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
  \( <E_\nu> = 1.3\text{GeV}, \ 250\text{km baseline}; \)
  Results: \( \Delta m^2_{23} = (2.8 \pm 0.4) \times 10^{-3}\text{eV}^2 \ @ \ sin^2 2\theta_{23} = 1 \) (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
  \( <E_\nu> = \sim 4\text{GeV}, \ 735\text{km baseline} \)
  Results: \( \Delta m^2_{23} = (2.43 \pm 0.13) \times 10^{-3}\text{eV}^2 \ @ \ sin^2 2\theta_{23} = 1.05; \) Phys.Rev.Lett. arXiv:0806.2237, 2008

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

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

\[ p + C \rightarrow (interactions) \rightarrow \pi^+, K^+ \]
\[ \rightarrow (decay \ in \ flight) \rightarrow \mu^+ + \nu_\mu \]
K2K
K2K Neutrino Beam Line

$\nu_\mu \rightarrow \nu_\tau$ oscillation
$<E_\nu> = 1.3\text{GeV}, \text{250km baseline}$

ND: 1kt Water Cherenkov
FD: 50kt Superkamiokande

12 GeV PS
- Cycle 2.2sec
- Beam spill 1.1ms
- $\approx 6\cdot10^{12}$ protons/spill
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**

![Graph showing horn pulses over time](image)

**Strategy: preventive exchange every year**
- In total five 1\textsuperscript{st} horns, four 2\textsuperscript{nd} horns → Accessible, no remote handling!

**2004:**
- No exchange due to high radiation
- Nov 2004: Inner conductor of 1\textsuperscript{st} 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

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E. Gschwendtner, CERN  
NuFact2008, Valencia, 1 July 2008
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: ~500MeV (LSND: ~30MeV)
  - Baseline: MiniBooNE: ~500m (LSND: ~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 (71cm long, 1.7 \( \lambda \)), cooled by air flow
- **Horn**
  - 170kA, 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.
MiniBooNE Statistics

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

Number of Horn Pulses
- 268.01 Million
  - Largest week: 2.46 million
  - Latest week: 2.37 million

Number of Protons on Target
- 11 E20
  - Largest week: 0.1085 E20
  - Latest week: 0.1053 E20

Number of Neutrino Events
- 880703
  - Largest week: 11447
  - Latest week: 2143

Weekly million
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: 10$\mu$s
- 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 \times 10^{20} \text{ Protons on Target as of 02 June} \ '08

Average intensity/pulse (2007/2008): \ < 3.08 \times 10^{13} \text{ ppp} >

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

E. Gschwendtner, CERN

NuFact2008, Valencia, 1 July 2008
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:
  - 2x 2.4 · 10^{13} ppp
- $\sigma \sim 0.5$mm
- Beam performance:
  - 4.5· 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
  - $8.5 \times 10^{17}$ pot
- 2007: 6 weeks CNGS run
  - $7.9 \times 10^{17}$ pot
    - 38 OPERA events in bricks (~60000 bricks)
    - Maximum intensity: $4 \times 10^{13}$ pot/cycle
    - Radiation limits in PS
→ OPERA detector completed by June 2008
→ CNGS modifications finished
- 2008: CNGS run: June-November → NOW! ←
  - $5.43 \times 10^{17}$ pot on Friday, 27Jun08, after 9 days running
    → more than 50 OPERA events in bricks!
  - Expected protons in 2008: $\sim 2.6 \times 10^{19}$ 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)

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**Muon Detector**

- 270 cm
- 11.25 cm

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![Graph showing measurements for positive, horizontal, and negative charges]
... 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

FLUKA simulations, P. Sala et al 2008
CNGS Target

Target: 13 graphite rods, 10cm long, Ø = 5mm and/or 4mm

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 $4 \times 10^5$ 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.

Super-K: 50 kton
Water Cherenkov

Kamioka

J-PARC
0.75MW 50GeV PS

Tokai

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 angel between 2° and 2.5° ($E_\nu = 0.8\,\text{GeV} \sim 0.65\,\text{GeV}$)
T2K Beam Line

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

Installed and aligned

First Neutrino Beam: April 2009

295km to Super-Kamiokande

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

Near Neutrino Detector
Assembly Sep08
Installation Oct08

Finished Aug08

10/14 doublets installed
Completed in Dec 08

SCFM at ARC Section
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!