Results and Lessons from the Operation of Current Beams for Existing Neutrino Experiments

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Outline

• Overview of Operating Neutrino Beams
• Results and Lessons from
  – K2K
  – MiniBooNE
  – NuMI
  – CNGS
  – T2K
• Summary
Other Talks on Experience with Operating Beams for Neutrino Experiments

- Working Group 3, Session 7 → Friday 4 July 2008

1. Horn Operational Experience in K2K, MiniBooNE, NuMI and CNGS
   Ans Pardons

2. Radiation Protection Lessons
   Heinz Vincke

3. Delivering High Intensity Proton Beam: Lessons for the Next Beam Generations
   Sam Childress
Overview

• **K2K (1999-2004)**
  \( \nu_\mu \rightarrow \nu_\tau \) oscillation
  \(<E_\nu> = 1.3\text{GeV, 250km baseline};\)
  Results: \( \Delta m_{23}^2 = (2.8 \pm 0.4) \times 10^{-3} \text{eV}^2 @ \sin^2 2\theta_{23} = 1 \) (90\%CL); Phys.Rev.D74:072003, 2006

• **MiniBooNE (2002-)**
  Tests LSND indication of \( \nu_\mu \rightarrow \nu_e \) oscillation
  with similar L/E (500MeV/500m)
  Results: no evidence for \( \nu_\mu \rightarrow \nu_e \) appearance. Phys.Rev.Lett.98, 231801, 2007

• **NuMI (2004-)**
  \( \nu_\mu \rightarrow \nu_\tau \) disappearance oscillation
  \(<E_\nu> = \sim 4\text{GeV, 735km baseline}\)
  Results: \( \Delta m_{23}^2 = (2.43 \pm 0.13) \times 10^{-3} \text{eV}^2 @ \sin^2 2\theta_{23} = 1 - 0.05; \) Phys.Rev.Lett. arXiv:0806.2237, 2008

• **CNGS (2006-)**
  \( \nu_\mu \rightarrow \nu_\tau \) appearance oscillation
  \(<E_\nu> = 17\text{GeV, 735km baseline}\)

• **T2K (2009-)**
  \( \nu_\mu \rightarrow \nu_e \) appearance (non-zero \( \theta_{13}; \))
  precise meas. of \( \nu_\mu \rightarrow \nu_x \) disappearance (\( \theta_{23}, \Delta m_{23}^2, \Delta m_{13}^2 \))
  \(<E_\nu> = 0.7\text{GeV, 2.5° off-axis, 295km baseline}\)
Conventional Neutrino Beams

Components

- **Proton beam**
- **Production target**
  - Target length: compromise between probability of protons to interact and produced particle scattering
  - Target heating with many protons → cooling needed
- **Focusing system**
  - Horns with pulsed high current
  - Minimize material
- **Decay region**
  - Length depends on energy of pions and if very long also muons decay → ν_e contamination
  - Compromise between evacuating or filling with air or helium volume and window thicknesses
- **Absorber**
  - Collect protons not interacted
  - Cooling needed
- **Beam instrumentation**
  - Pion, muon detectors
  - Near detector: flux and energy spectrum of neutrinos

→ Produce pions to make neutrinos

\[ p + C \rightarrow \text{(interactions)} \rightarrow \pi^+, K^+ \]

\[ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu \]
K2K
K2K Neutrino Beam Line

\[ \nu_\mu \rightarrow \nu_\tau \text{ oscillation} \]
\[ \langle E_\nu \rangle = 1.3 \text{GeV}, 250 \text{km baseline} \]

ND: 1kt Water Cherenkov
FD: 50kt Superkamiokande

12 GeV PS

- Cycle 2.2sec
- Beam spill 1.1ms
- \( \sim 6 \cdot 10^{12} \) protons/spill

Super Kamiokande
50kt water Cherenkov detector
K2K Secondary Beam Line

- **Target**: Al (66cm length, 3cm diameter), part of horn1
- **2 horns**: water cooled, 250kA, 0.5 Hz, 2.5ms pulse width
- **Pion monitor**: Cherenkov detector
- **Decay tube**: 200m, He filled
- **Beam dump**: 2.5m iron, 2m concrete
- **Muon monitors**: ionization chamber, silicon pad detectors
K2K Protons on Target
(includes Beam studies and tunings)


K2K-I
From June 1999 to July 2001
Delivered POT: $5.61 \times 10^{19}$
Used for physics analysis: $4.79 \times 10^{19}$

K2K-II
From Dec. 2002 to Nov. 2004
Delivered POT: $4.88 \times 10^{19}$
Used for physics analysis: $4.43 \times 10^{19}$

Total delivered POT (K2K I+II)
$1.049 \times 10^{20}$
Used for analysis
$0.922 \times 10^{20}$
K2K Horn

Strategy: preventive exchange every year

In total five 1st horns, four 2nd horns → Accessible, no remote handling!

2004:

- No exchange due to high radiation
- Nov 2004: Inner conductor of 1st horn broke
- Radiation too high for replacement

Dec 2004: end of run

- POT almost $10^{20}$ as scheduled

Lessons:
- In-situ work reaches RP limit
- Design with remote handling & spare systems
- Decouple target and horn
MiniBooNE
Test LSND indication of $\nu_\mu \rightarrow \nu_e$ oscillation

- Keep L/E same, but different energy, systematic errors, background, add anti-neutrino capability
  - Neutrino Energy: MiniBooNE: $\sim$500MeV (LSND: $\sim$30MeV)
  - Baseline: MiniBooNE: $\sim$500m (LSND: $\sim$30m)
- MiniBooNE detector: 800t pure mineral oil
- Operation since Nov 2002

**MiniBooNE Proton Beam Line**

- 8 GeV proton beam from Booster
  - 1.6 $\mu$s spill
  - 5Hz rate
  - Maximum intensity: $5 \times 10^{12}$ ppp
- Beam on target: $\sigma < 1$mm
MiniBooNE Secondary Beam Line

- **Target**
  - 7 Be slugs (71 cm long, 1.7 $\lambda$), cooled by air flow
- **Horn**
  - 170 kA, 140 $\mu$s, 5 Hz average; water cooled, polarity change possible (~1-2 weeks)
- **Decay pipe**
  - Filled with air, earth around can be cooled via air ducts and heat exchanger
- **25 m absorber**: IN/OUT movable: provides systematic checks on $\nu_e$ contamination from $\mu$ decays
- **50m absorber**
- **Little Muon counter (LMC)**:
  - In situ measurement of Kaon background by counting muons produced from K decays.

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MiniBooNE Statistics

Motivation for Anti-neutrino mode:
- Continue cross-section measurements
- Searching for anti-neutrino disappearance

- 268.01 Million
- 11 E20
- 880703
MiniBooNE Horn

- Water leak and ground fault killed first horn at ~96 million pulses (detected ~end 2003, removed Oct 2004)
  - Stripline/horn connection was corroded
  - Suspect is galvanic corrosion at bellows seal, due to stagnant water around the spray nozzles
- New horn:
  Bottom water outlet bellows:
  - Reduce number of material transitions by welding flanges
  - Avoid stagnant water by refitting with drain lines and new dehumidification system
  → Second horn: already 187 million pulses

Lessons:
- We know how to design inner conductors to resist fatigue
- Concentrate on peripherals
- Galvanic corrosion: avoid trapped water, foresee drainage, choose material carefully
MiniBooNE Absorber

- Observation during early anti-neutrino run (2006):
  - Decreasing Nu/POT
- After much effort problem was understood:
  - Several absorber plates from 25m movable absorber fell into the beam
  - Caused drop in event yield

→ Hardened steel chains weakened by radioactive atmosphere
→ Plates were remounted using softer steel which is not subject to hydrogen embrittlement effect

Lessons:
→ air in decay tube → aggressive radicals
→ CNGS: vacuum; K2K & T2K: Helium
→ NuMI: vacuum, since Dec 07 Helium
NuMI
**NuMI: Neutrinos at the Main Injector**

- **Search for oscillation**
  - $\nu_{\mu} \rightarrow \nu_{\tau}$ disappearance

- **735 km baseline**
  - From Fermilab to Minnesota
  - Elevation of 3.3°
  - Near detector: ~1ktons
  - Far detector: MINOS 5.4 ktons

- **Commissioned in 2004**
- **Operating since 2005**

**NuMI Proton Beam Line**

- **From Main Injector:** 120 GeV/c
- **Cycle length:** 1.9 s
- **Pulse length:** 10μs
- **Beam intensity:** $3 \cdot 10^{13}$ ppp
- $\sigma \sim 1$ mm
NuMI Secondary Beam Line

- **Water cooled graphite target**
  - 2 interaction lengths
  - Target movable in beam direction inside horn to change $\nu$ energy
- **2 horns**
  - Water cooled, pulsed with 2ms half-sine wave pulse of up to 200kA
- **Decay pipe:**
  - 675m, diameter 2m, vacuum 1 mbar, since Dec07: Helium 1bar
- **Hadron absorber:**
  - Absorbs ~100kW protons and other hadrons
- **1 hadron monitor:** fluxes and profiles
- **3 muon monitor stations:** fluxes and profiles
NuMI Proton Parameters

4.86\times10^{20} \text{ Protons on Target as of 02 June '08}

**Average intensity/pulse (2007/2008):**  < 3.08\times10^{13} \text{ ppp} >

**Average beam power (2007/2008):**  < 233.6 \text{ kW} >

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NuMI Target

47 graphite segments, 20mm length and 6.4 x 15mm² cross-section
0.3mm spacing between segments,
total target length 95.4 cm (2 interaction lengths)

Water cooling tube → provides mechanical support

Target/Baffle carrier
Allows for 2.5 m of target motion to vary the beam energy
... NuMI Target

1. Water leak soon after turn-on (March 2005)
   → ‘fixed’ with He backpressure holding back water from leak

2. September 2006: Target motion drive shaft locked due to corrosion
   → lead to target replacement

3. June 2008: Target longitudinal drive failure
   → In work cell repaired
   → reinstall

Water in target vacuum chamber
NuMI Horns Experience

Several problems:

- Ground fault, water line contamination by resin beads, water leaks at ceramic isolator...

• System designs looked toward hot component replacement, not repair
• However, most problems have been repairable
  – Challenging after beam operation
• Most recent failure (June 08) led to replacement of horn 1 due to high radiation field making repair too challenging

Lessons:
- Concentrate in design on peripherals (insulating water lines)
- Design with repair in mind; test thoroughly without beam
- Foresee tooling, training
- Work Cell
NuMI Work Cell

Installed in most downstream part of target area

Connections done through module by person on top of work cell

- Railing
- Module
- Lead-glass window
- Horn
- Remote lifting table
- Concrete wall

3 m
NuMI Radiological Aspects

• Target hall shielding effectiveness and air activation levels
  – Matched expectations

• Tritium levels: major issue! Levels much greater than expected in water pumped from NuMI tunnel
  – Very low levels compared to regulatory limits, but important to solve
  – Major source: traced to production in steel surround for target hall chase. Carried to tunnel water by moisture in chase air.
  – Effective remedy: through major dehumidification of target hall and chase air
    • Positive side effect: controlling corrosion effects for technical components (previously 60% rel humidity, now <20%).
CNGS

- **Search for** $\nu_\mu - \nu_\tau$ oscillation (appearance experiment)
- **732 km baseline**
  - From CERN to Gran Sasso (Italy)
  - Elevation of 5.9°
  - Far detector: OPERA 146000 emulsion bricks (1.21 kton), Icarus 600 tons
- **Commissioned 2006**
- **Operation since 2007**

**CNGS Proton Beam Line**

- **From SPS**: 400 GeV/c
- **Cycle length**: 6 s
- **Extractions**:
  - 2 separated by 50ms
- **Pulse length**: 10.5µs
- **Beam intensity**:
  - $2 \times 2.4 \cdot 10^{13}$ ppp
- $\sigma \sim 0.5$mm
- **Beam performance**:
  - $4.5 \cdot 10^{19}$ pot/year
CNGS Secondary Beam Line

Air cooled graphite target magazine
- 4 in situ spares
- 2.7 interaction lengths
- Target table movable horizontally/vertically for alignment

• TBID multiplicity detector
• 2 horns (horn and reflector)
  - Water cooled, pulsed with 10ms half-sine wave pulse of up to 150/180kA, 0.3Hz, remote polarity change possible

• Decay pipe:
  - 1000m, diameter 2.45m, 1mbar vacuum
• Hadron absorber:
  - Absorbs 100kW of protons and other hadrons
• 2 muon monitor stations: muon fluxes and profiles
CNGS Beam

- **2006**: CNGS Commissioning
  - $8.5 \cdot 10^{17}$ pot
- **2007**: 6 weeks CNGS run
  - $7.9 \cdot 10^{17}$ pot
    - 38 OPERA events in bricks (~60000 bricks)
    - Maximum intensity: $4 \cdot 10^{13}$ pot/cycle
    - Radiation limits in PS

→ OPERA detector completed by June 2008
→ CNGS modifications finished

- **2008**: CNGS run: June-November → NOW! ←
  - $5.43 \cdot 10^{17}$ pot on Friday, 27Jun08, after 9 days running
    → more than 50 OPERA events in bricks!
  - Expected protons in 2008: ~$2.6 \cdot 10^{19}$ pot
CNGS Polarity Puzzle

Muon detectors very sensitive to any beam change – give online feedback for neutrino beam quality!!

- Observation of asymmetry in horizontal direction between
  - Neutrino (focusing of mesons with positive charge)
  - Anti-neutrino (focusing of mesons with negative charge)
... CNGS Polarity Puzzle

Explanation: Earth magnetic field in 1km long decay tube!
- Calculate B components in CNGS reference system
- Partially shielding of magnetic field due to decay tube steel
→ Results in shifts of the observed magnitude
→ Measurements and simulations agree very well

Lessons:
→ Useful to change polarity quickly

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CNGS Target

Target: 13 graphite rods, 10cm long, $\varnothing = 5\text{mm}$ and/or $4\text{mm}$

Ten targets (+1 prototype) have been built. They are assembled in two magazines.
...CNGS Target

Alignment of target-horns- beam done with survey team during installation
- sensitivity of order of 1mm
- changes every year

→ beam based alignment of target hall components

1.) Beam scan across target

2.) Target scan across horn

Lessons:
→ alignment with beam to be done during every start-up
→ muon detectors very sensitive! Offset of target vs horn at 0.1mm level, beam vs target at 0.05mm level.
CNGS Horn and Reflector

- Remote electrical connection
- Remote water connection
- Remote shielding handling

→ Exchange of horn remotely!
CNGS Horn and Reflector

- Leak in water outlet of cooling circuit of reflector after $4 \cdot 10^5$ pulses (Oct 06)
  - Design fault in ceramic insulator brazing
  - Repair and exchange possible
    - Replace brazed connections by connections under pressure
    - Detailed dose planning
    - Detailed tooling and training
    - Additional local shielding
      - total integrated dose: 1.6mSv
- Aug 2007: Cracks in busbar flexible connection of reflector
  - New design during shutdown 2007/08 for horn and reflector

Lessons:
- Concentrate in design on peripherals (insulating water lines)
- Design with repair in mind; test thoroughly without beam
- Foresee tooling, training
CNGS Radiation Issues

CNGS: no surface building above CNGS target area  
→ Large fraction of electronics in tunnel area

- During CNGS run 2007:
  - Failure of ventilation system installed in the CNGS tunnel area due to radiation effects in the control electronics (SEU due to high energy hadron fluence)
- Modifications during shutdown 2007/08:
  - move as much electronics as possible out of CNGS tunnel area
  - Create radiation safe area for electronics which needs to stay in CNGS
  - Add shielding → decrease radiation by up to a factor $10^6$

Lessons:
→ move electronics to surface building if possible
→ don’t design straight tunnels between target area and service gallery-
  - use chicane design
→ be aware of standard components in electronics
→ address radiation hardness of installed electronics and material for high intensity areas
... CNGS Radiation Issues

- Tritium level in sumps, similar observation like at NuMI
- Special treatment required for water
  - Alkaline (activated) water in hadron stop sump
  - Collection of hydrocarbons upstream of target area – luckily not activated
- Ventilation and water cooling system
  - Fine tuning of valves, ventilator: tedious, long commissioning time
  - Efficient leak detection in case of water leak
T2K

Long baseline neutrino oscillation experiment from Tokai to Kamioka.

Physics goals
- Discovery of $\nu_\mu \rightarrow \nu_e$ appearance
- Precise meas. of disappearance $\nu_\mu \rightarrow \nu_x$

Pseudo-monochromatic, low energy off-axis beam, tunable by changing the off-axis angle between 2° and 2.5° ($E_\nu = 0.8\text{GeV} \sim 0.65\text{GeV}$)
First Neutrino Beam:
April 2009

Construction of building: Jun08
Target: full prototype Dec08
Horns 1&3: delivered and tested
Horn2: delivered Jun08
Assembly starts Aug08

On axis detector:
Available day one
Off axis detector:
Fall 09 for high-intensity operation

10/14 doublets installed
Completed in Dec 08

SCFM at ARC Section

Near Neutrino Detector
Beam Dump
Decay Volume

Installed and aligned

Installed Mar 08

Primary Beam-line

Muon Monitoring Pit

295km to Super-Kamiokande

Assembly Sep08
Installation Oct08

Finished Aug08
Summary
Summary

• **Neutrino beam design**
  – Basics are ‘straightforward’ + lots of experience
    (Beam optics, Monte Carlo, mechanical/electrical design tools)

• **Start-up and initial (lower intensity) running**
  – Generally very smooth

**BUT Challenges:**

• **Hostile environment**
  – Radioactivity (high intensity, high energy proton beams)
  – Humidity (water cooling, infiltrations, …)
  – Mechanical shocks (particle and electric pulses)

• **Design tends to be compromise of**
  – Long lifetime of equipment
  – Maximal performance of beam
  – Remote repair vs. remote exchange of equipment

→ **Problems start at higher intensities…**
... Summary

- **Problem areas found:**
  - Corrosion (horn, target, auxiliary components)
  - Fatigue (design flaws...)
  - Tritium
  - Electronics (radiation issues of standard components)

**Example CNGS:**

- **2006: initial commissioning (20 days)**
  - Horn water leak after ~6 weeks of running
    - design/brazing error
    - lesson: test COMPLETE systems

- **2007: re-commissioning (11 days)**
  - Ventilation problems after ~3 weeks of running
    - radiation on electronics, SEU
    - lesson: any object on the market today contains electronics components

- **2008: re-commissioning: (7 days)**
  - Keep running now!!!
Many Thanks for all Contributions!!

Sam Childress, Sacha Kopp, Peter Kasper, Kazuhiro Tanaka, Takashi Kobayashi, Ans Pardons, Heinz Vincke
Proton Beam Lines for Neutrino Beams - Extraction, Transport and Targeting

• For all Neutrino beam lines
  – Careful design
  – Extraction line equipment stable and reproducible
  – Good magnet stability in transfer line
  – Fully automated beam position control
  – Negligible beam losses
  – Comprehensive beam interlock system

→ No major problems!
→ Watch out for much higher intensities!