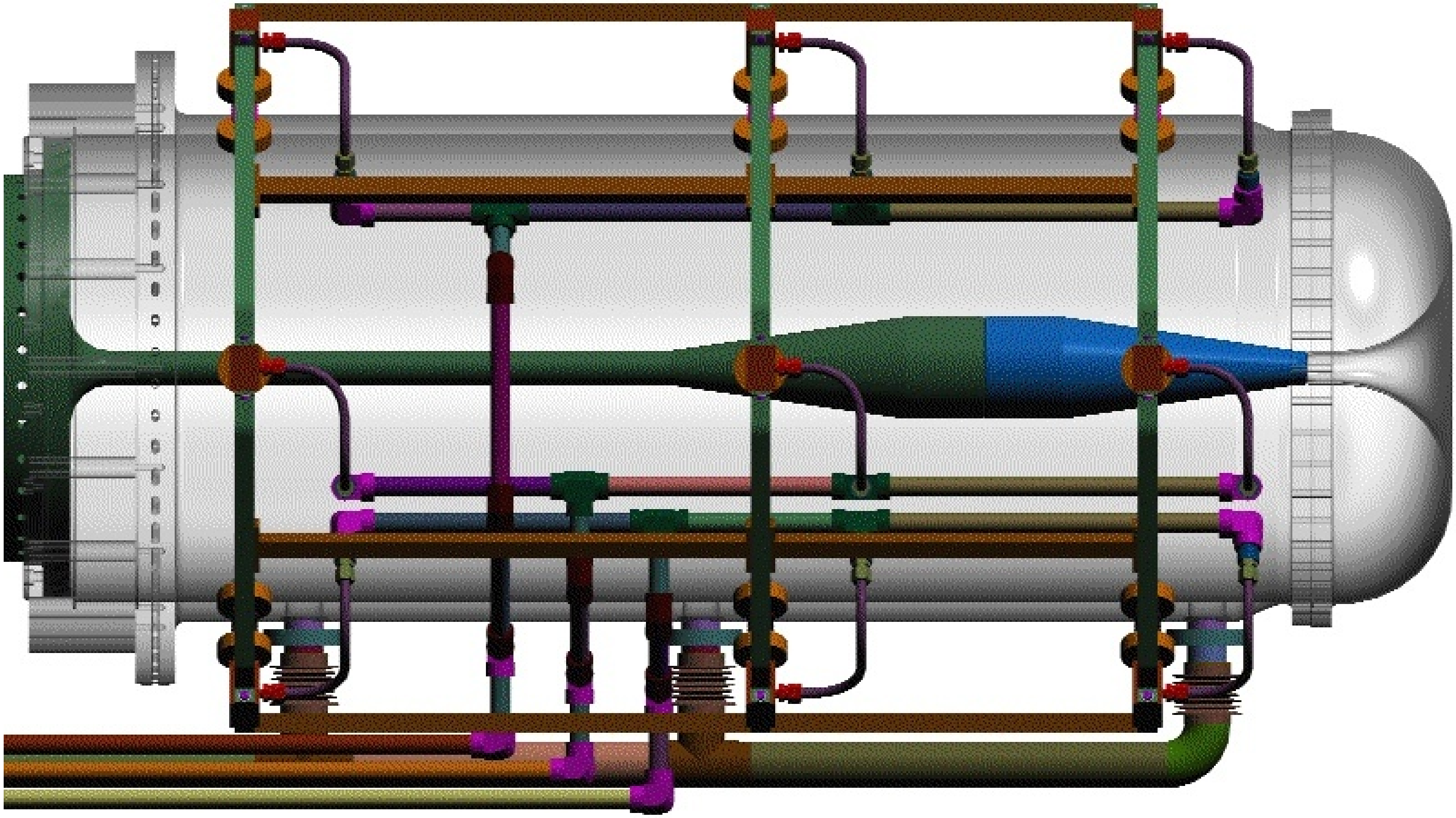
- Additional requirements:

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

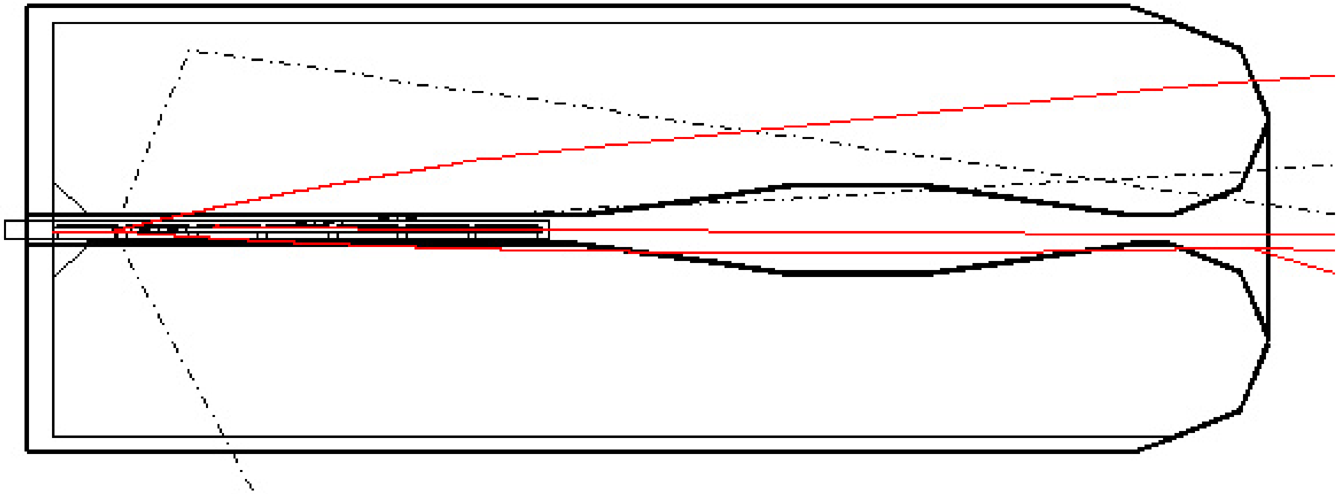
MiniBooNE Horn Characteristics

- 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 μs long, half-simusoidal 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

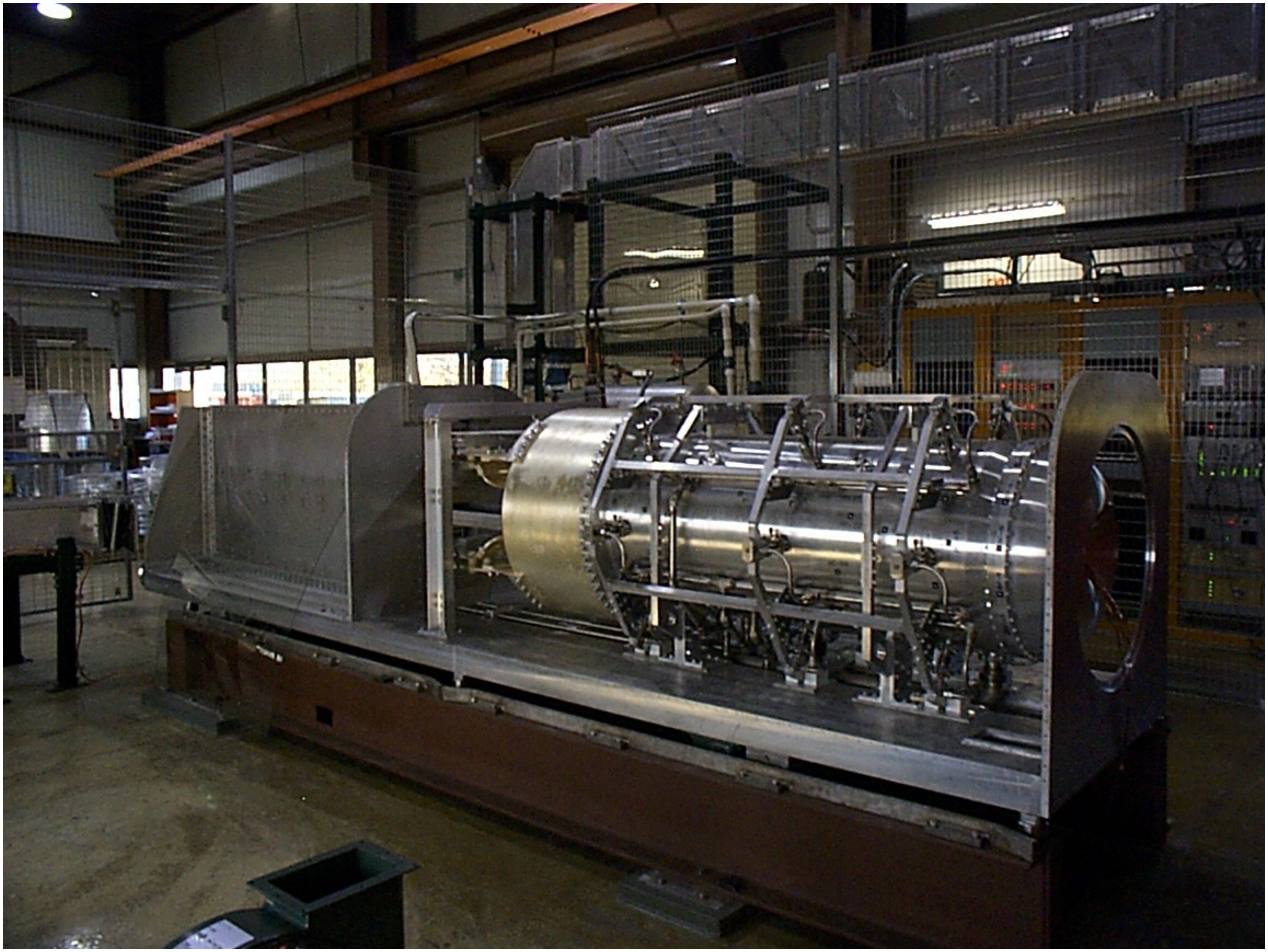


Particle Trajectories in the Horn

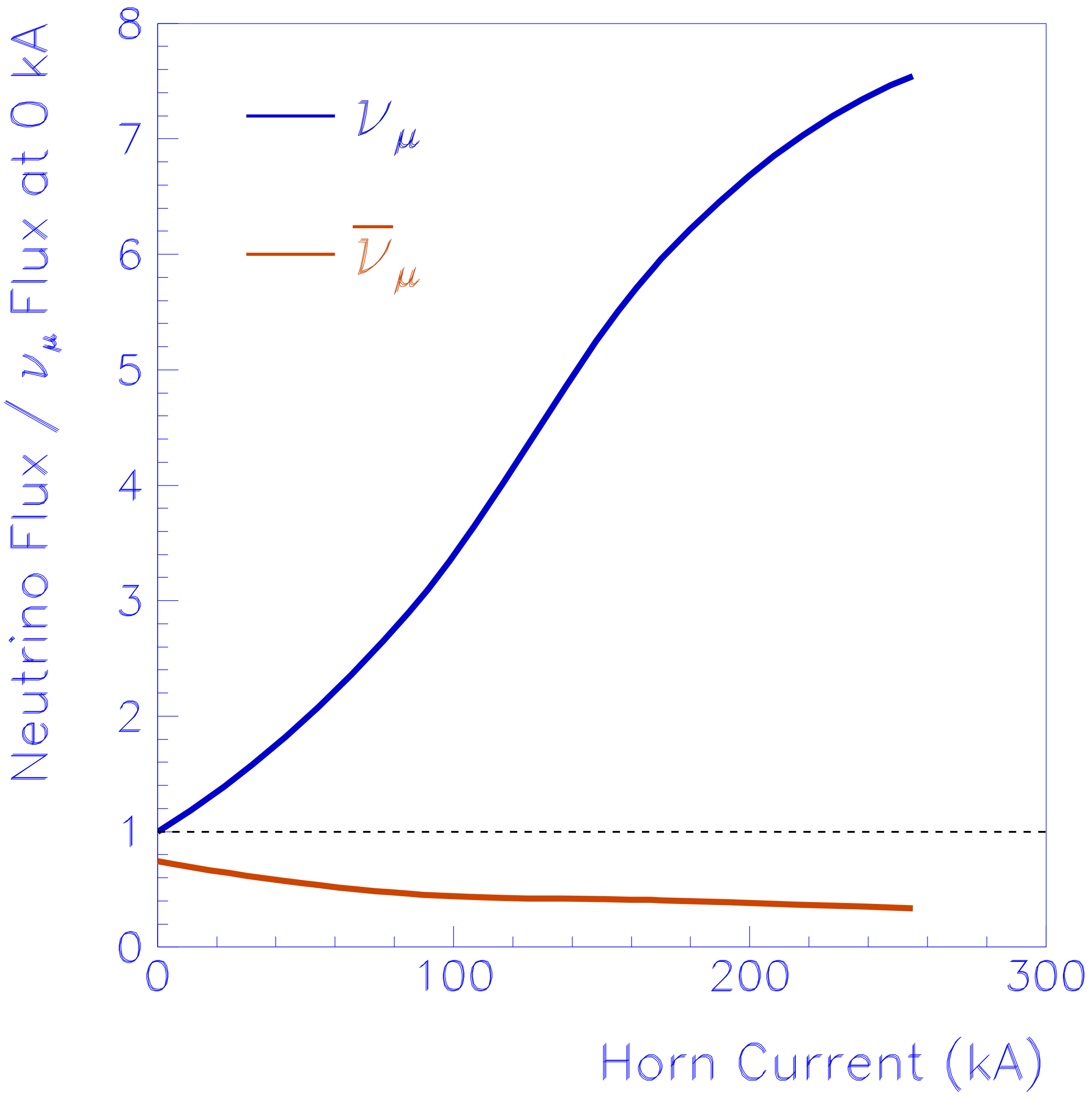


- Red tracks: charged particles
- Black tracks: neutral particles

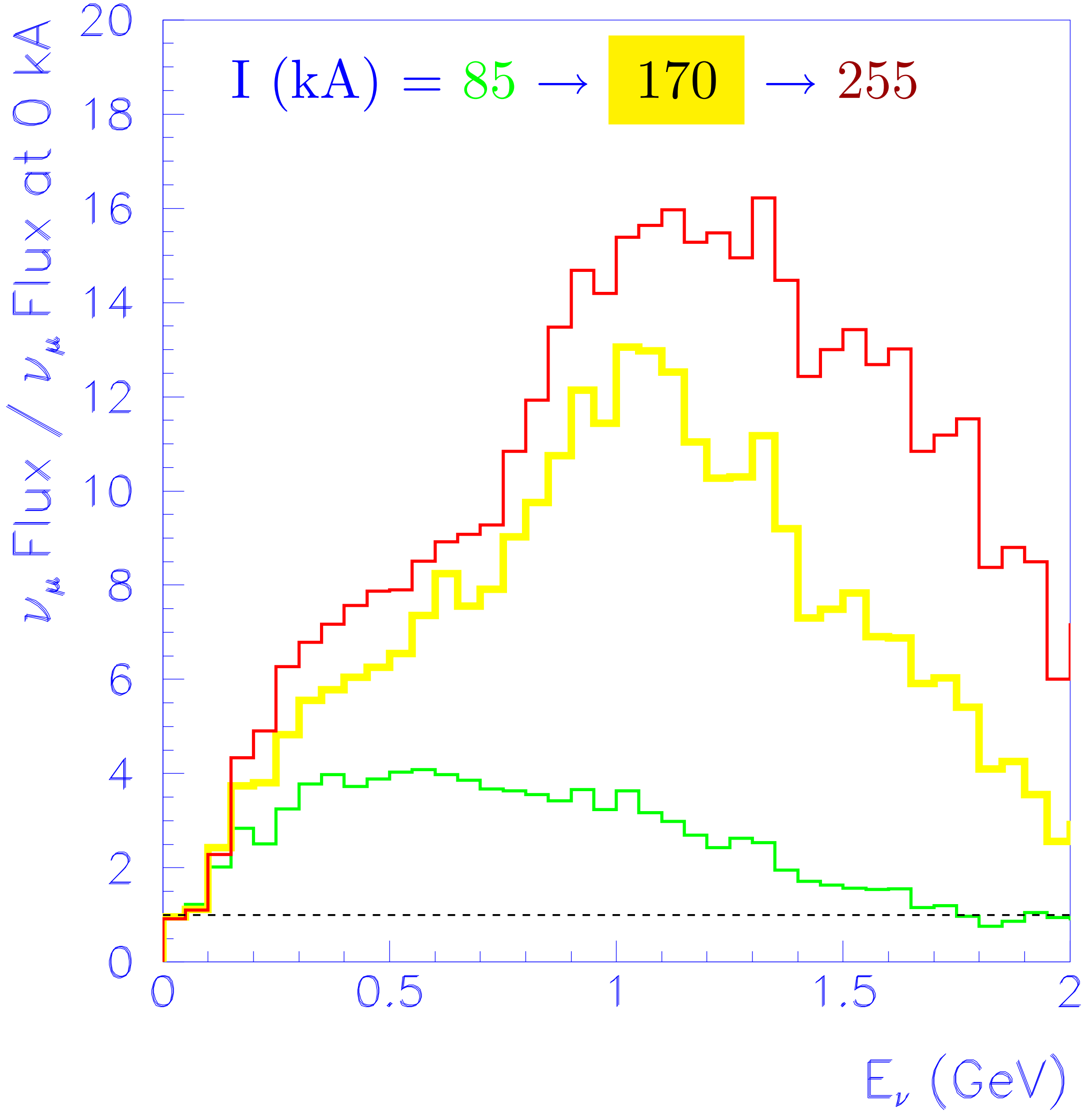
Horn Module Overview



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

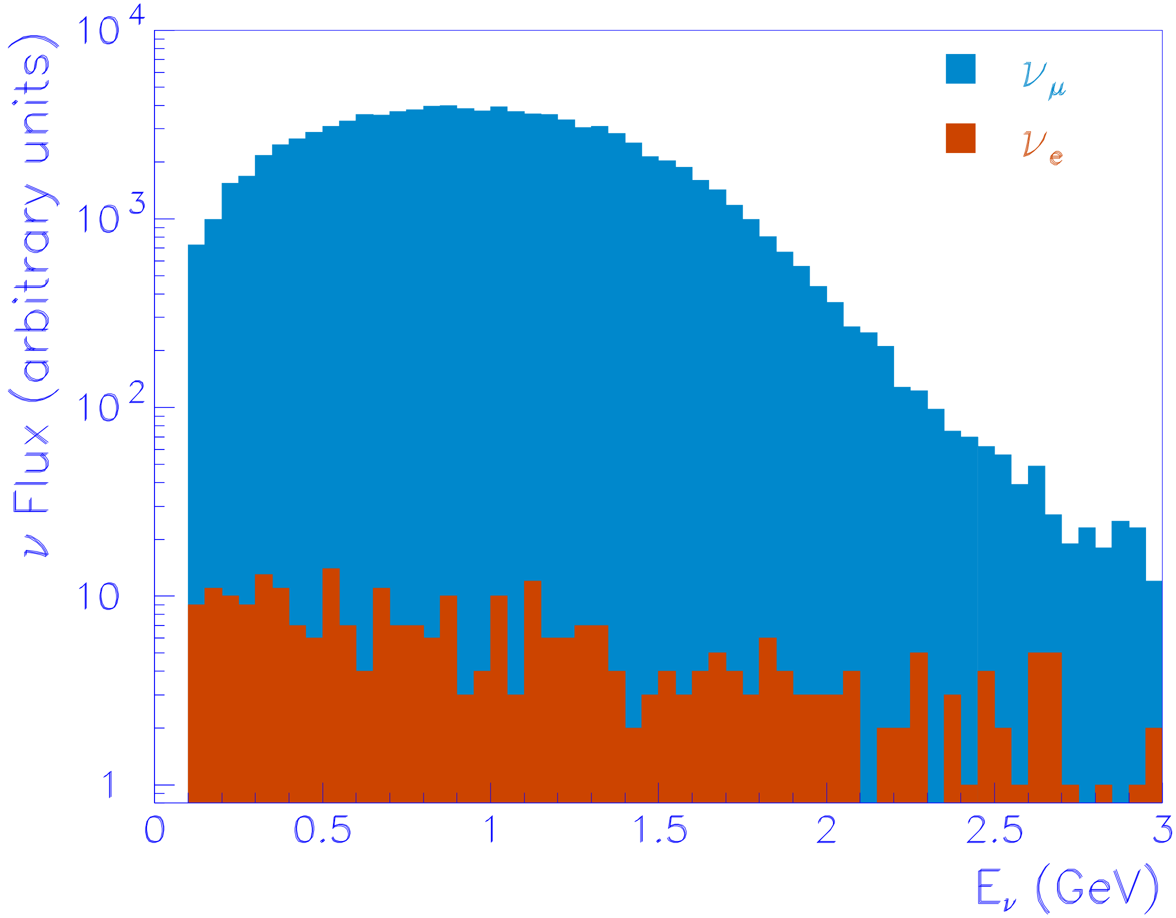


Simulated Neutrino Flux at the MiniBooNE Detector: Neutrino Energy and Horn Current



Neutrino Fluxes at the Detector with a 170 kA Horn

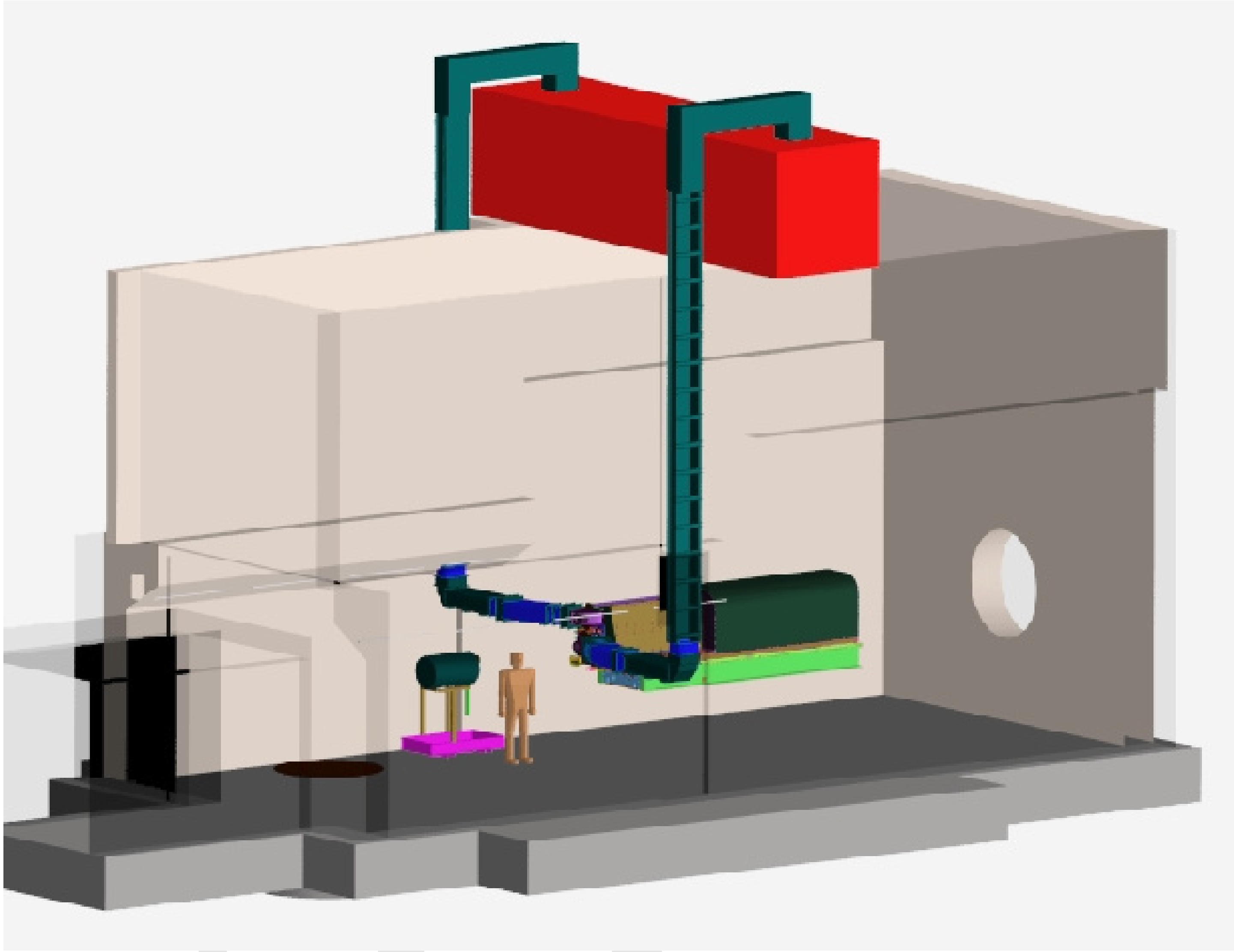
- 0.3-1.5 GeV ν_μ flux with very low (0.3%) ν_e contamination:



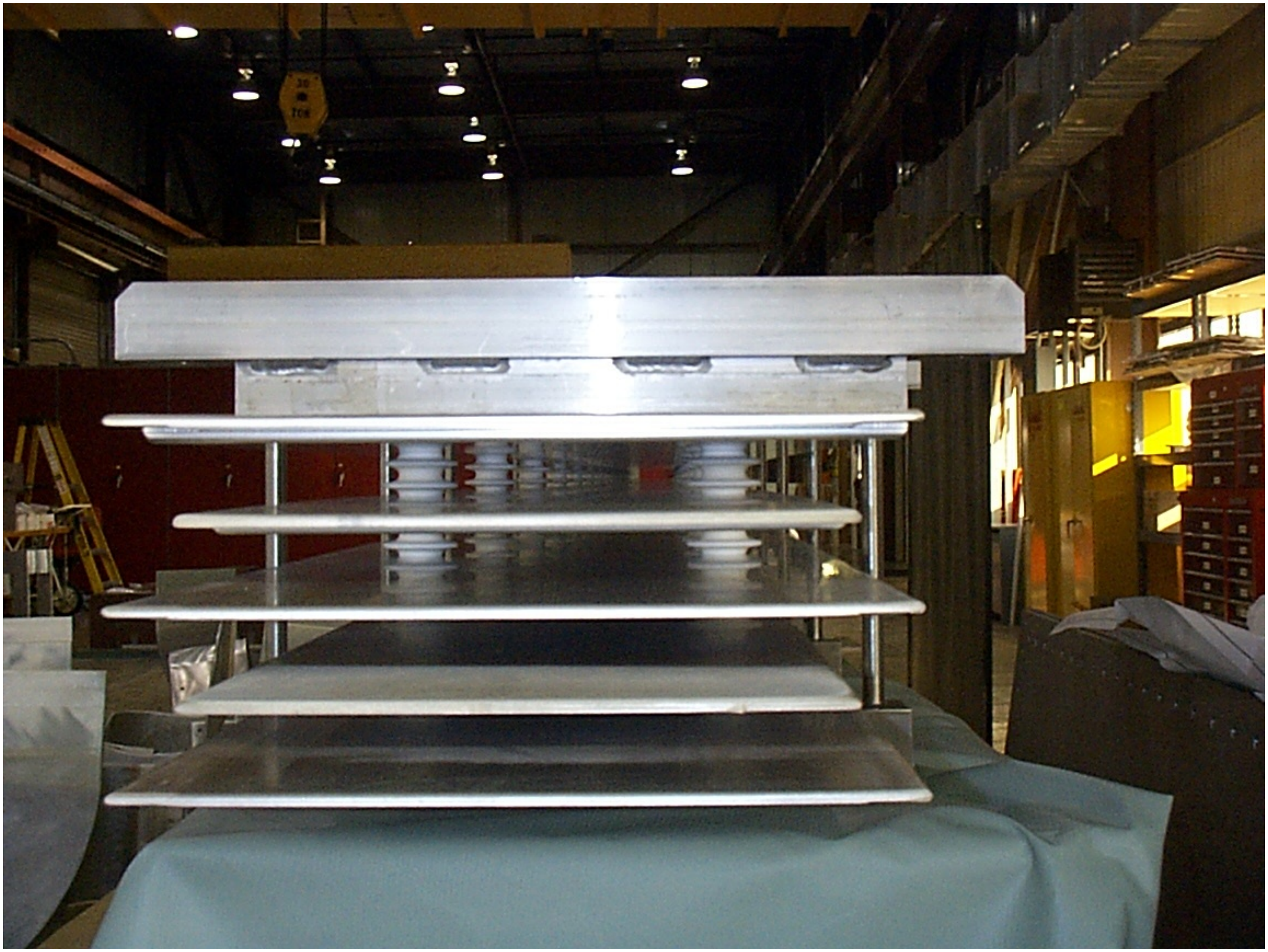
Horn Striplines

- 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

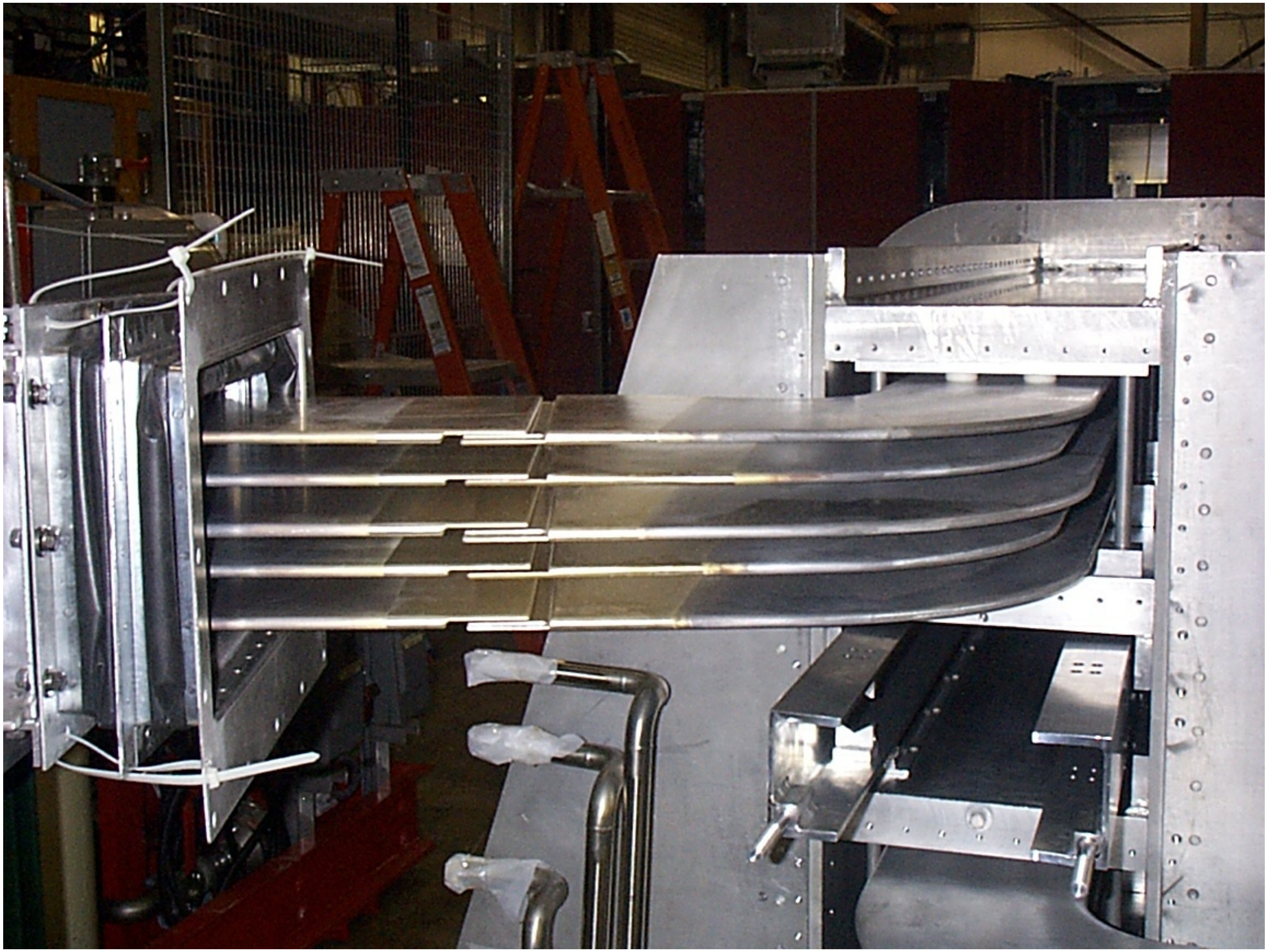
Striplines connecting the power supply to the horn



View of a Stripline



View of a Stripline Joint

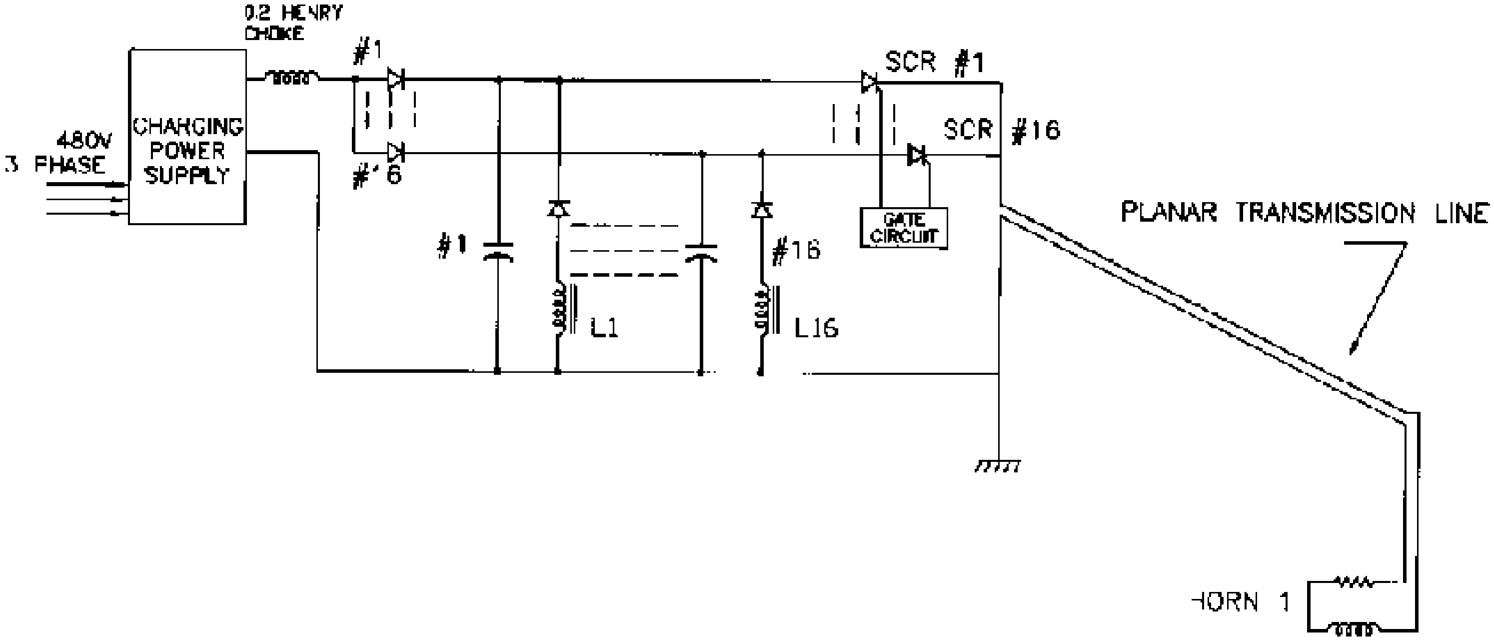


Horn Power Supply

- 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 μs 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:

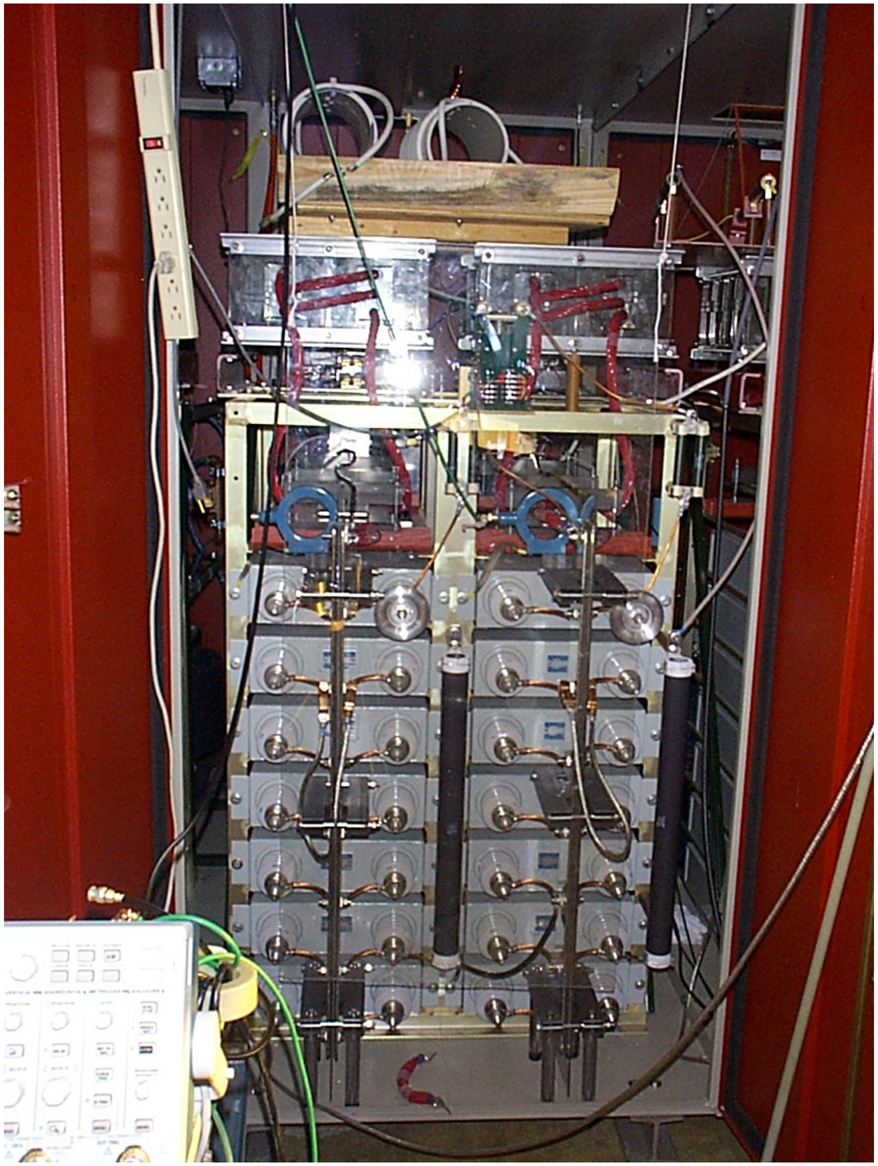
Component	Inductance	Resistance	Power
Horn	$0.70\ \mu H$	$0.24\ m\Omega$	$2.4\ kW$
Stripline (20 meters)	$0.26\ \mu H$	$0.50\ m\Omega$	$5.0\ kW$
Capacitor Bank plus losses	$0.37\ \mu H$	$3.0\ m\Omega$	$30\ kW$
Total	$1.33\ \mu H$	$3.74\ m\Omega$	$37.4\ kW$

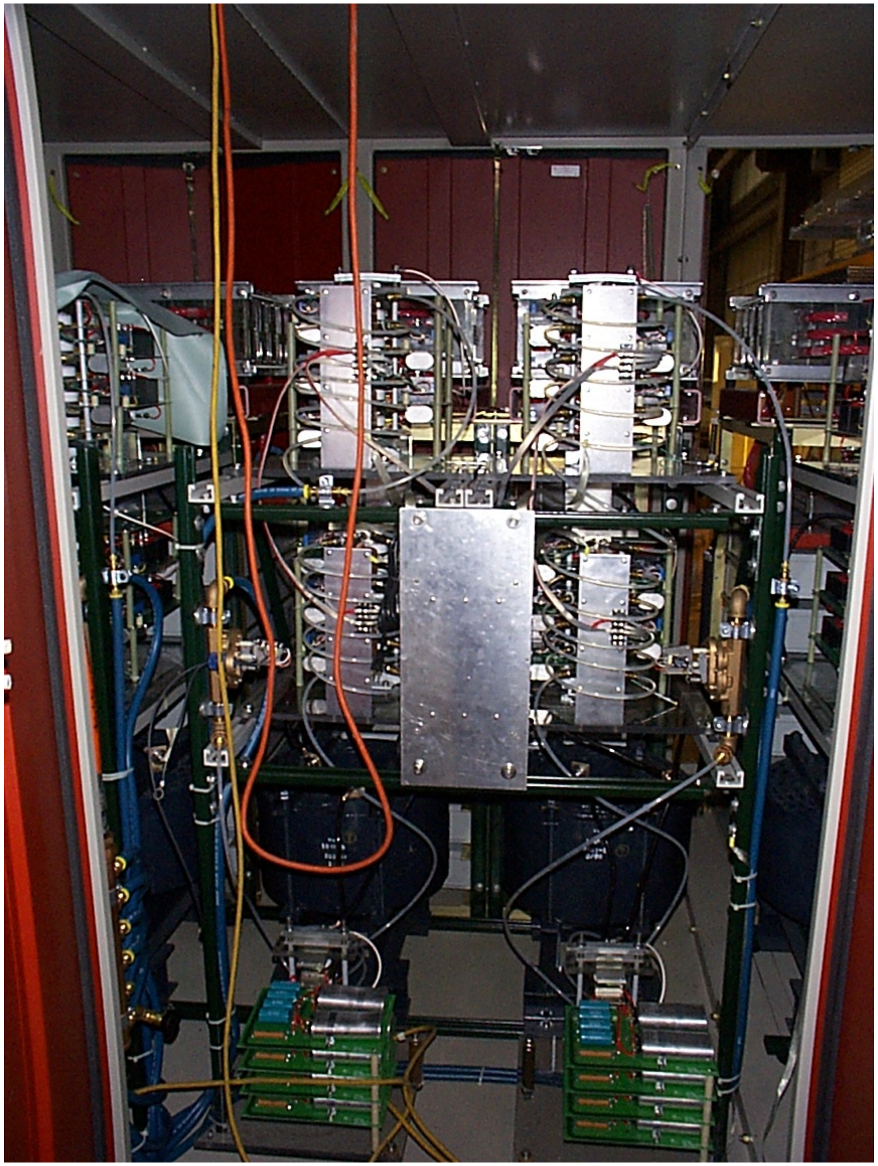
Power Supply Schematic and Mode of Operation



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

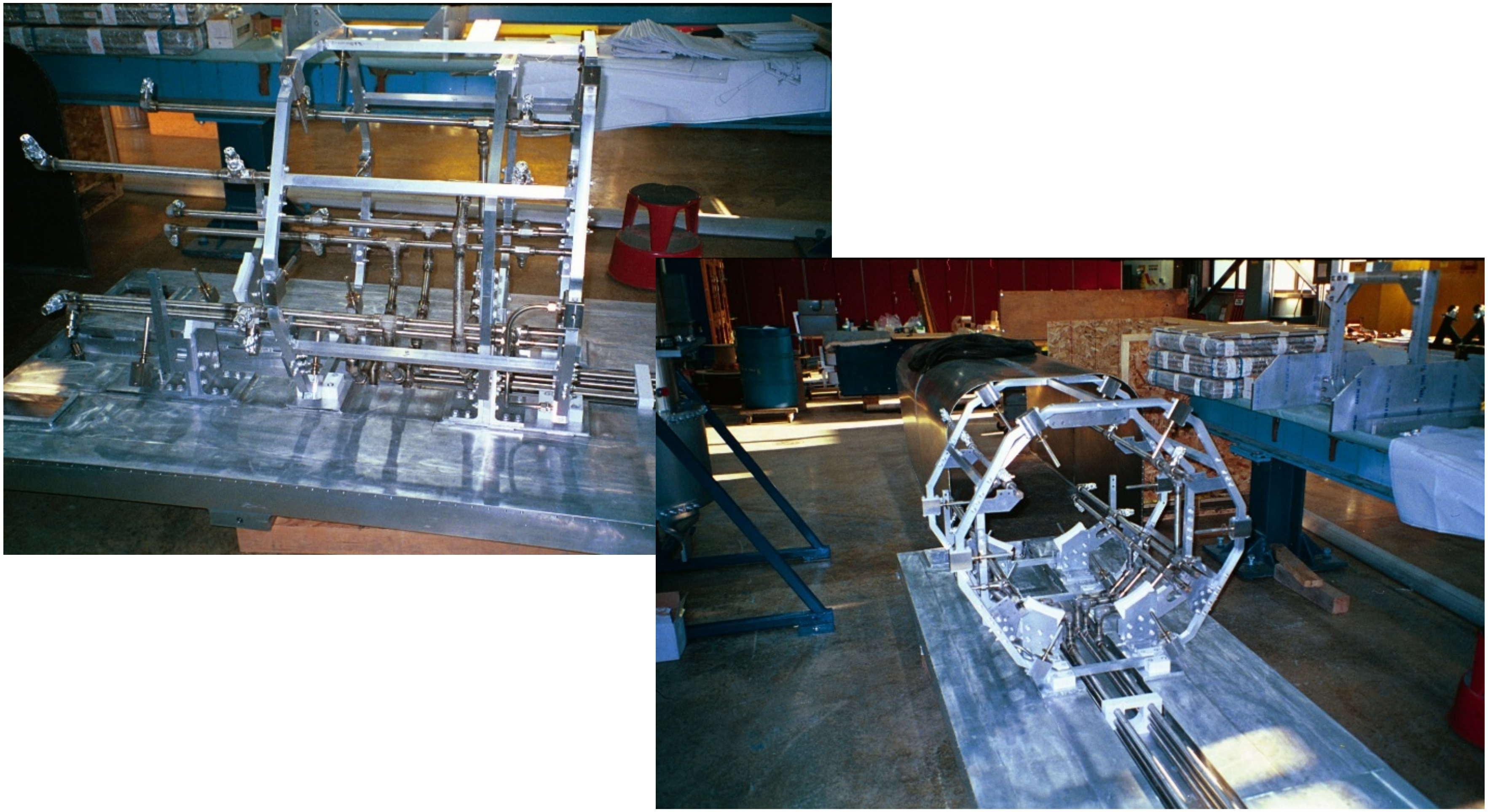
- Forged horn outer conductor
- Horn water cooling: the water spraying system is vibration isolated from the outer conductor, and has its own support structure
- Solid twist transitions, to connect the flat striplines to the cylindrically symmetric horn
- The horn inner conductor was welded at Fermilab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

Outer Conductor after Forging

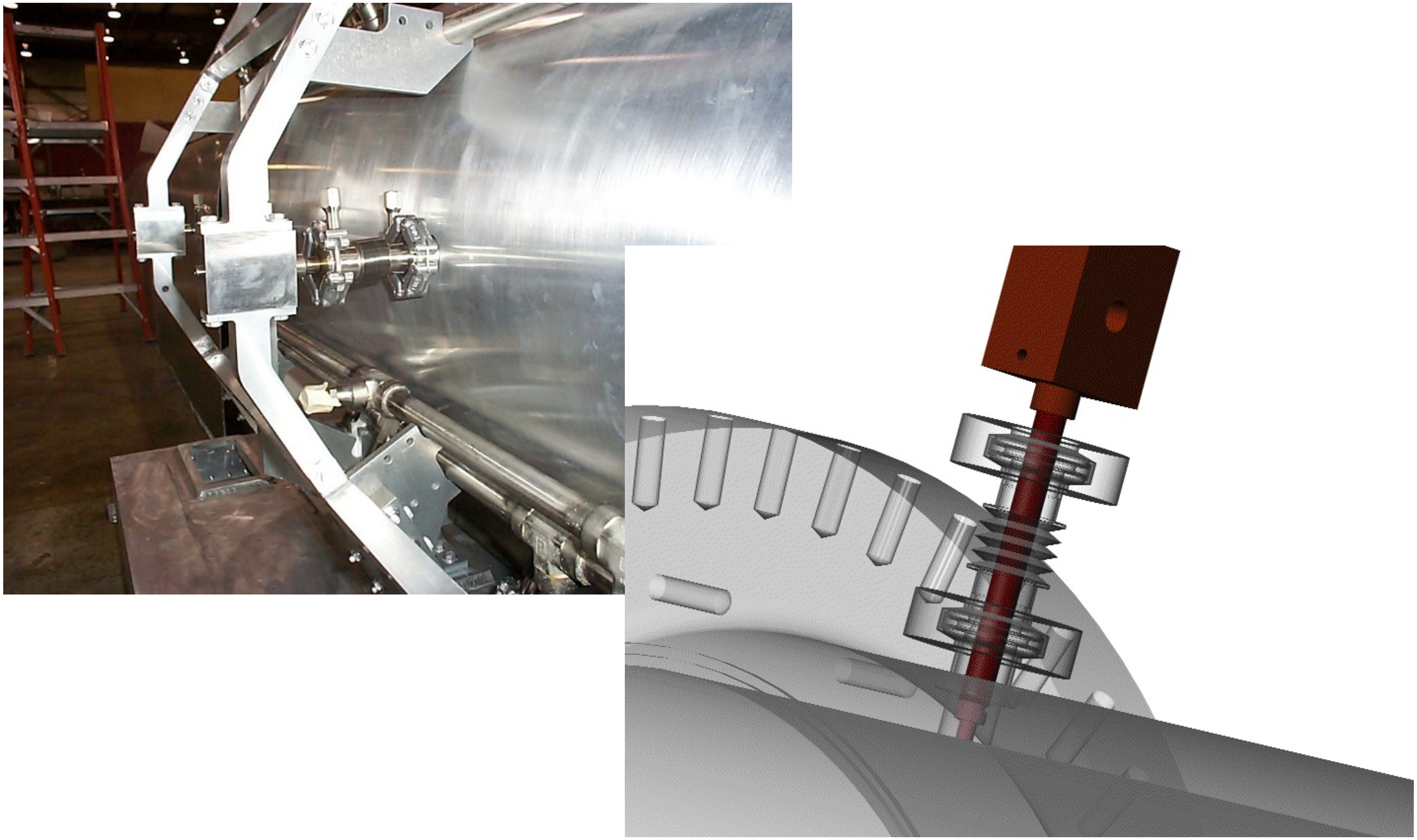
Outer Conductor after Machining

Outer Conductor after Welding

Horn Cooling: Support Structure and Water Manifolds

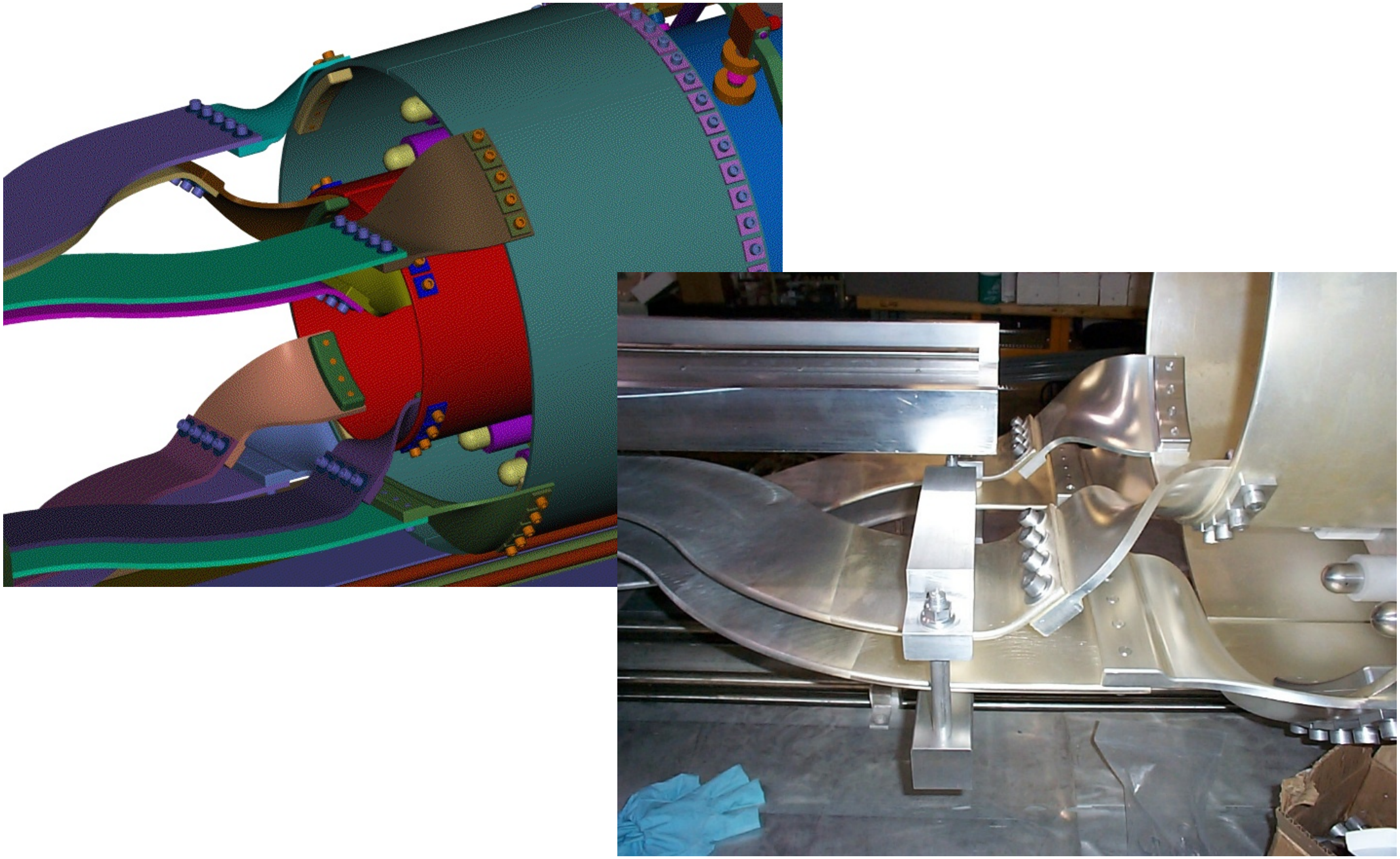


Horn Cooling: Details of a Vibration Isolation Bellows and Nozzle

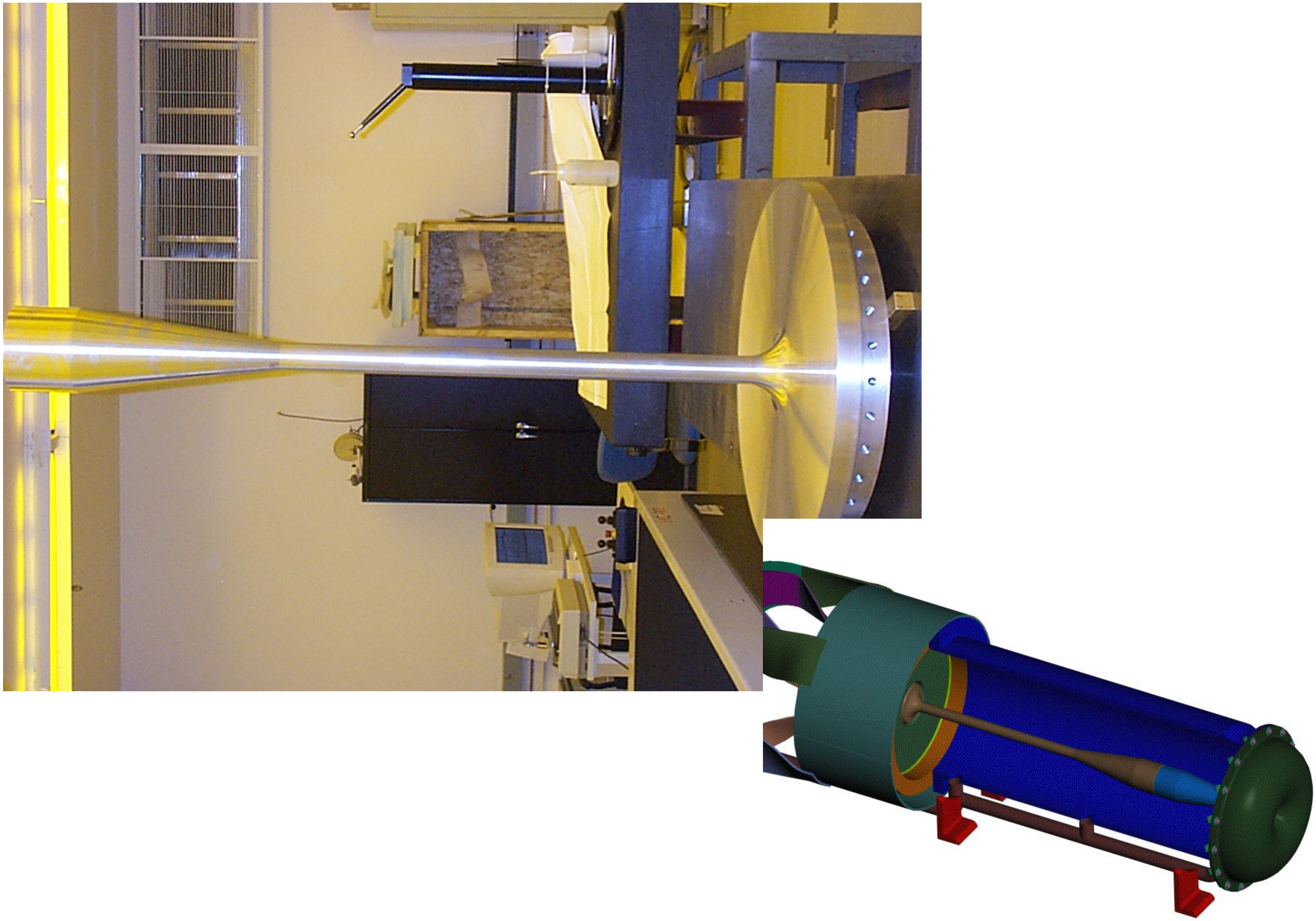


Outer Conductor with Cooling System

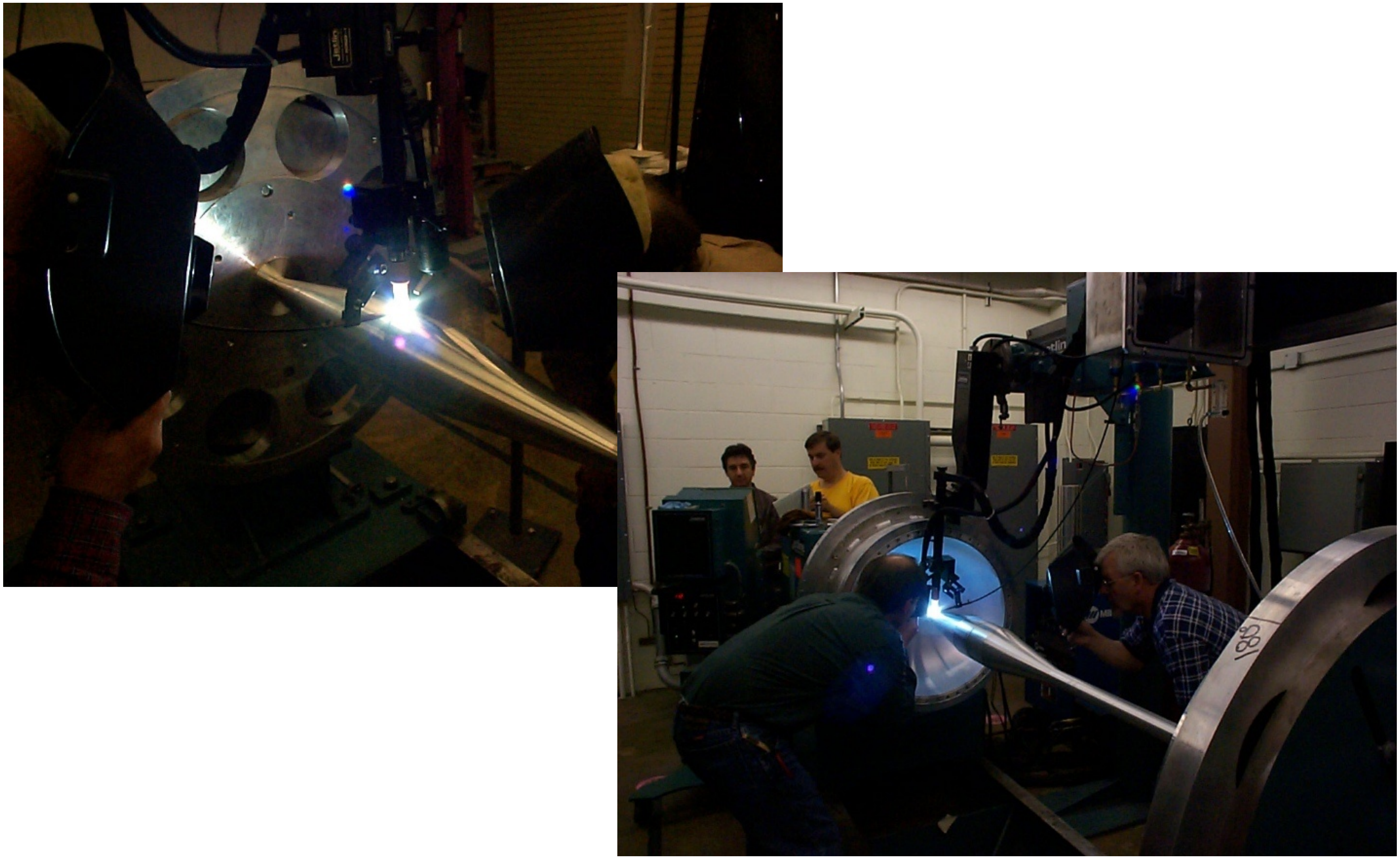
Twist Transitions



Inner Conductor before Welding



Inner Conductor Welds



Radiography of Large Weld

Inserting the Inner into the Outer Conductor

Horn testing

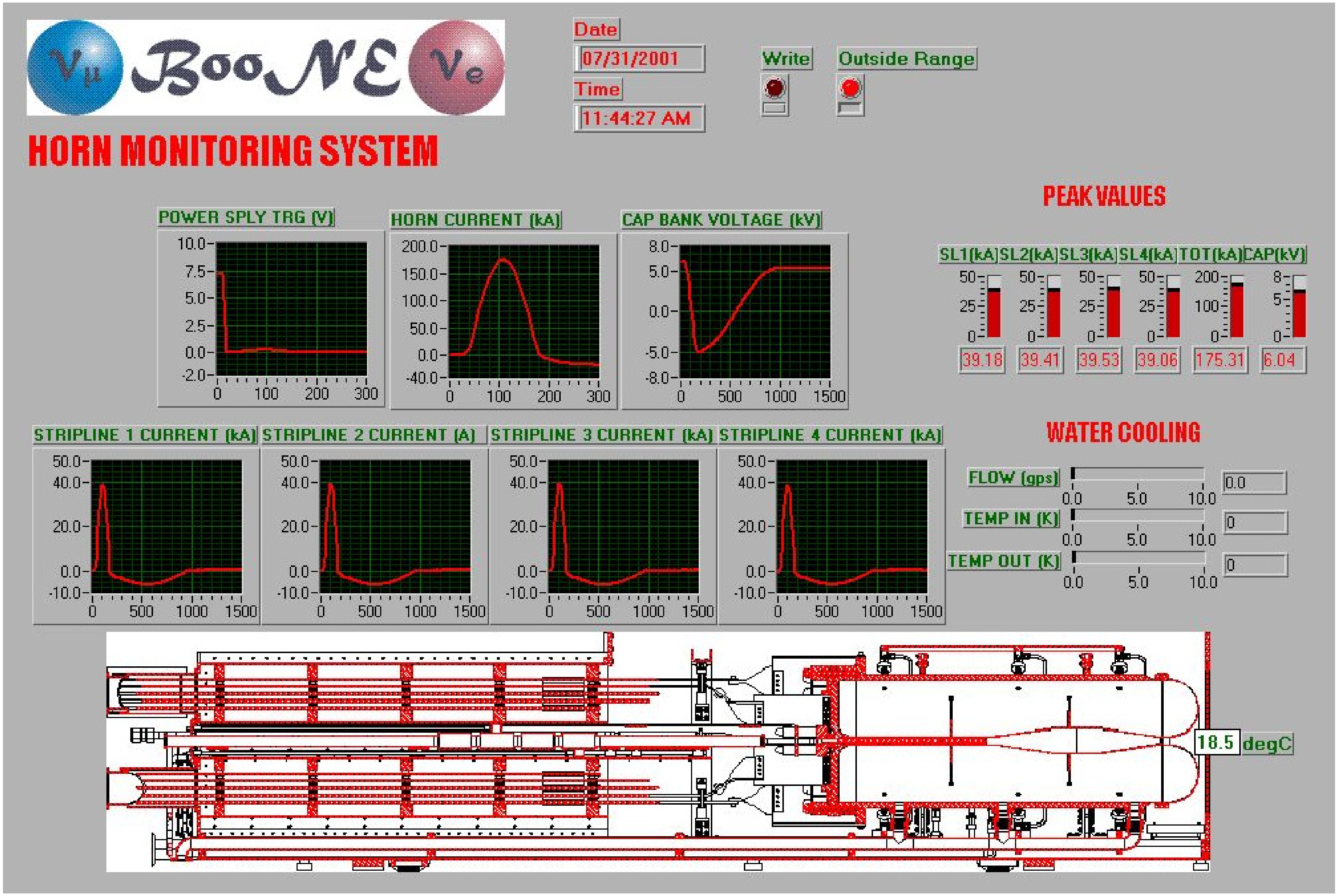
- We tested the MiniBooNE horn system at the MI-8 Test Area between Jul-01 and Feb-02

- 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



Date 07/31/2001

Time 11:44:27 AM

SL1(kA)	SL2(kA)	SL3(kA)	SL4(kA)	TOT(kA)	CAP(kV)
39.18	39.41	39.53	39.06	175.31	6.04

FLOW (gps) 0.0

TEMP IN (K) 0

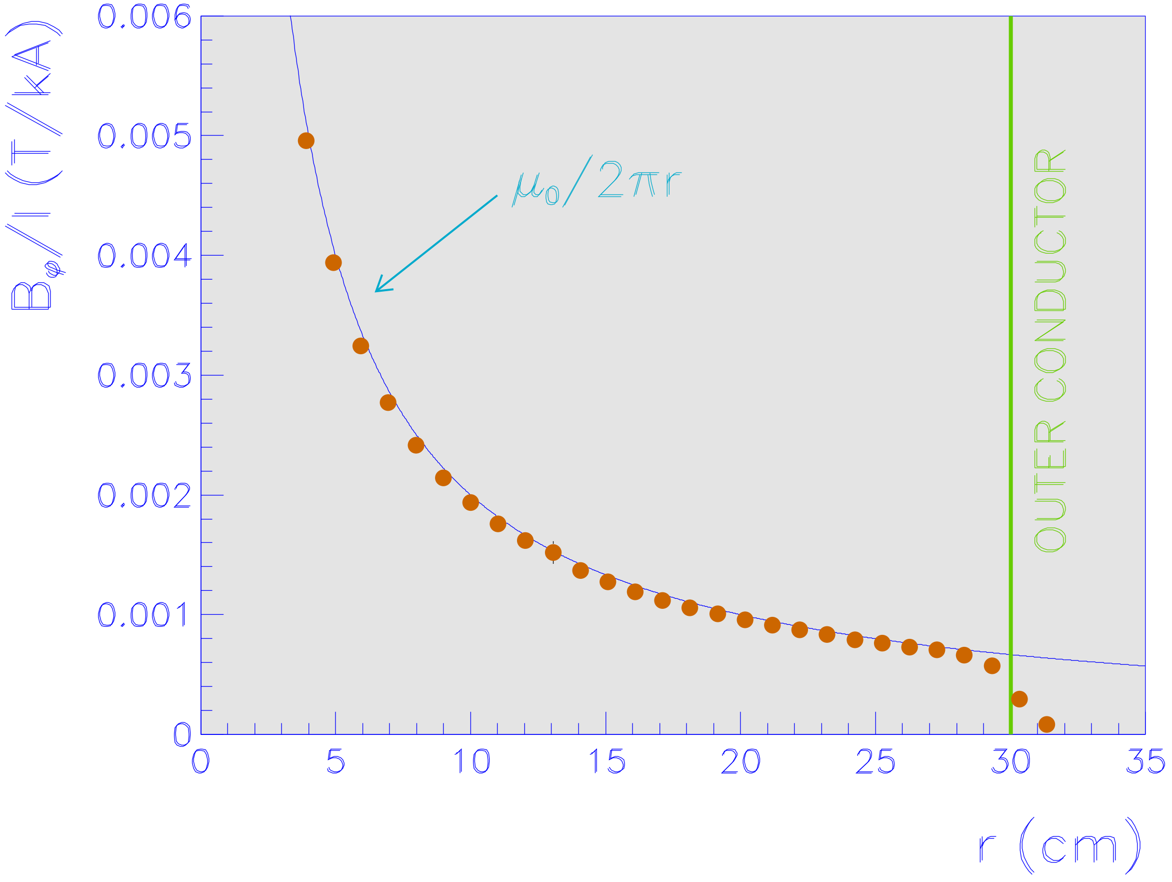
TEMP OUT (K) 0

18.5 degC

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

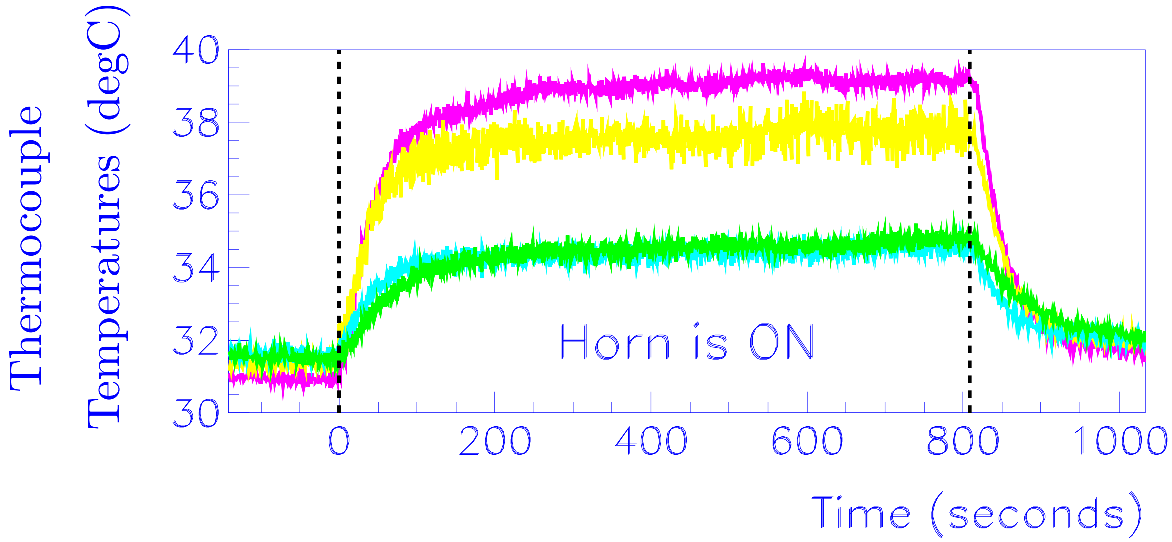
Horn Magnetic Field: Radial Dependence



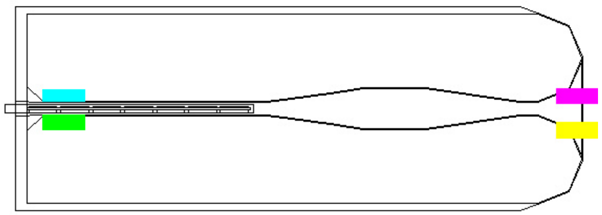
- B_φ: measured magnetic field (azimuthal component)
- I: horn current
- r: radial distance from the horn axis

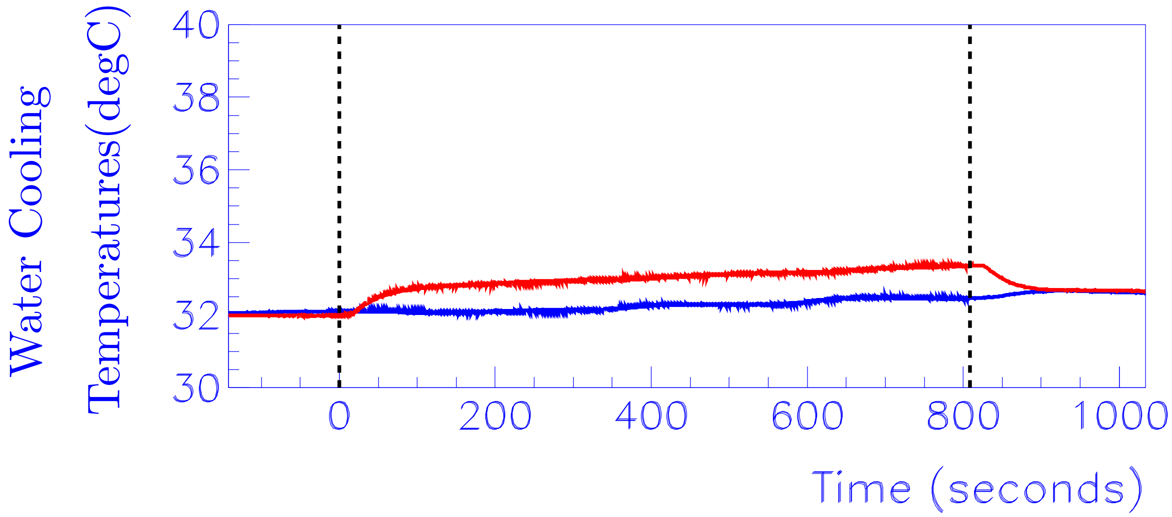
Horn Temperature Measurements

- 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:

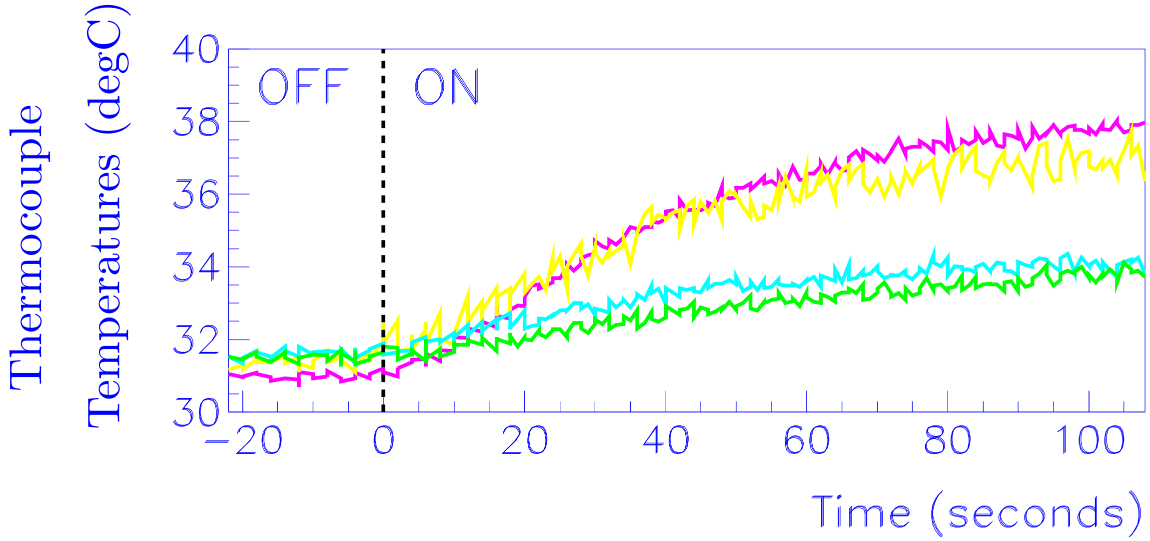




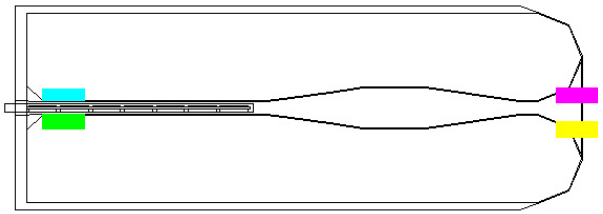
Water Cooling Temperatures:
Supply, Return

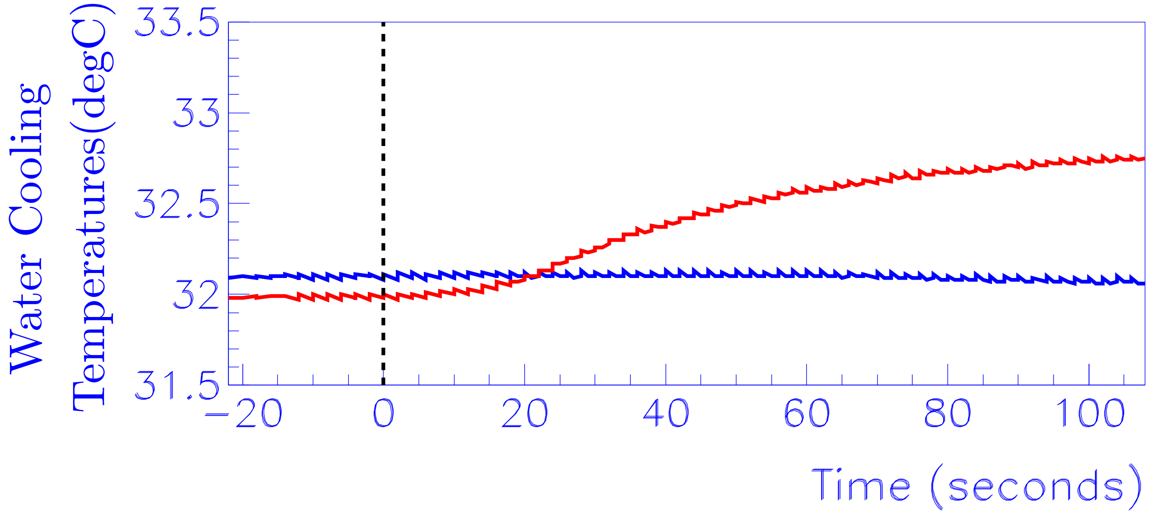
Horn Temperature Measurements (cont'd)

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



Thermocouple locations:





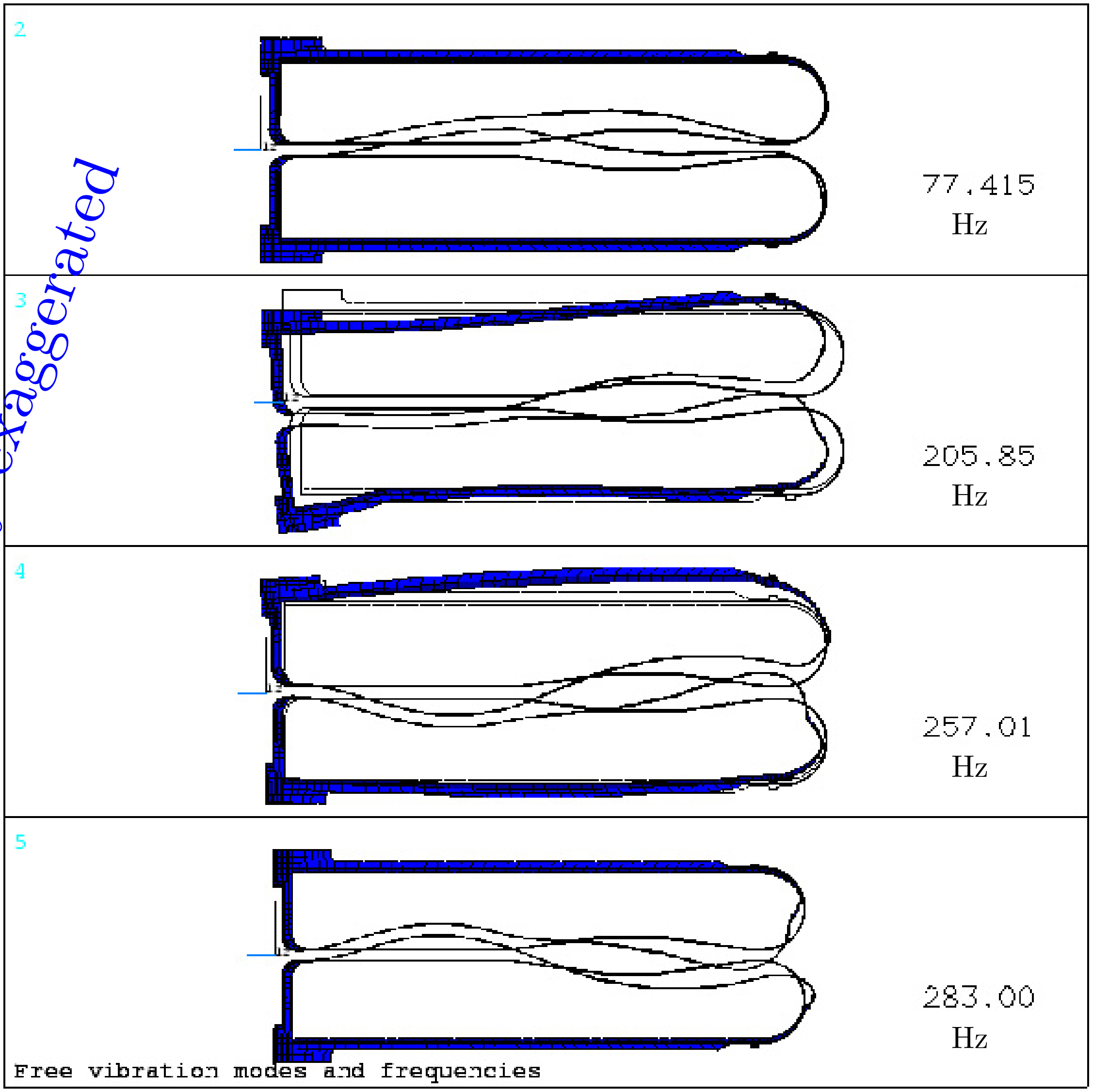
Water Cooling Temperatures:

Supply, Return

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

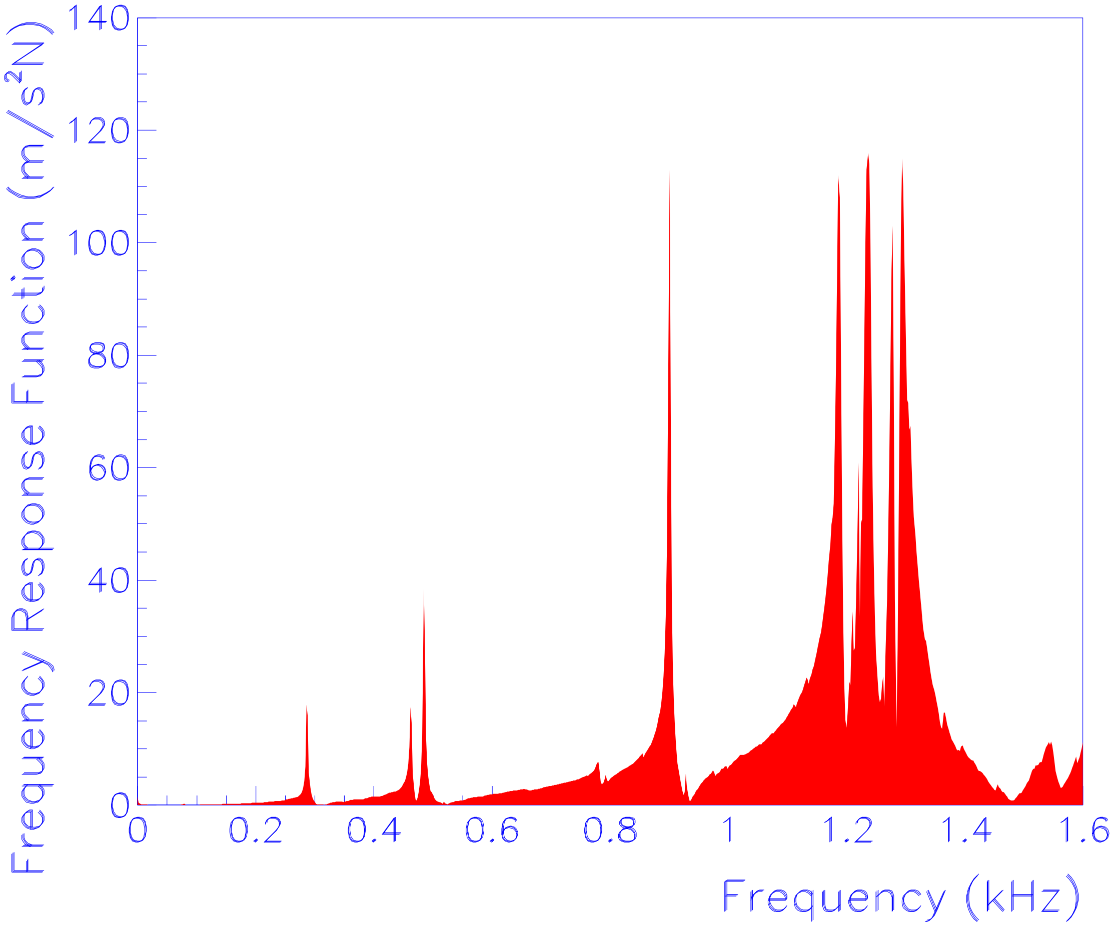
- The pulsing of the horn causes vibrations of the horn's mechanical structure
- The 143 μs-long pulse repeats 10 times, 1/15 sec between each pulse, then the horn is off until 2 seconds from the first pulse in train
- A Fourier analysis of this current pattern shows that the MiniBooNE horn has significant 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

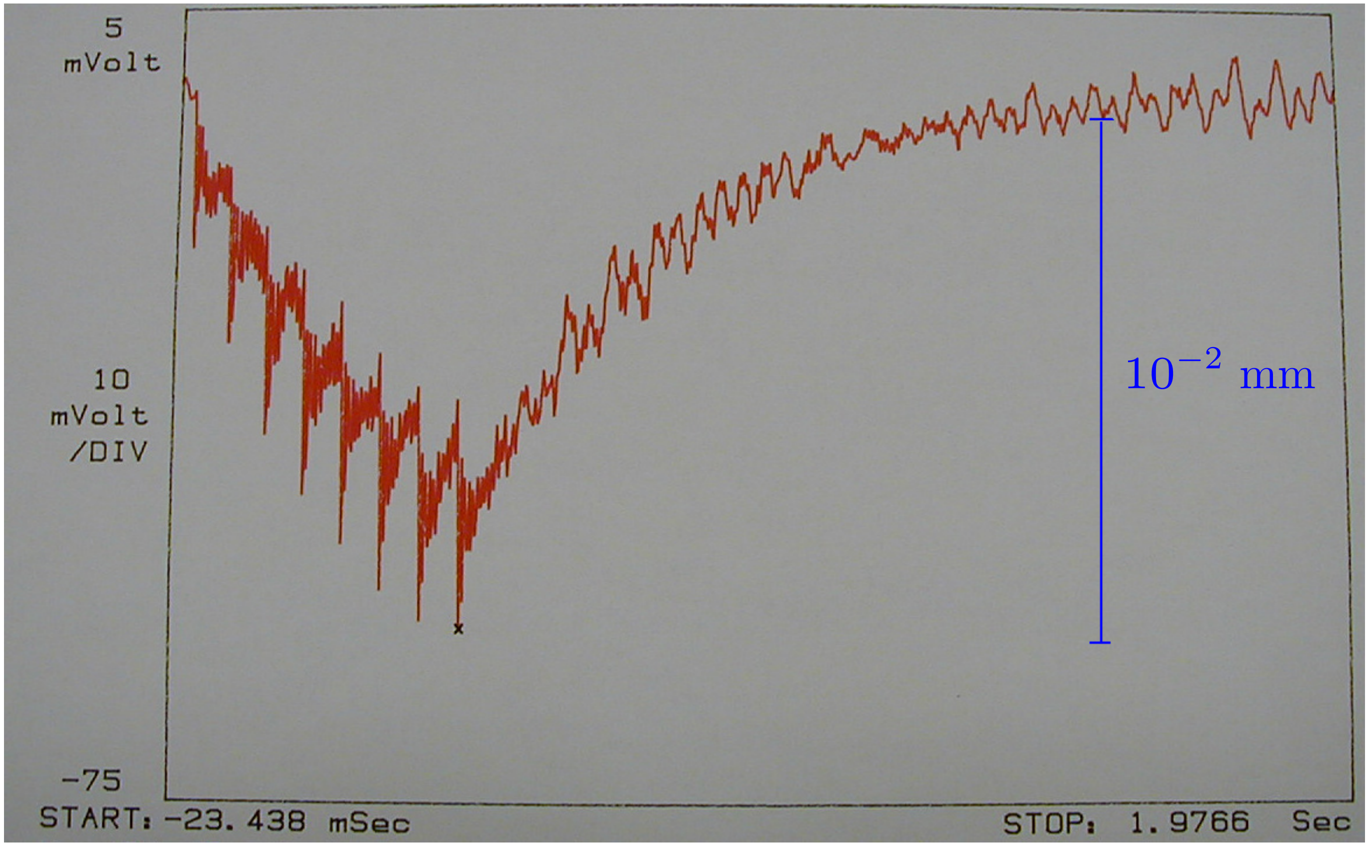
Measurement: Vibrations in the Frequency Domain



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

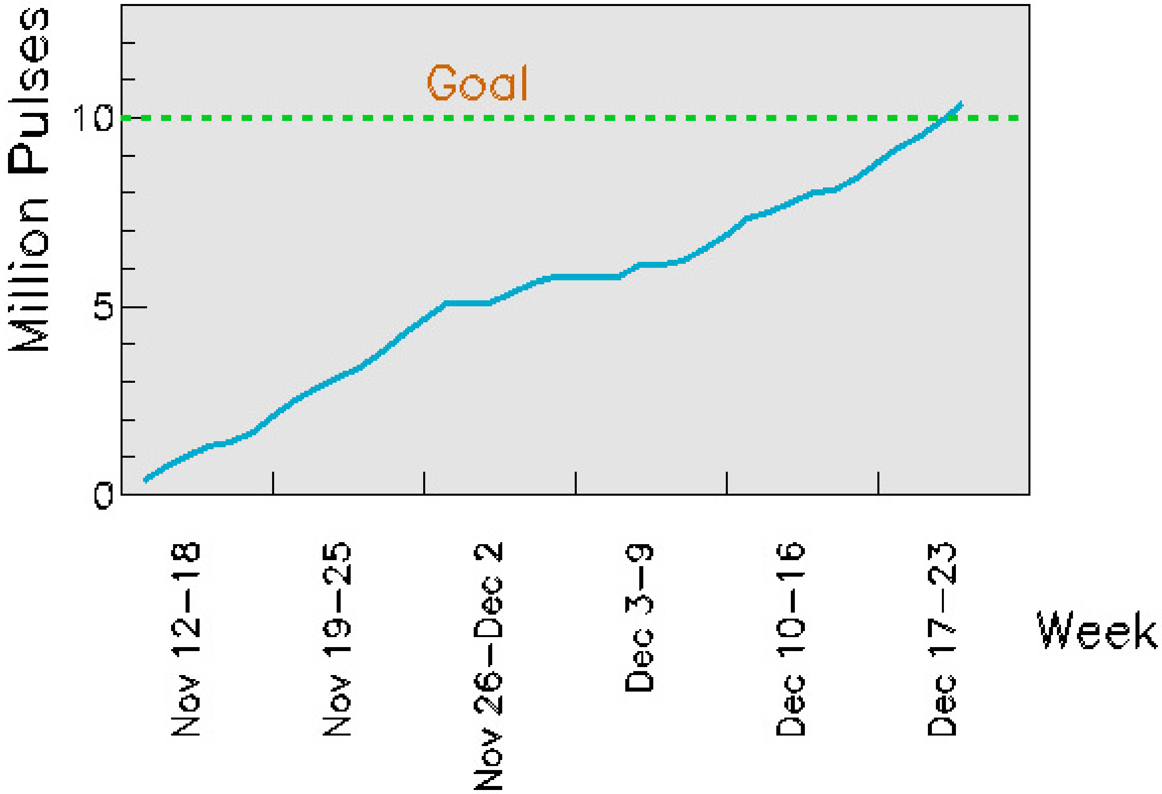
Measurement: Vibrations in the Time Domain and Thermal Expansion

- 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



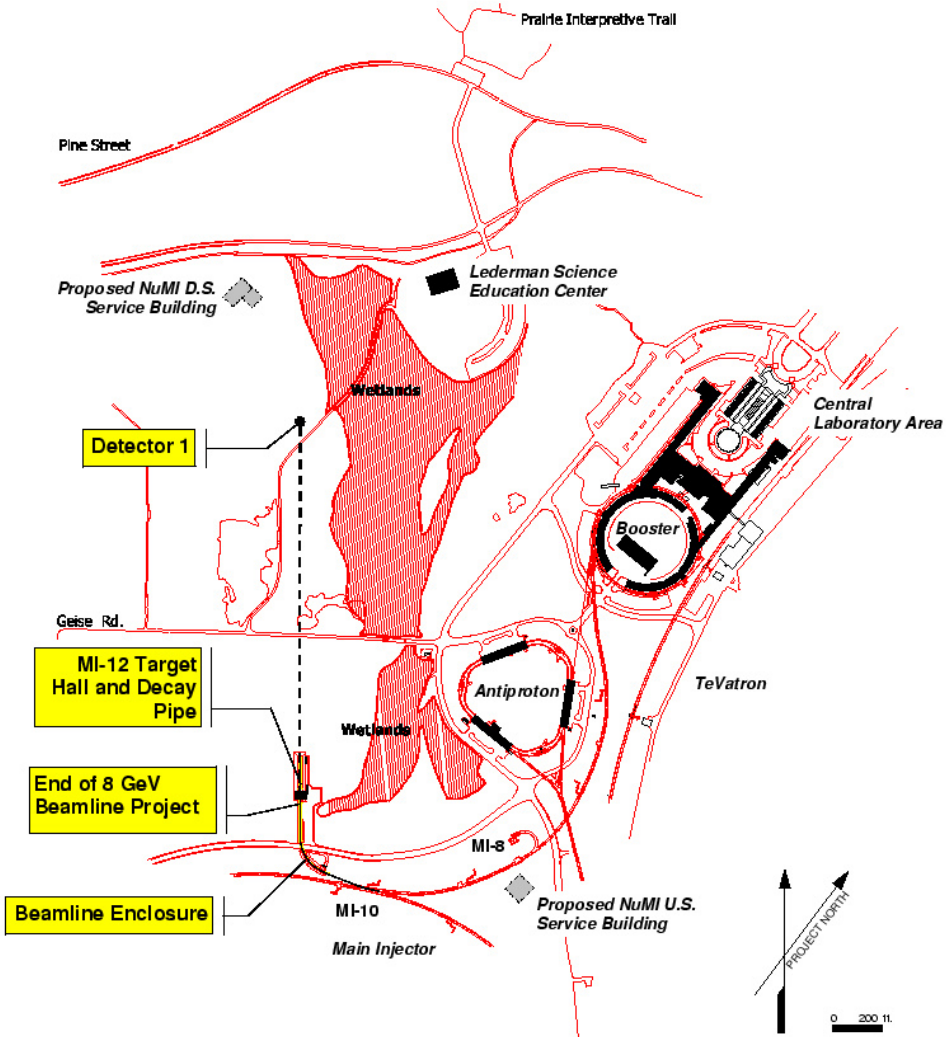
Horn Endurance Test

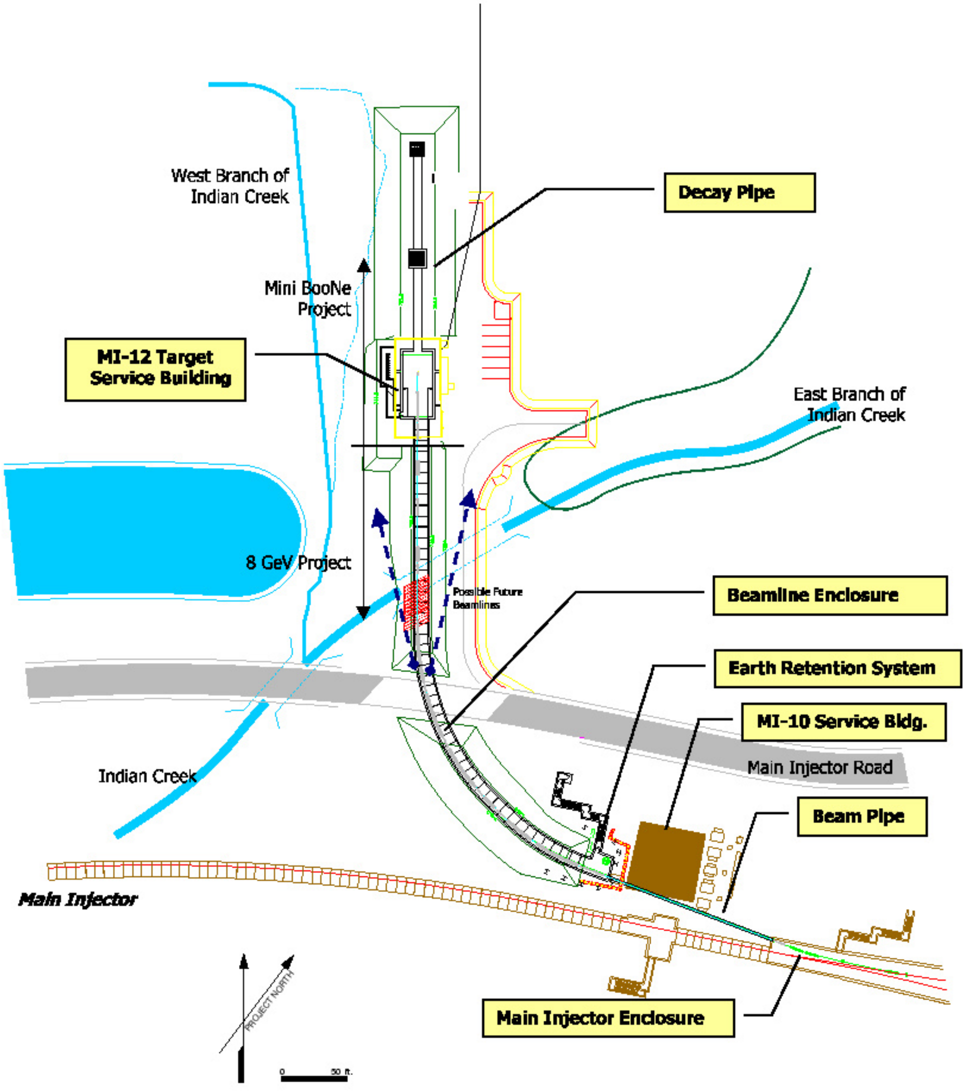
- The horn was succesfully tested for 6 weeks of almost continous operation
- The total number of current pulses through the horn during testing was about 10 millions, or 5% of its design lifetime
- With 10 million pulses, the MiniBooNE horn is already the horn with the longest lifetime ever built



Target Hall

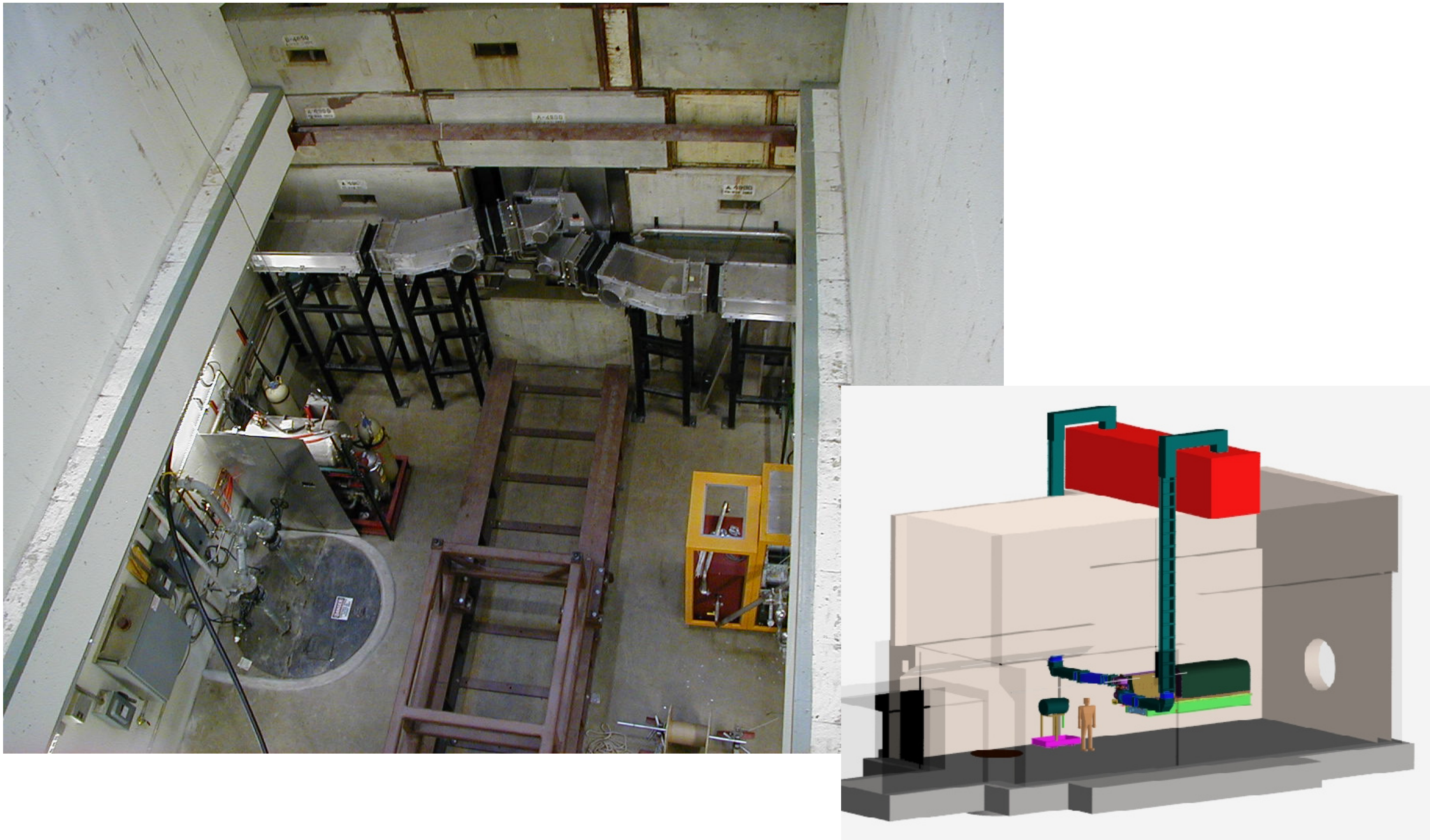
- In March, we started the move the horn to its final destination, the MI-12 target hall:





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}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

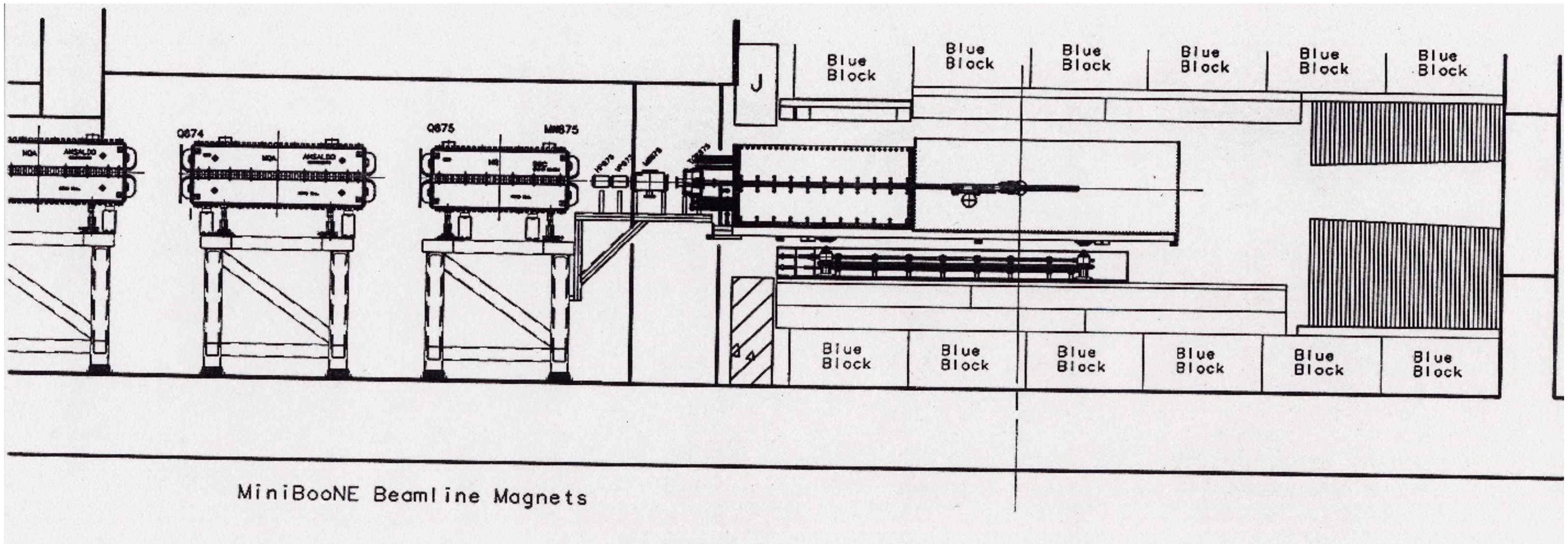
Inner and Outer Coffins

- 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

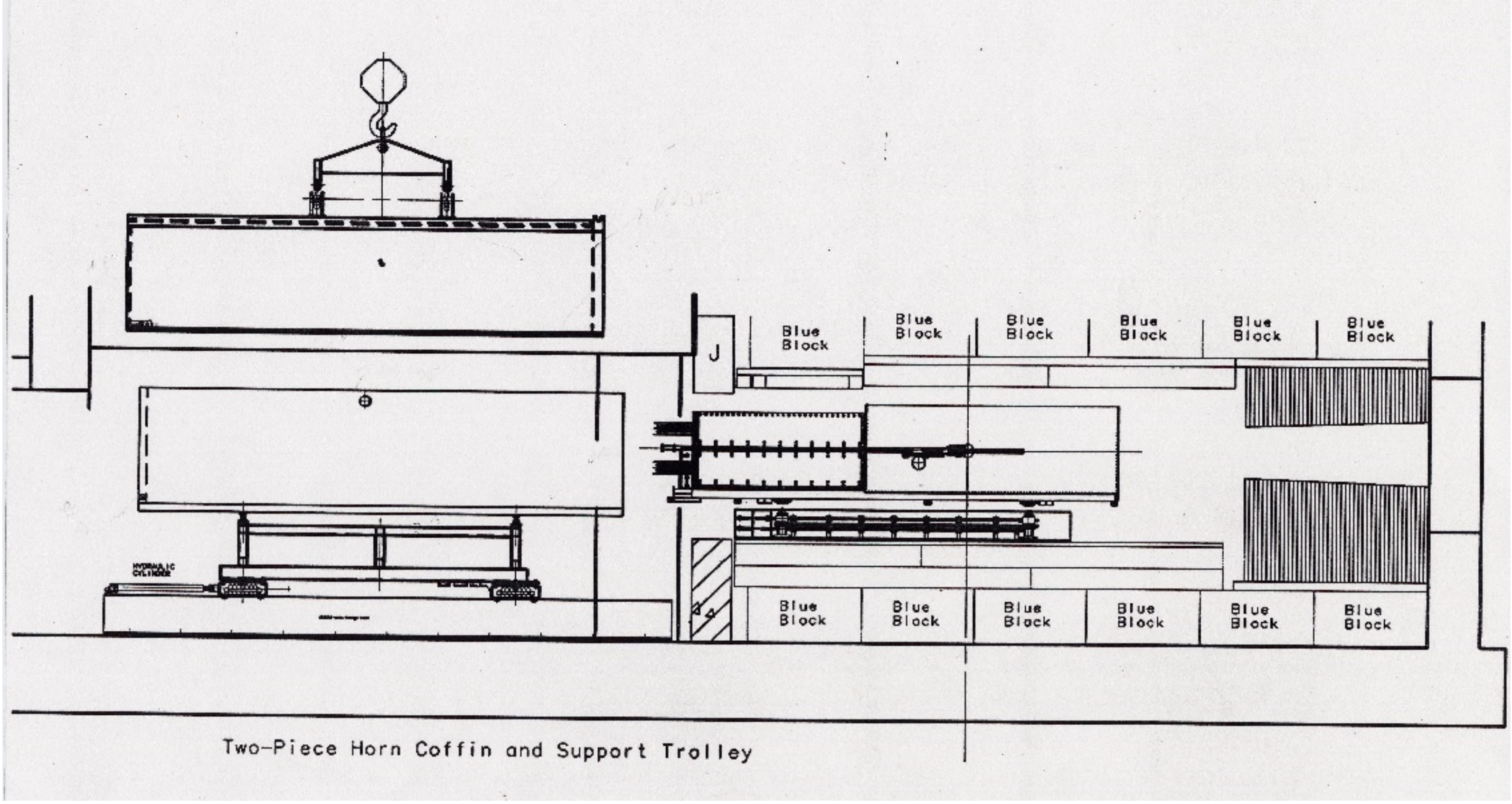
Horn Changeover (cont'd)

- 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

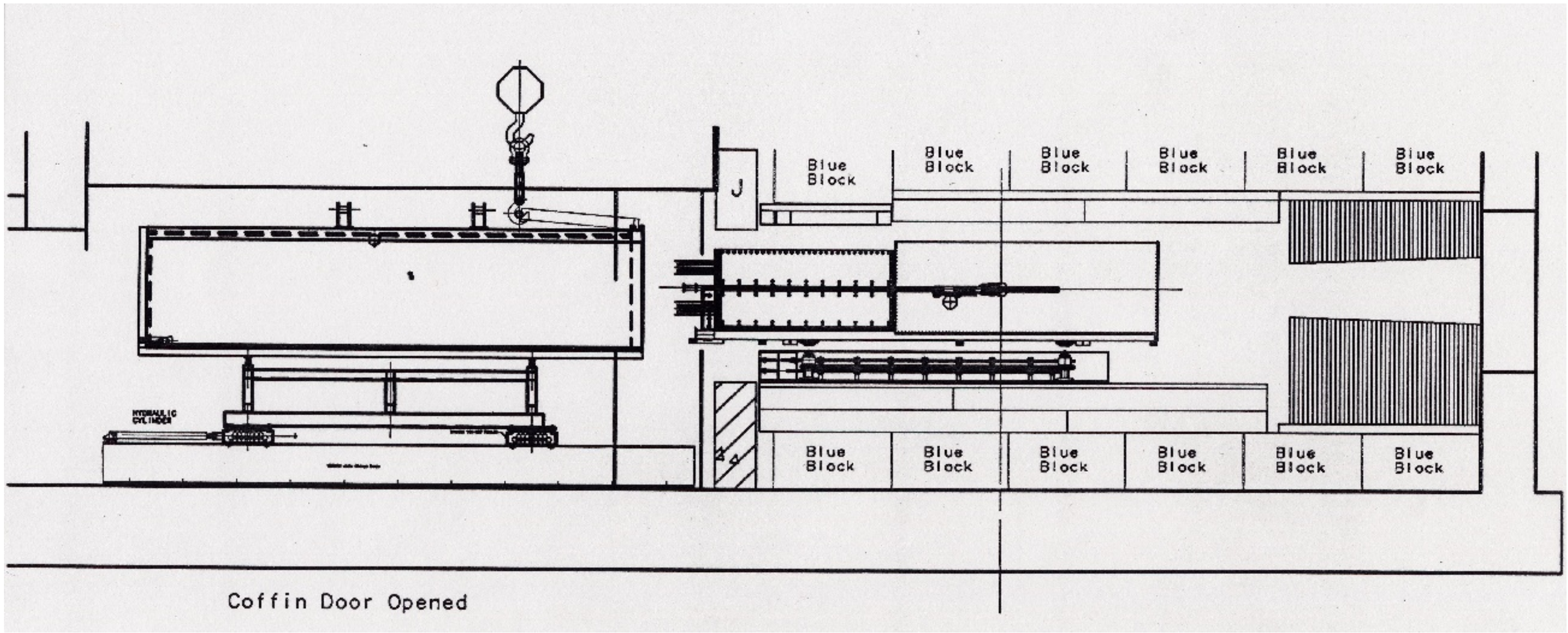


Step 2: Lower Inner and Outer Coffins

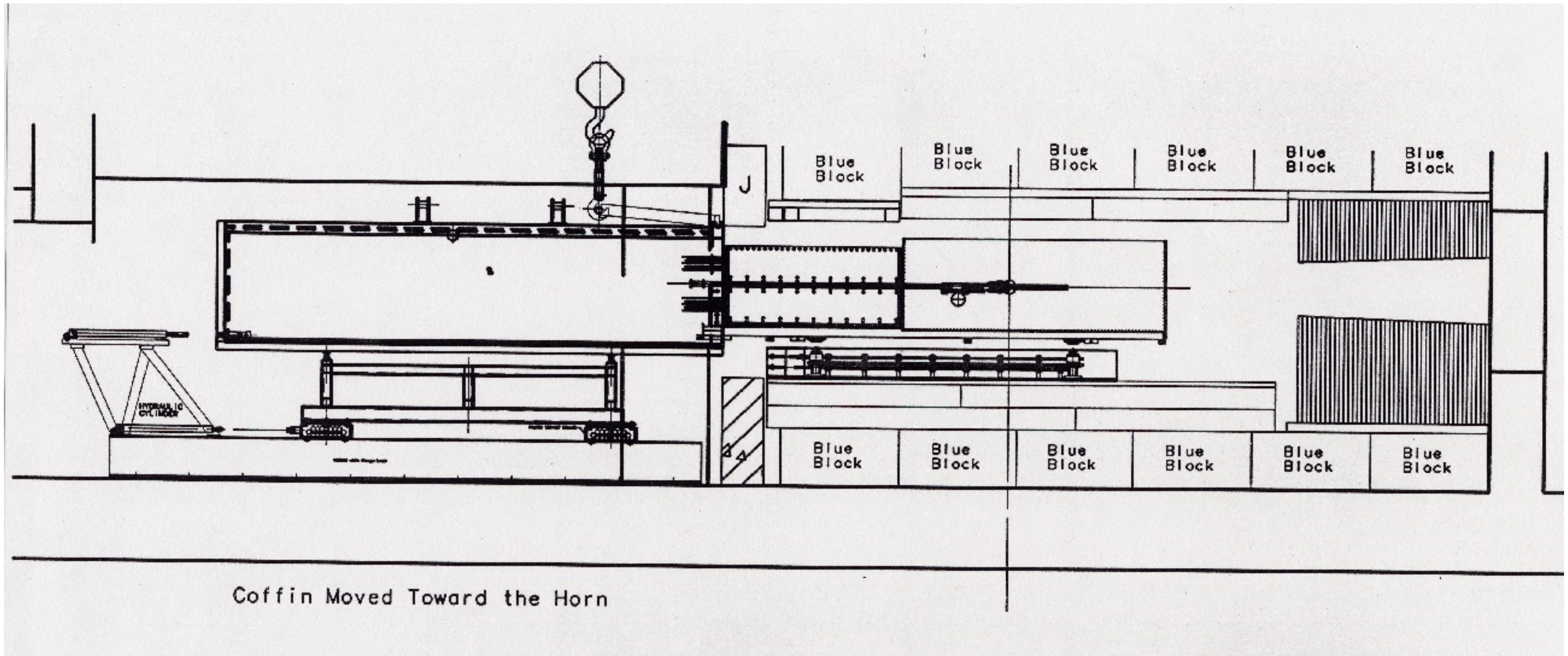


Two-Piece Horn Coffin and Support Trolley

Step 3: Open Inner Coffin Door

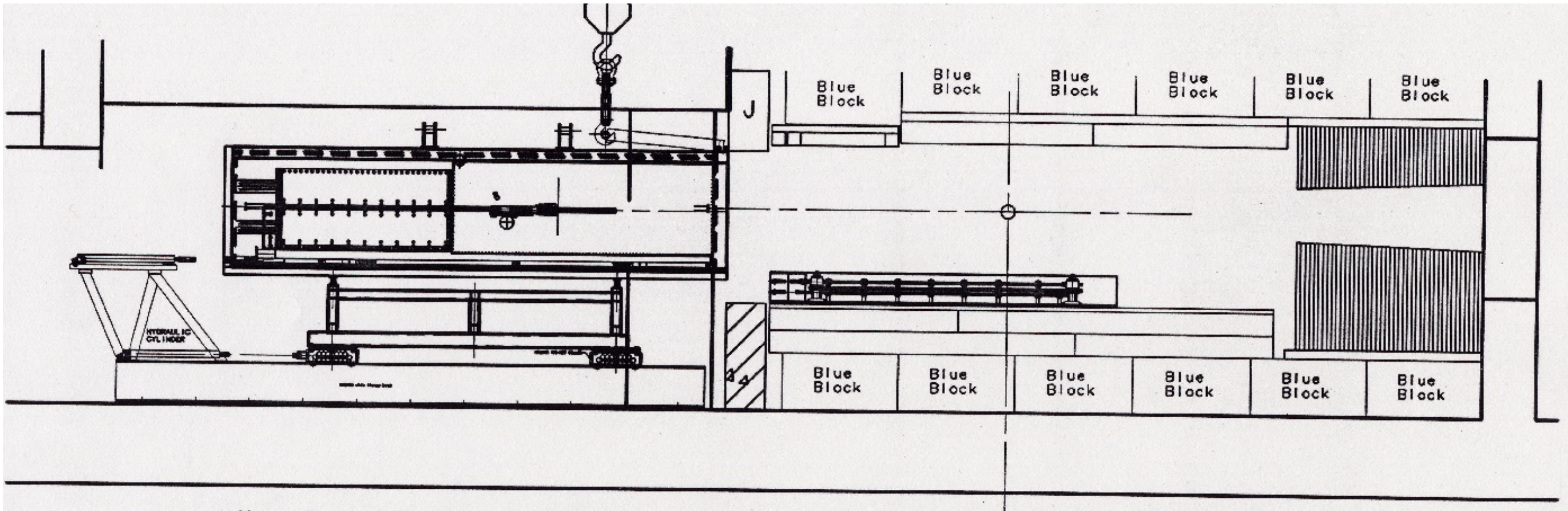


Step 4: Position the Coffins next to the Horn Module



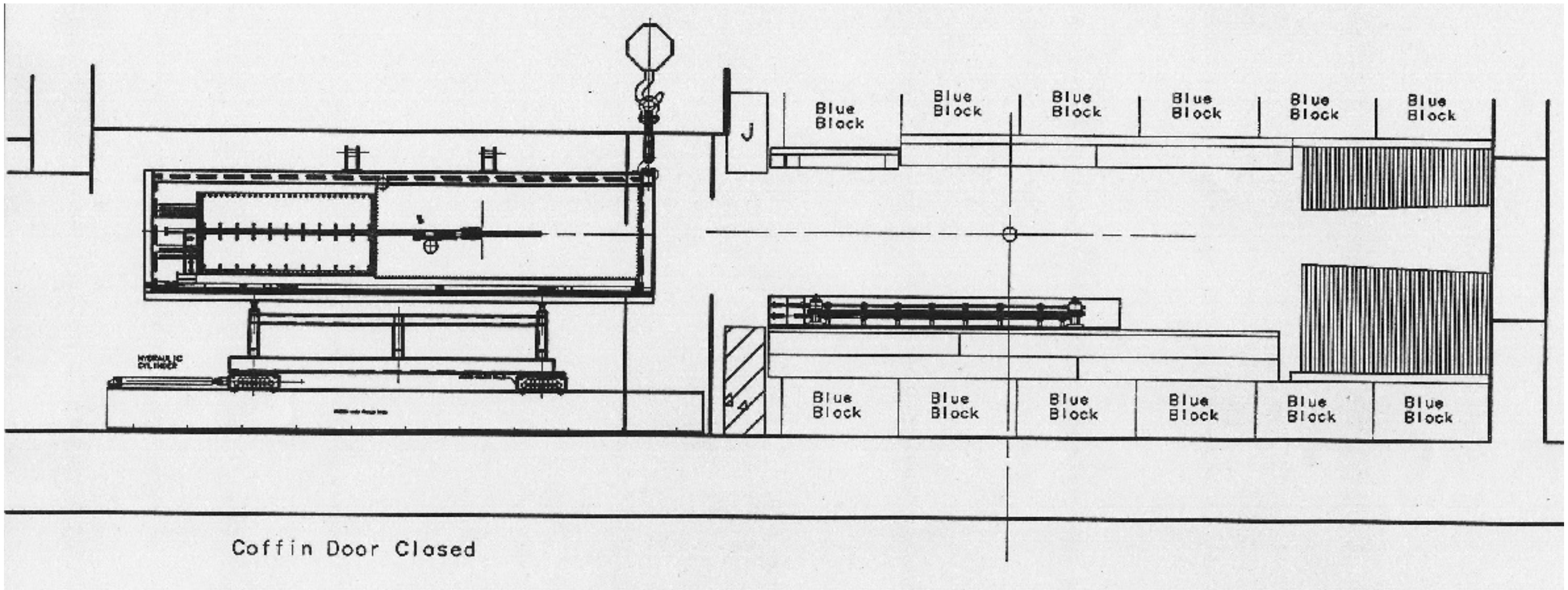
Coffin Moved Toward the Horn

Step 5: Pull the Horn Module in the Coffin



Horn Pulled Inside the Coffin

Step 6: Close Inner Coffin Door



Coffin Door Closed

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