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**
  $\langle E_\nu \rangle$ **= 1.3GeV, 250km baseline;**
  Results: $\Delta m^2_{23}=(2.8 \pm 0.4)\times10^{-3}eV^2$ **@** $\sin^2 2\theta_{23}=1$ **(90%CL); Phys.Rev.D74:072003, 2006**

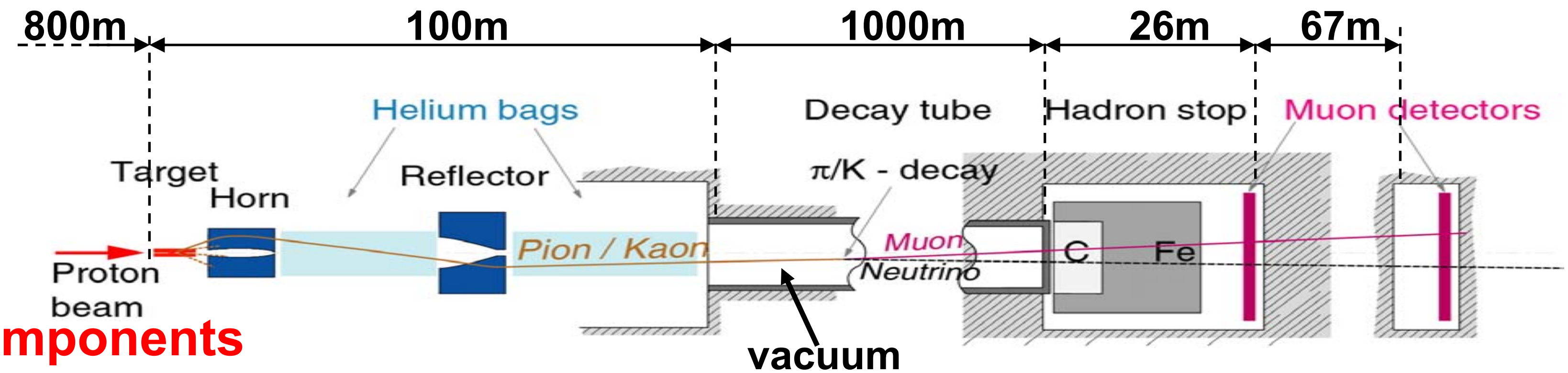
- **MiniBooNE (2002-)**
  Tests LSND indication of $\nu_\mu \rightarrow \nu_e$ **oscillation**
  with similar L/E (500MeV/500m)
  Results: no evidence for $\nu_\mu \rightarrow \nu_e$ **appearance. Phys.Rev.Lett.98, 231801, 2007**

- **NuMI (2004-)**
  $\nu_\mu \rightarrow \nu_\tau$ **disappearance oscillation**
  $\langle E_\nu \rangle$ **= ~4GeV , 735km baseline**
  Results: $\Delta m^2_{23}=(2.43 \pm 0.13)\times10^{-3}eV^{2\ 2}$ **@** $\sin^2 2\theta_{23}=1_{-0.05}$**; Phys.Rev.Lett. arXiv:0806.2237, 2008**

- **CNGS (2006-)**
  $\nu_\mu \rightarrow \nu_\tau$ **appearance oscillation**
  $\langle E_\nu \rangle$ **= 17GeV, 735km baseline**

- **T2K (2009-)**
  $\nu_\mu \rightarrow \nu_e$ **appearance (non-zero** θ_{13}**);**
  precise meas. of $\nu_\mu \rightarrow \nu_x$ **disappearance (**$\theta_{23}, \Delta m^2_{23}, \Delta m^2_{13}$**)**
  $\langle E_\nu \rangle$ **= 0.7GeV, 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

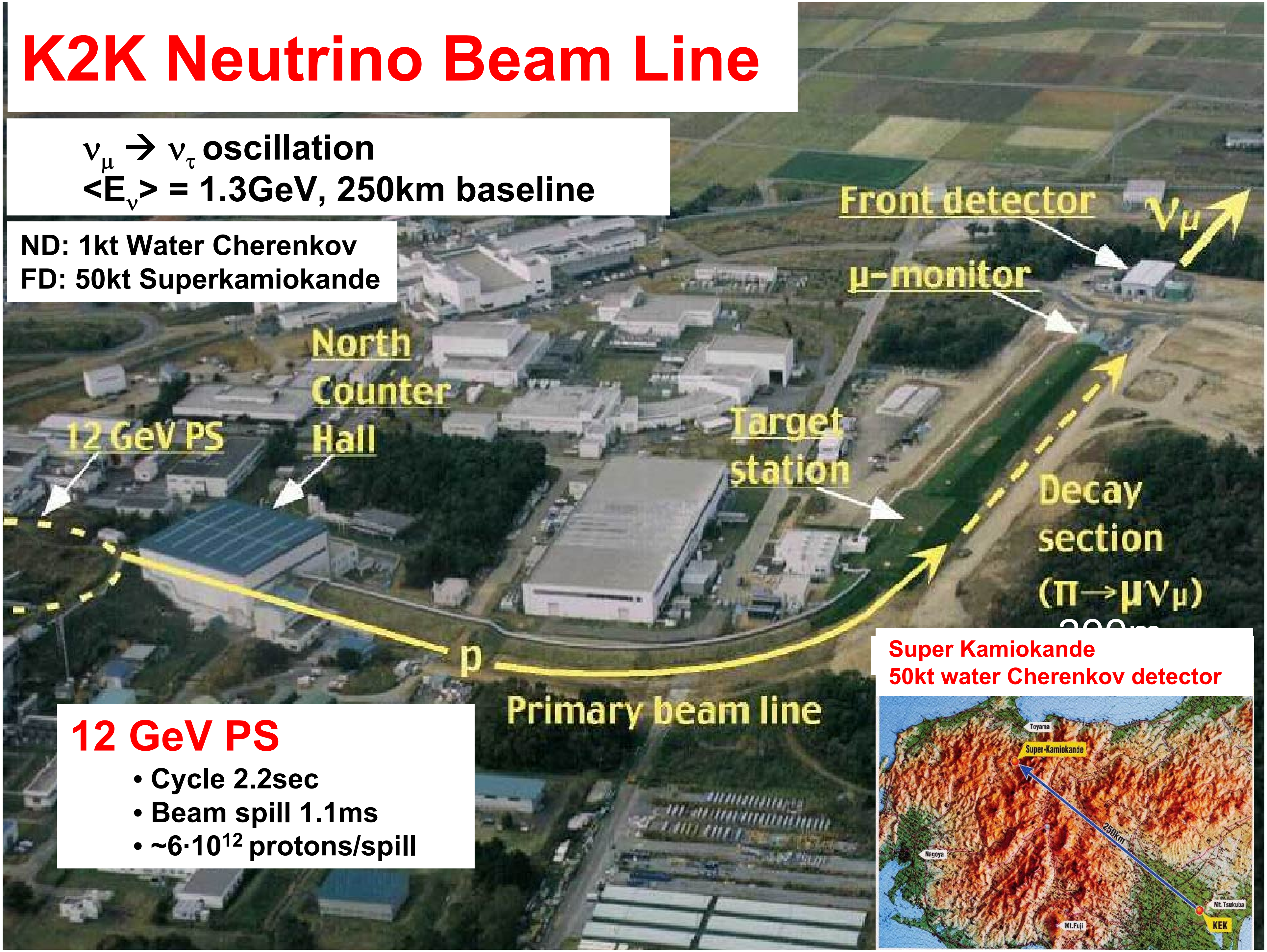
$$p + C \rightarrow \text{(interactions)} \rightarrow \pi^+, K^+$$
$$\rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu$$

K2K

K2K Neutrino Beam Line

$\nu_\mu \rightarrow \nu_\tau$ oscillation
$\langle E_\nu \rangle$ = 1.3GeV, 250km baseline

ND: 1kt Water Cherenkov
FD: 50kt Superkamiokande

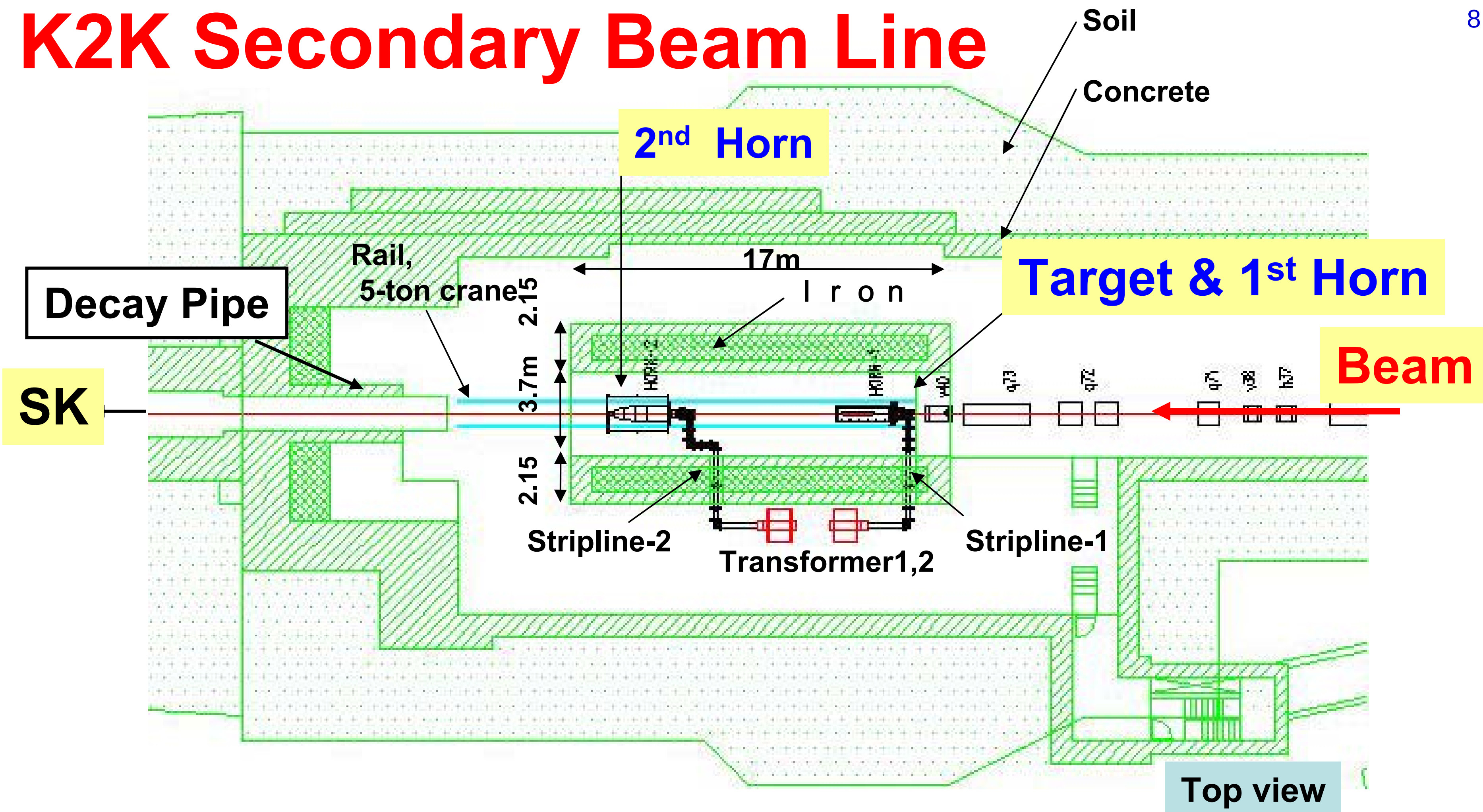


12 GeV PS

- Cycle 2.2sec
- Beam spill 1.1ms
- ~$6 \cdot 10^{12}$ protons/spill

Super Kamiokande
50kt water Cherenkov detector

K2K Secondary Beam Line

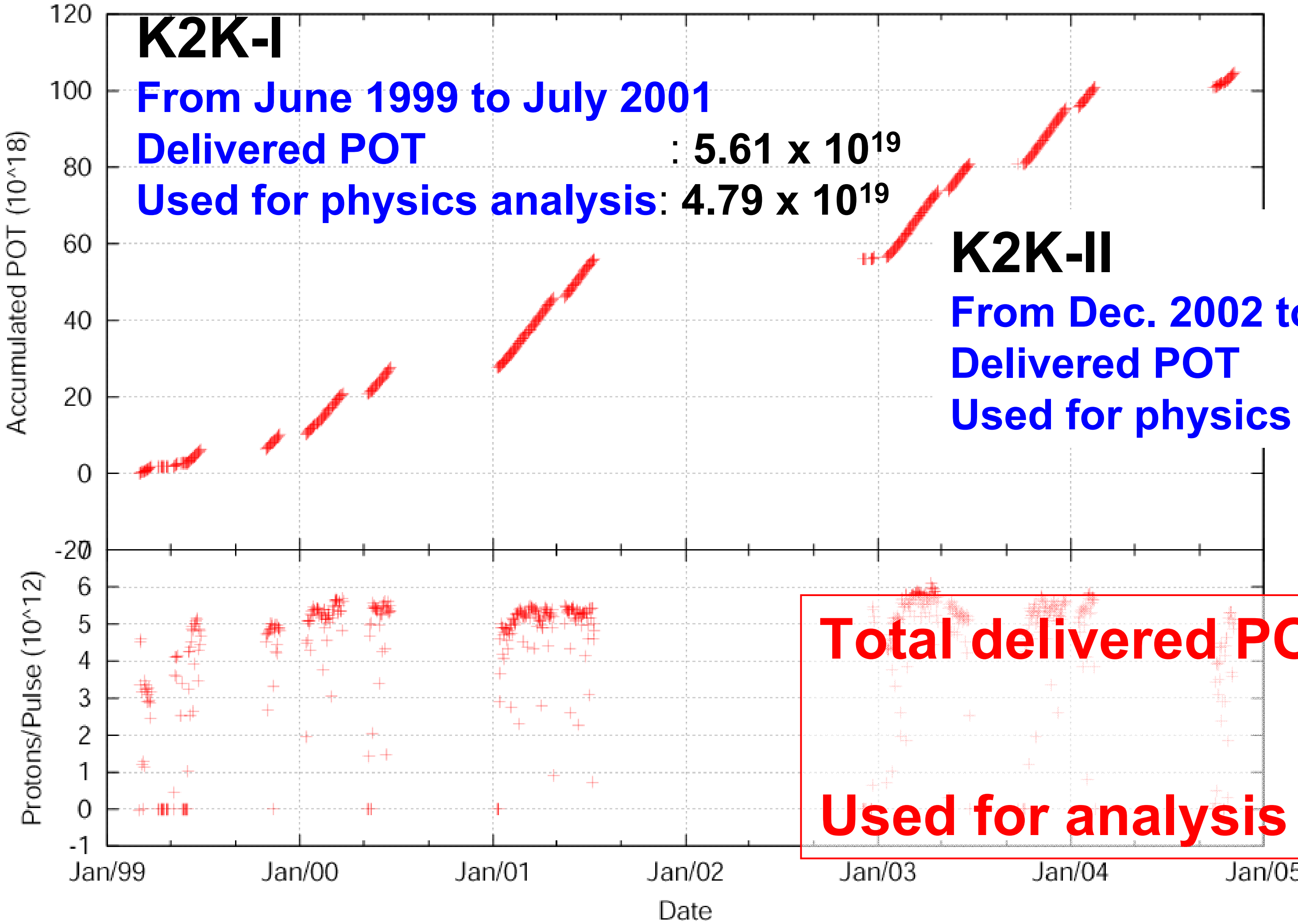


- **Target:** Al (66cm length, 3cm diameter), part of horn1
- **2 horns:** water cooled, 250kA, 0.5 Hz, 2.5ms pulse width
- **Pion monitor:** Cherenkov detector
- **Decay tube:** 200m, He filled
- **Beam dump:** 2.5m iron, 2m concrete
- **Muon monitors:** ionization chamber, silicon pad detectors

K2K Protons on Target

(includes Beam studies and tunings)

Physics run : From June 1999 to Nov. 2004.



K2K-I

From June 1999 to July 2001

Delivered POT : 5.61×10^{19}

Used for physics analysis: 4.79×10^{19}

K2K-II

From Dec. 2002 to Nov. 2004

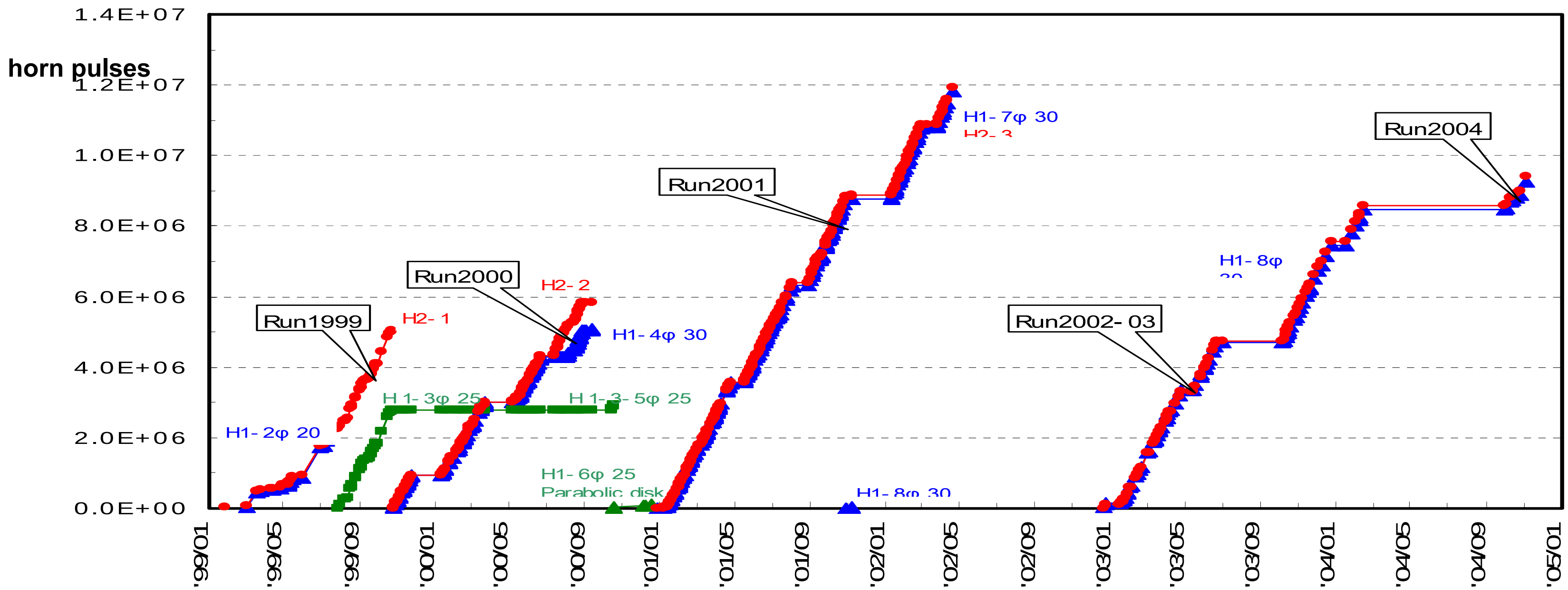
Delivered POT : 4.88×10^{19}

Used for physics analysis: 4.43×10^{19}

Total delivered POT (K2K I+II) 1.049×10^{20}

Used for analysis 0.922×10^{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**

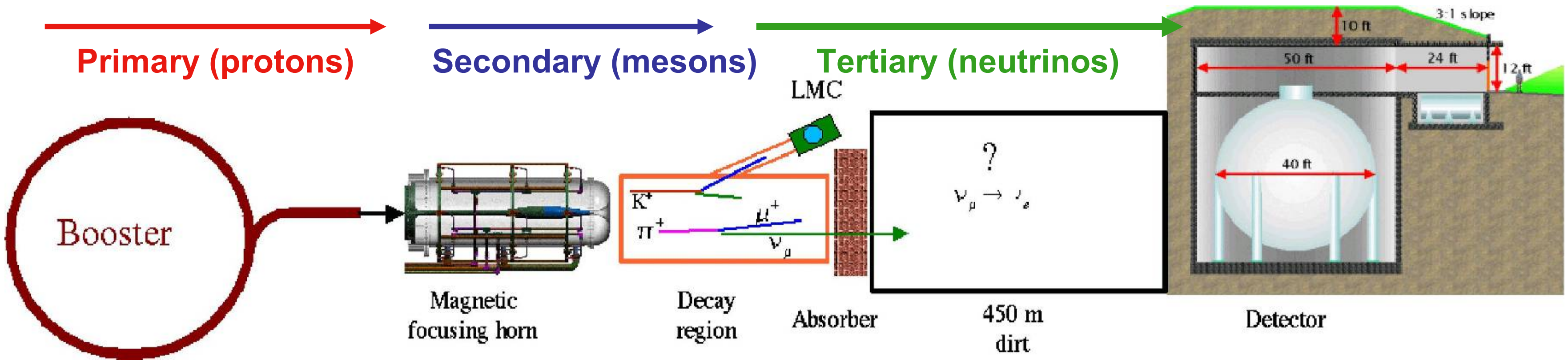
Dec 2004: end of run

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

Lessons:
→In-situ work reaches RP limit
→ Design with remote handling & spare systems
→ Decouple target and horn

MiniBooNE

MiniBooNE



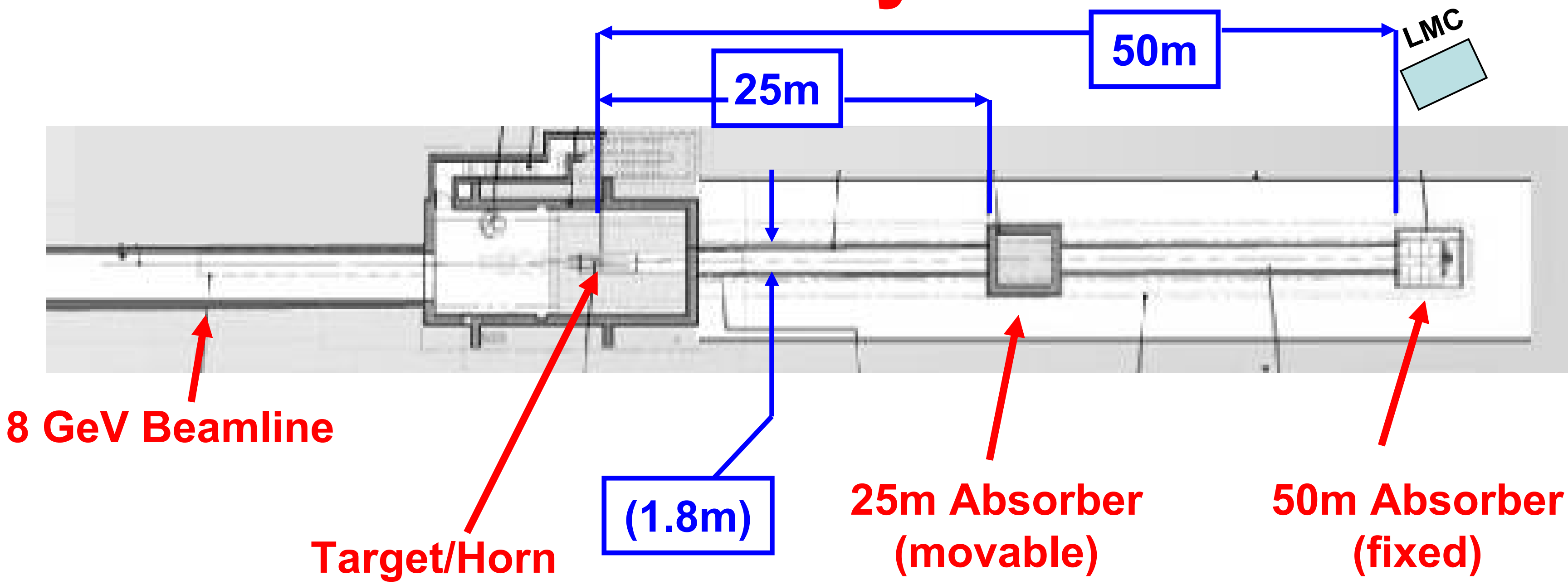
Test LSND indication of $\nu_\mu \rightarrow \nu_e$ oscillation

- **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

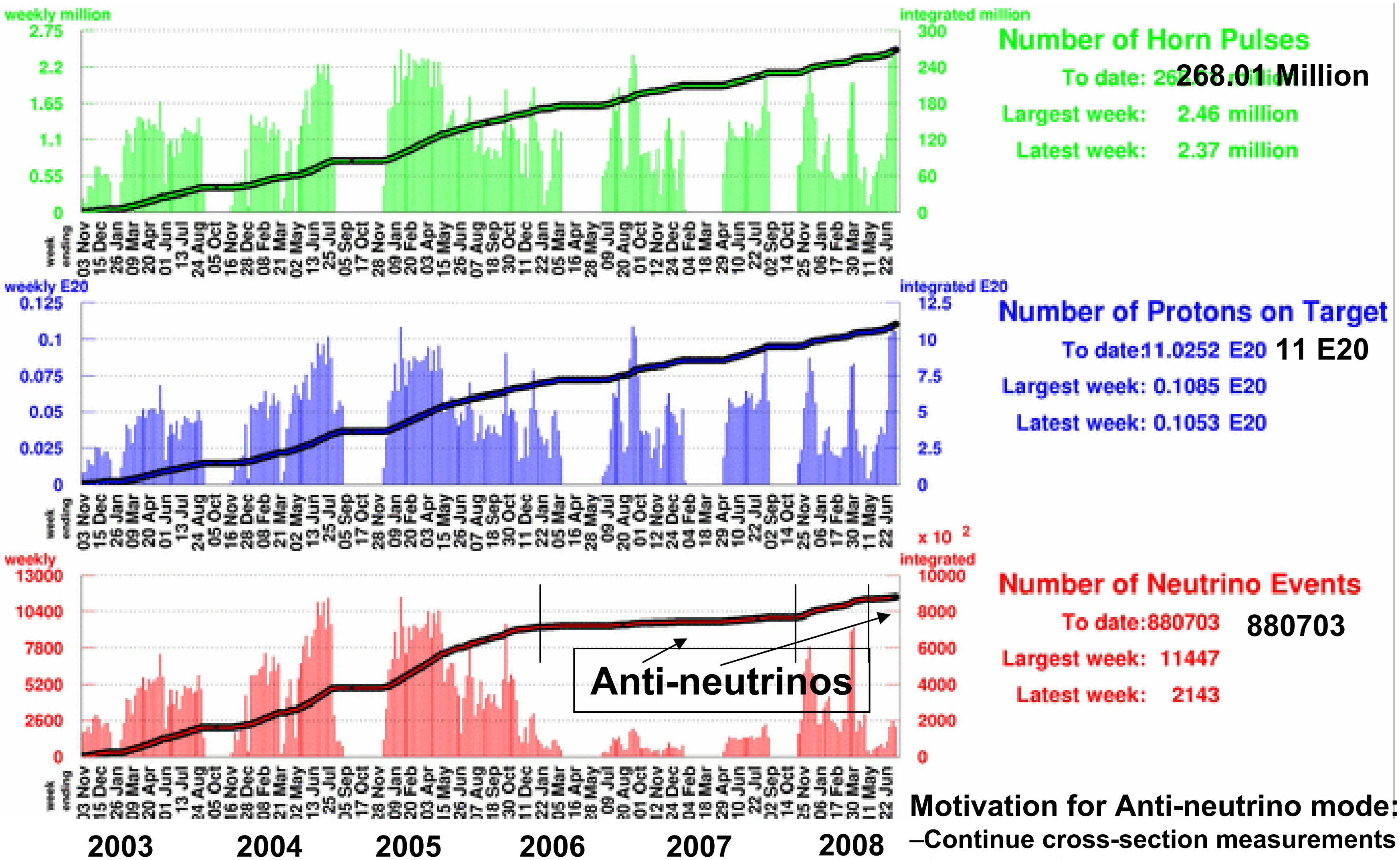
- **8 GeV proton beam from Booster**
  - **1.6 μs spill**
  - **5Hz rate**
  - **Maximum intensity: $5 \cdot 10^{12}$ ppp**
- **Beam on target: σ < 1mm**

MiniBooNE Secondary Beam Line



- **Target**
  - **7 Be slugs (71cm long, 1.7 λ), cooled by air flow**
- **Horn**
  - **170kA, 140 μs, 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 ν_e contamination from μ decays**
- **50m absorber**
- **Little Muon counter (LMC):**
  - **in situ measurement of Kaon background by counting muons produced from K decays.**

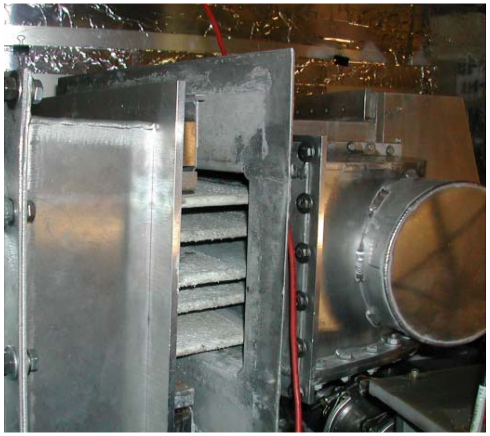
MiniBooNE Statistics

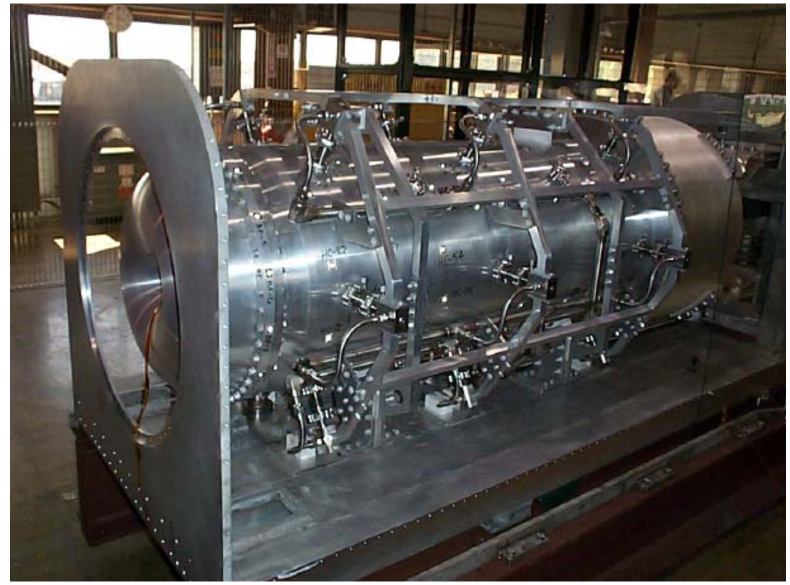


Motivation for Anti-neutrino mode:

- **Continue cross-section measurements**
- **Searching for anti-neutrino disappearance**

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

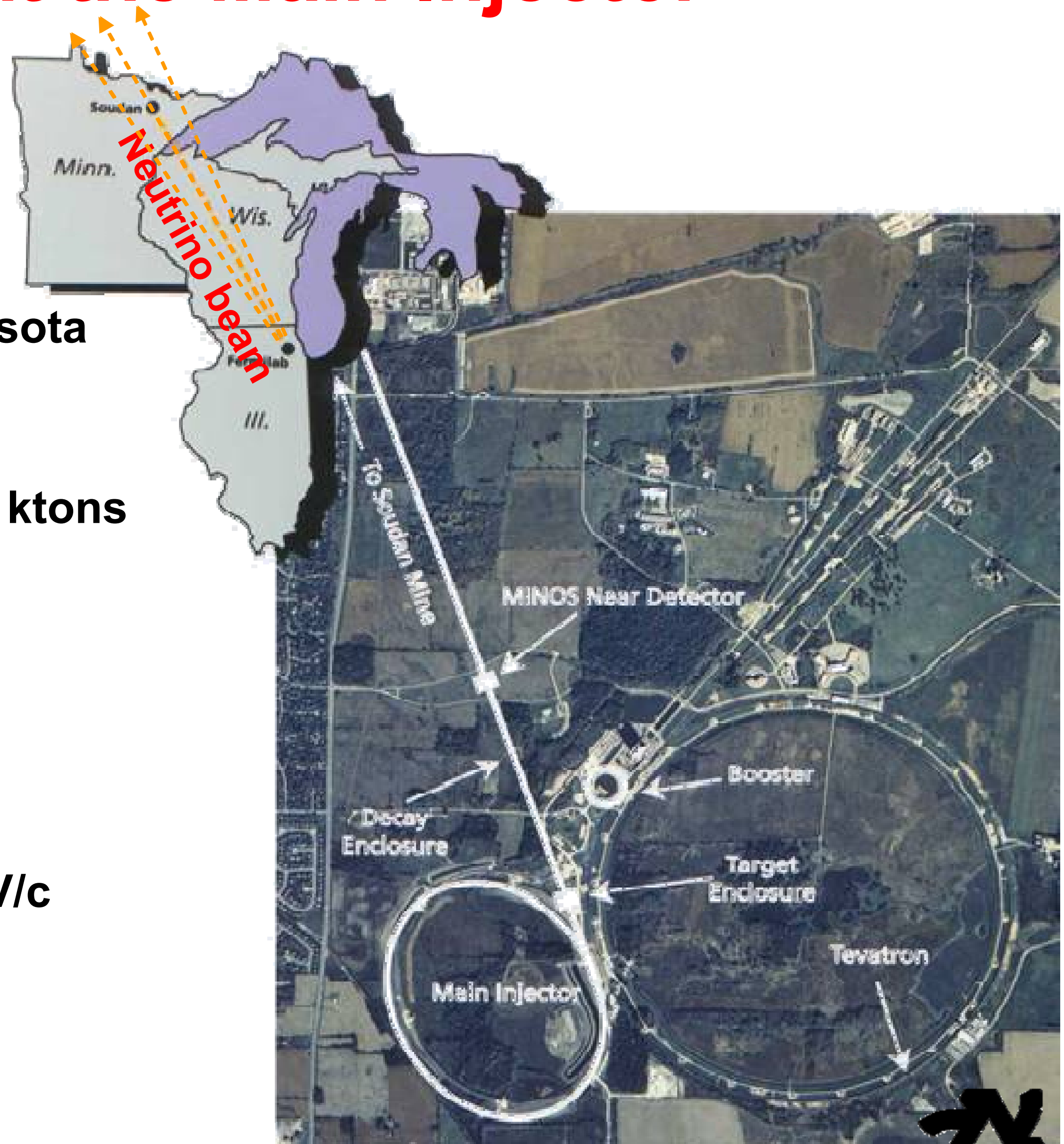
→ CNGS: vacuum; K2K & T2K: Helium

→NuMI: vacuum, since Dec 07 Helium

NuMI

NuMI: Neutrinos at the Main Injector

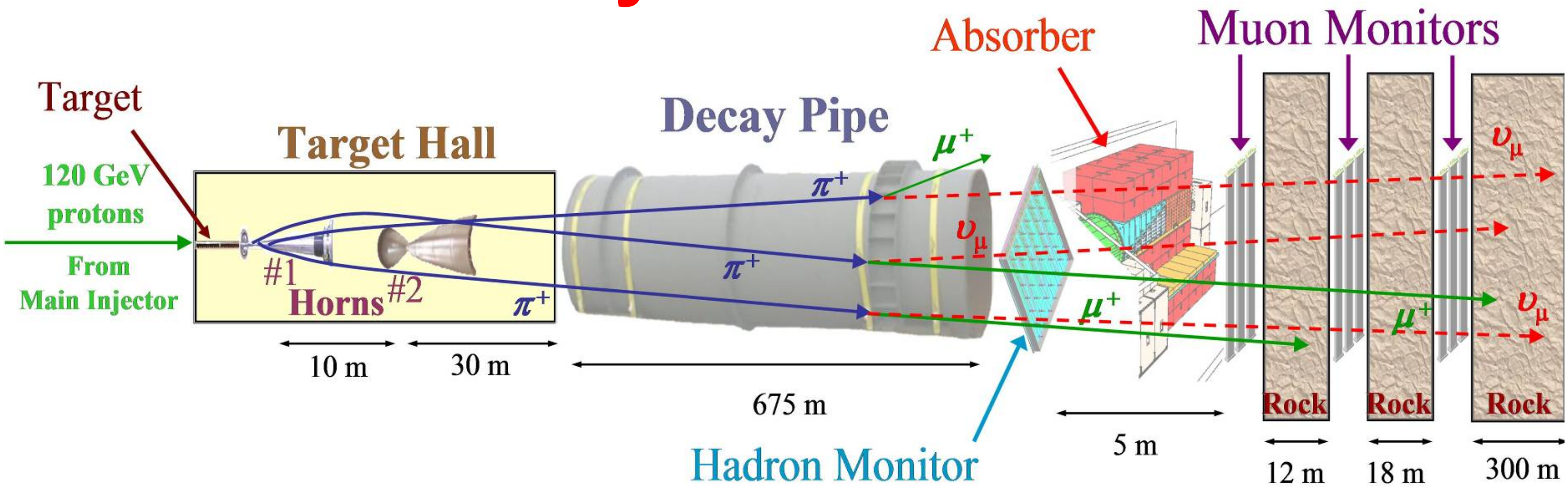
- **Search for oscillation $\nu_\mu \rightarrow \nu_\tau$ disappearance**
- **735 km baseline**
  - From Fermilab to Minnesota
  - Elevation of 3.3°
  - Near detector: ~1ktons
  - Far detector: MINOS 5.4 ktons
- **Commissioned in 2004**
- **Operating since 2005**



NuMI Proton Beam Line

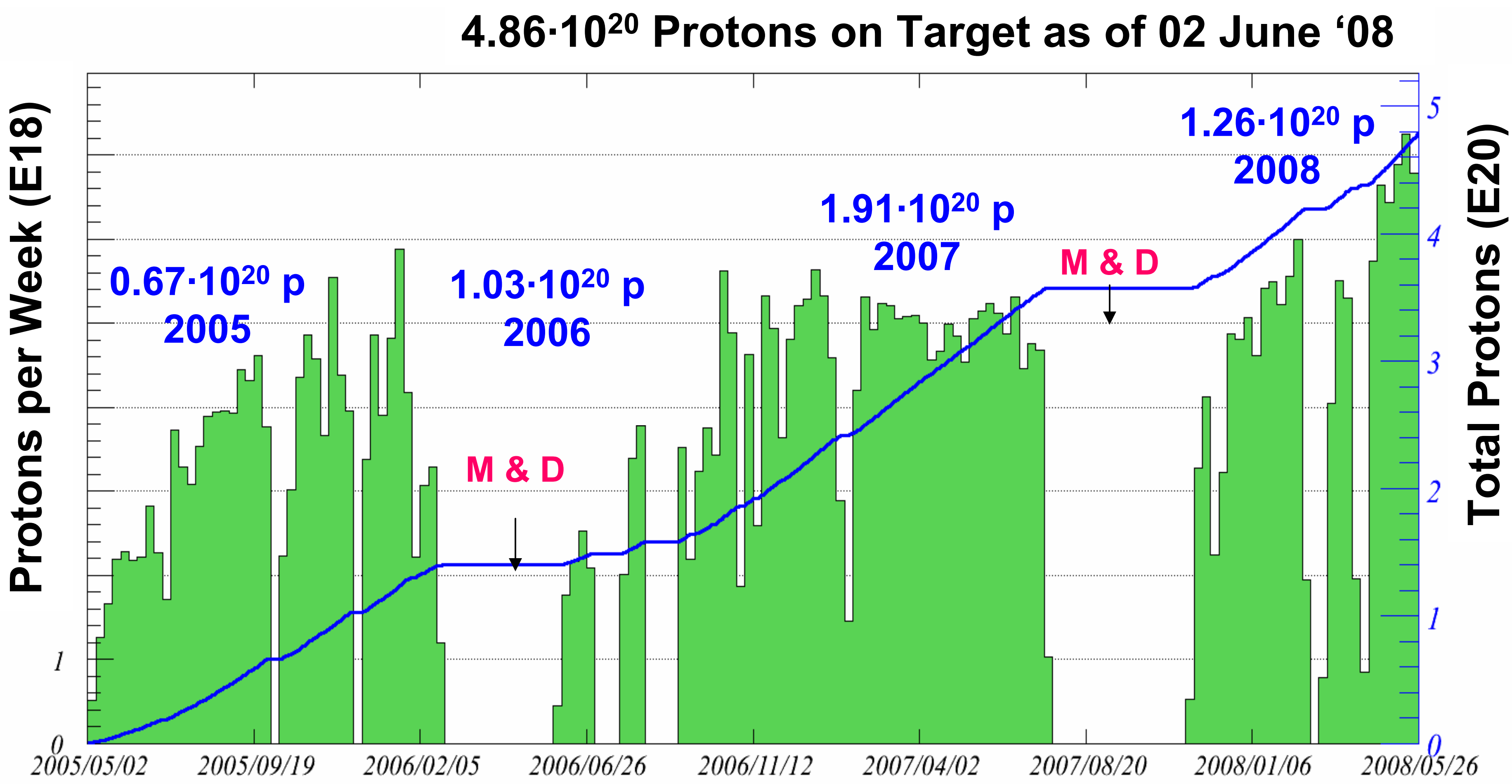
- **From Main Injector:** 120 GeV/c
- **Cycle length:** 1.9 s
- **Pulse length:** 10μs
- **Beam intensity:** $3 \cdot 10^{13}$ ppp
- $\sigma \sim 1$mm

NuMI Secondary Beam Line



- **Water cooled graphite target**
  - **2 interaction lengths**
  - **Target movable in beam direction inside horn to change ν 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



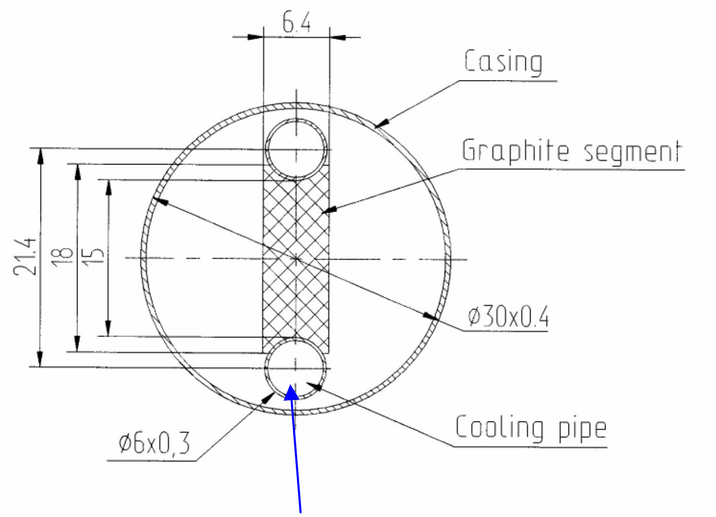
2008:
9 Booster batches to NuMI
→ allows increasing the MI beam power to 340 KW

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

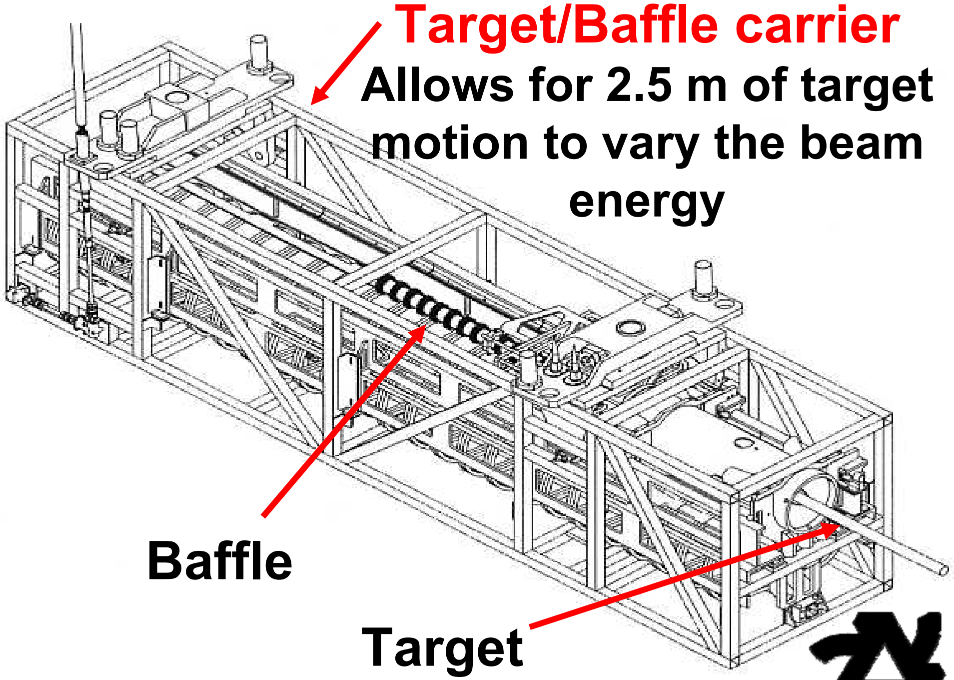
Average beam power (2007/2008): < 233.6 kW >

NuMI Target

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



Water cooling tube
→ provides mechanical support



… NuMI Target

1. Water leak soon after turn-on (March 2005)

   → **‘fixed’ with He backpressure holding back water from leak**

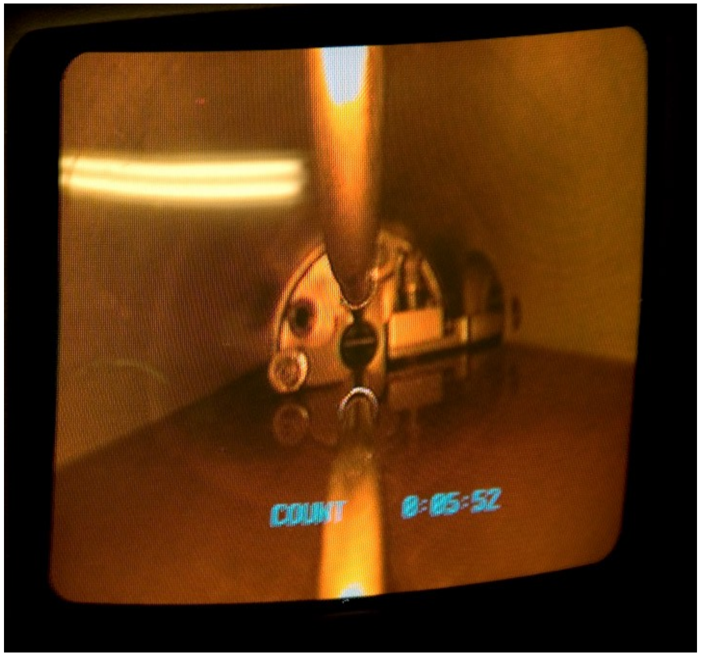
2. September 2006: Target motion drive shaft locked due to corrosion

   → **lead to target replacement**

3. June 2008: Target longitudinal drive failure

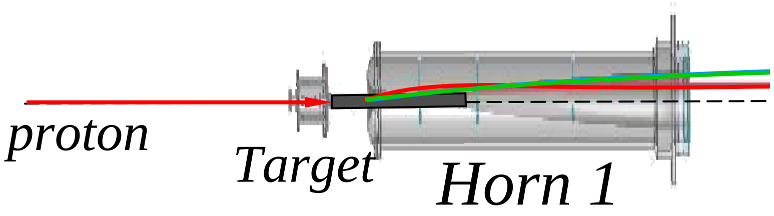
   → **In work cell repaired**

   → **reinstall**



Water in target

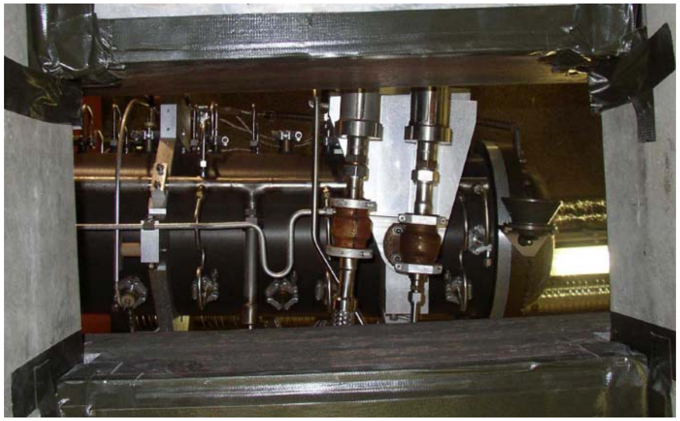
vacuum chamber



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

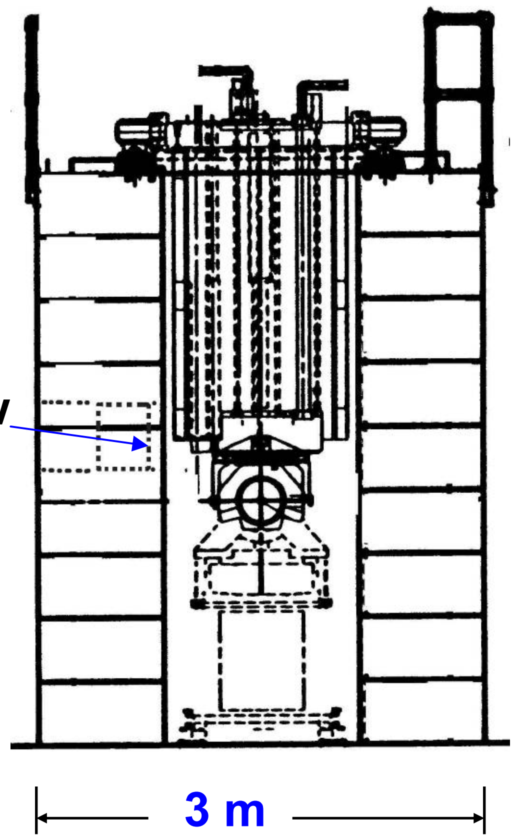
Module

Lead-glass window

Horn

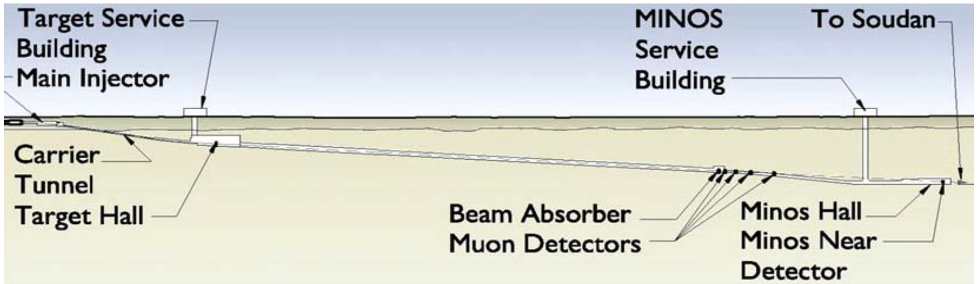
Remote lifting table

Concrete wall



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

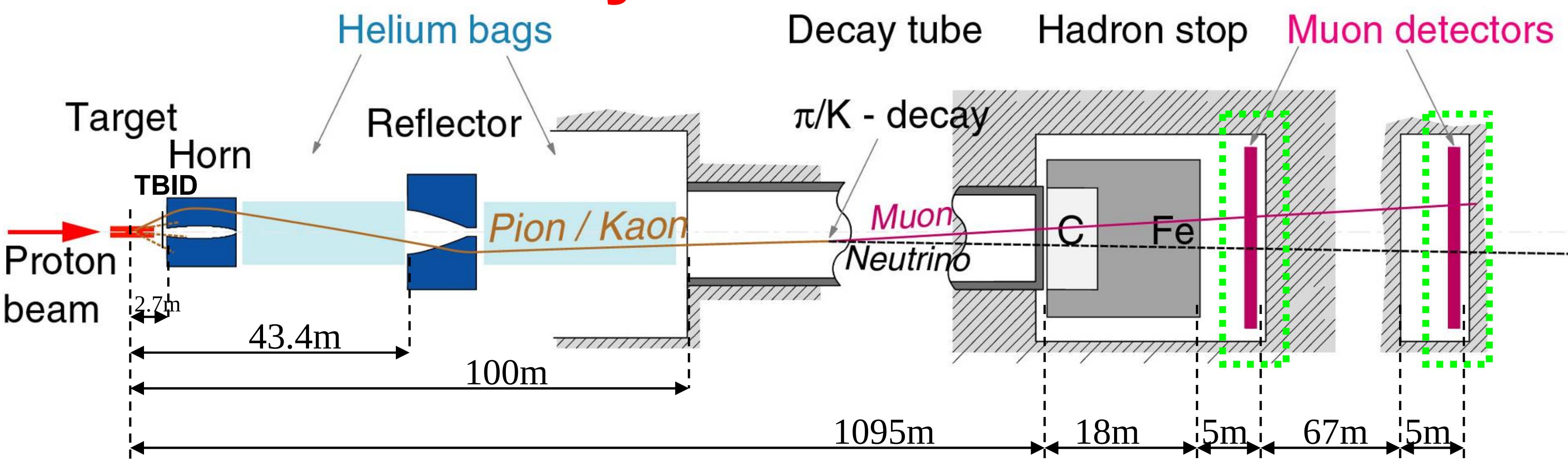
CNGS

- 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 $2.4 \cdot 10^{13}$ 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

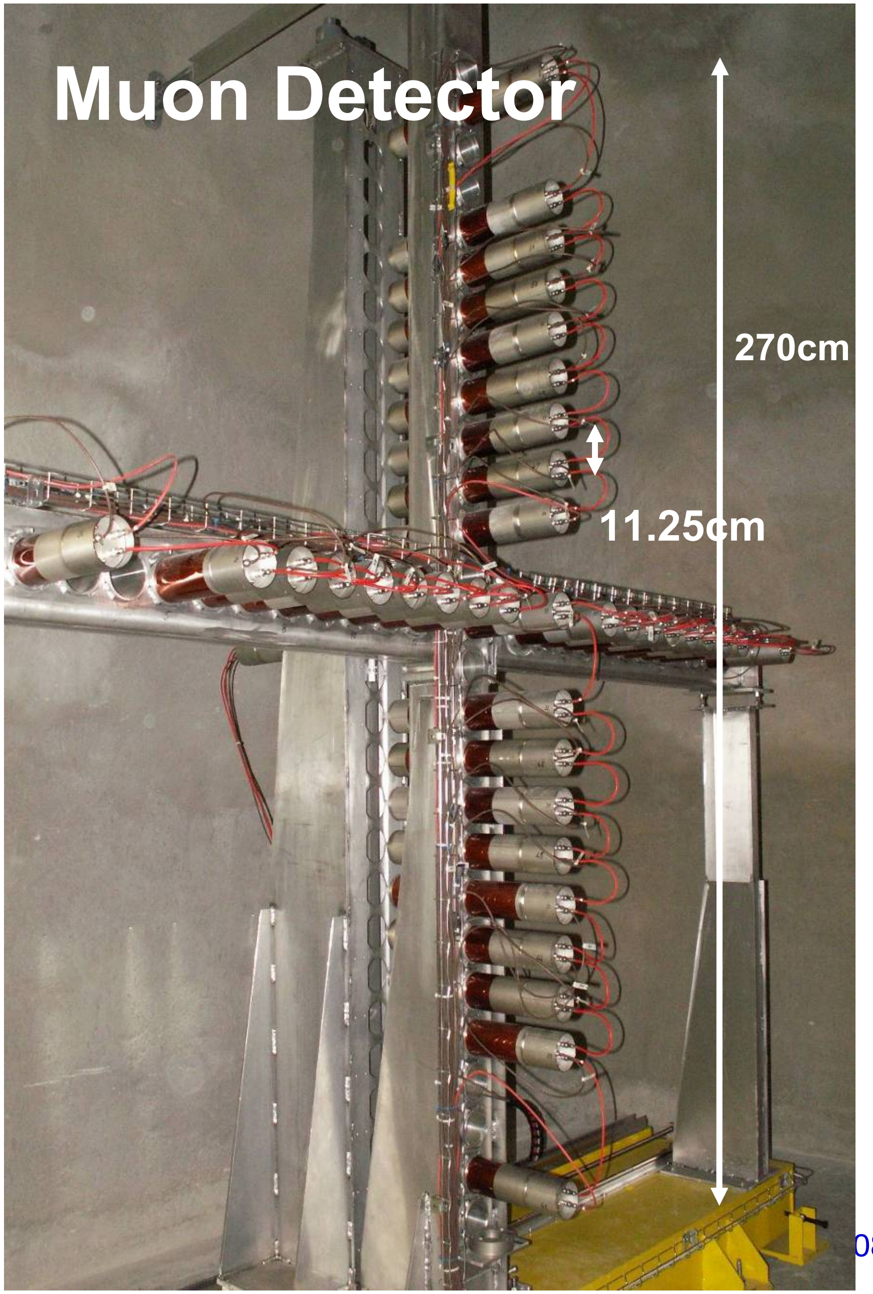
- **2006: CNGS Commissioning**
  - **$8.5 \cdot 10^{17}$ pot**
- **2007: 6 weeks CNGS run**
  - **$7.9 \cdot 10^{17}$ pot**
    - **38 OPERA events in bricks (~60000 bricks)**
  - **Maximum intensity: $4 \cdot 10^{13}$ pot/cycle**
    - **Radiation limits in PS**

→ OPERA detector completed by June 2008

→ CNGS modifications finished

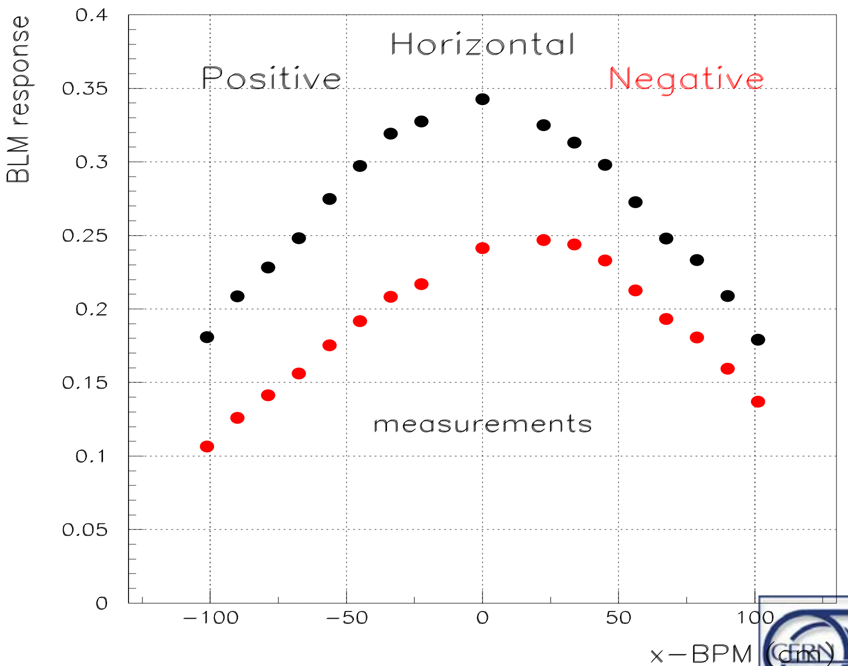
- **2008: CNGS run: June-November → NOW! ←**
  - **$5.43 \cdot 10^{17}$ pot on Friday, 27Jun08, after 9 days running**
    - **→ more than 50 OPERA events in bricks!**
  - **Expected protons in 2008: ~2.6 $\cdot 10^{19}$ pot**

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)**



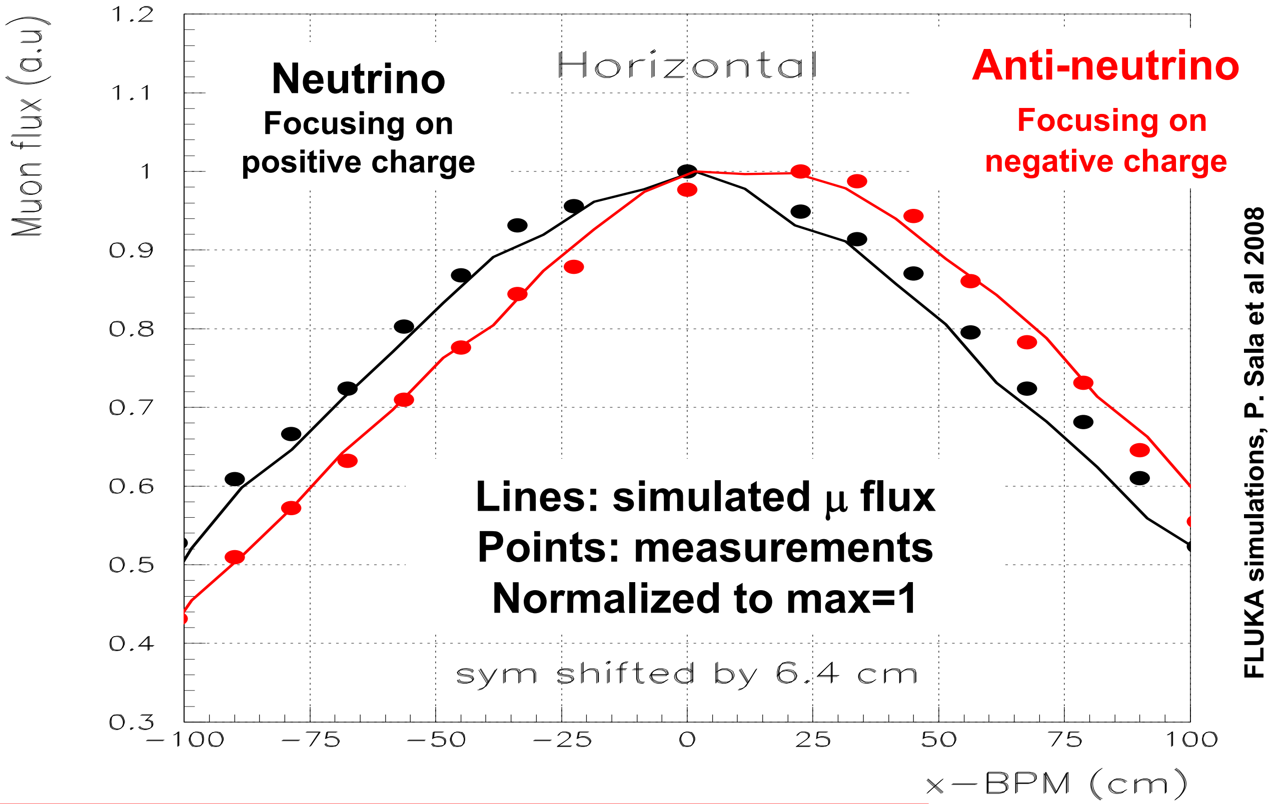
… CNGS Polarity Puzzle

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**



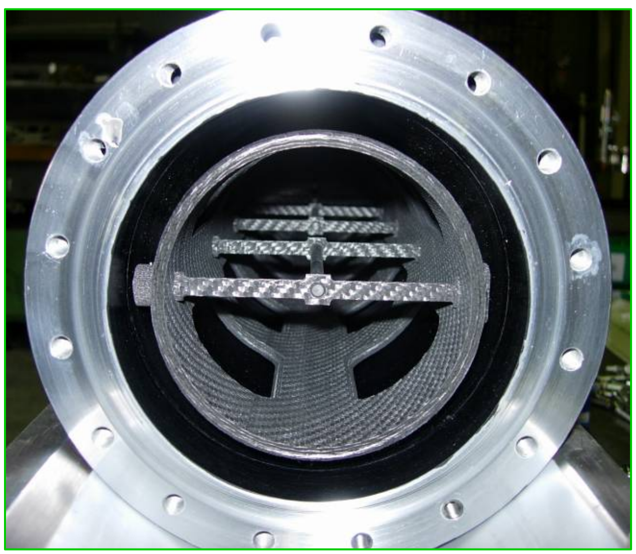
Lessons:

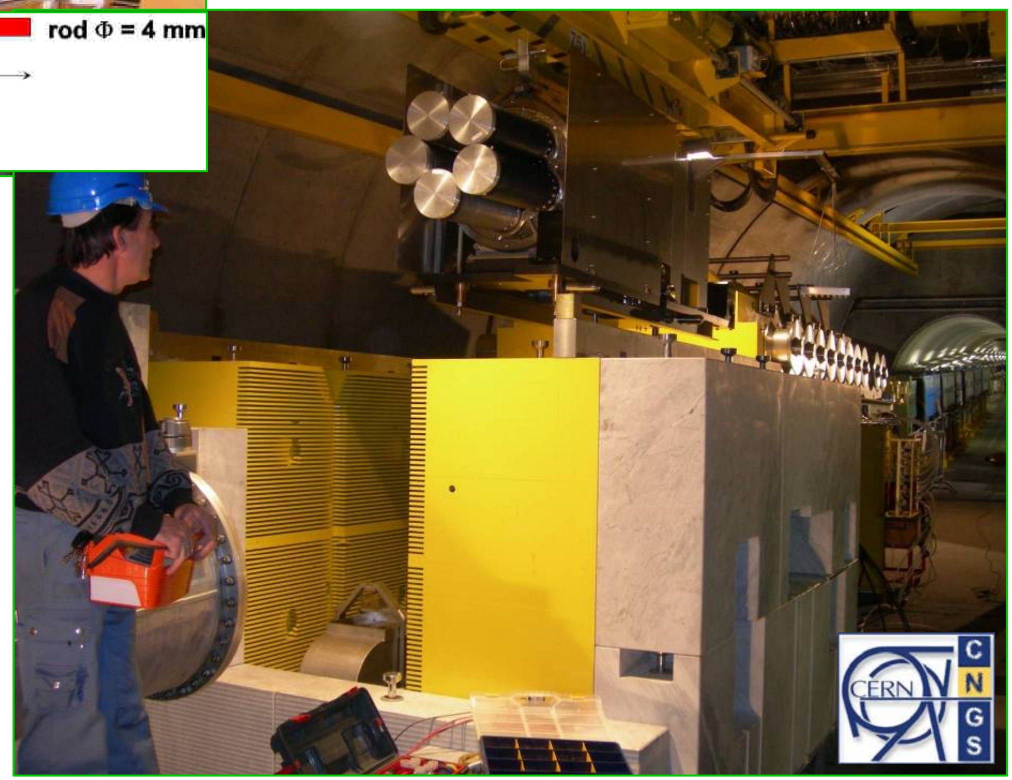
→ **Useful to change polarity quickly**

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.





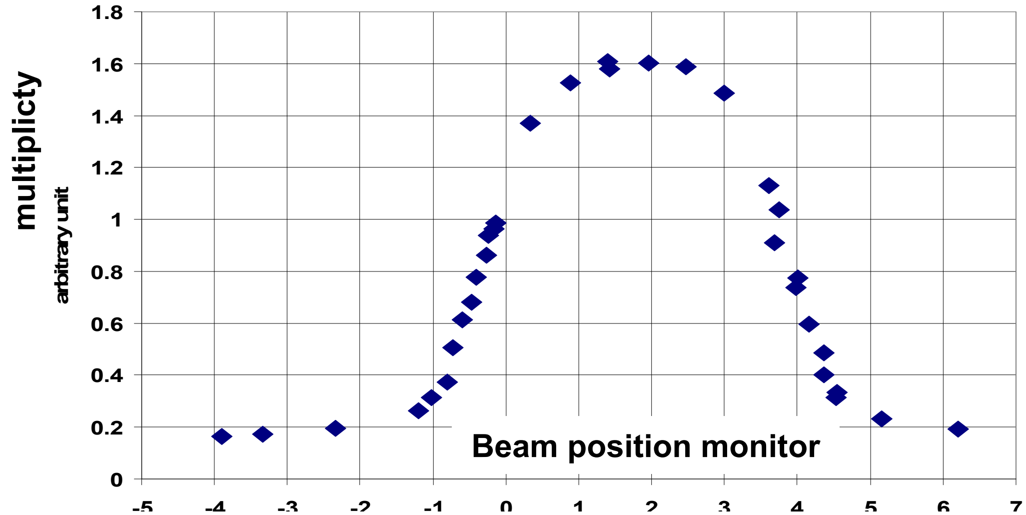
…CNGS Target

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



- Target table motorized
- Horn and Reflector tables NOT

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

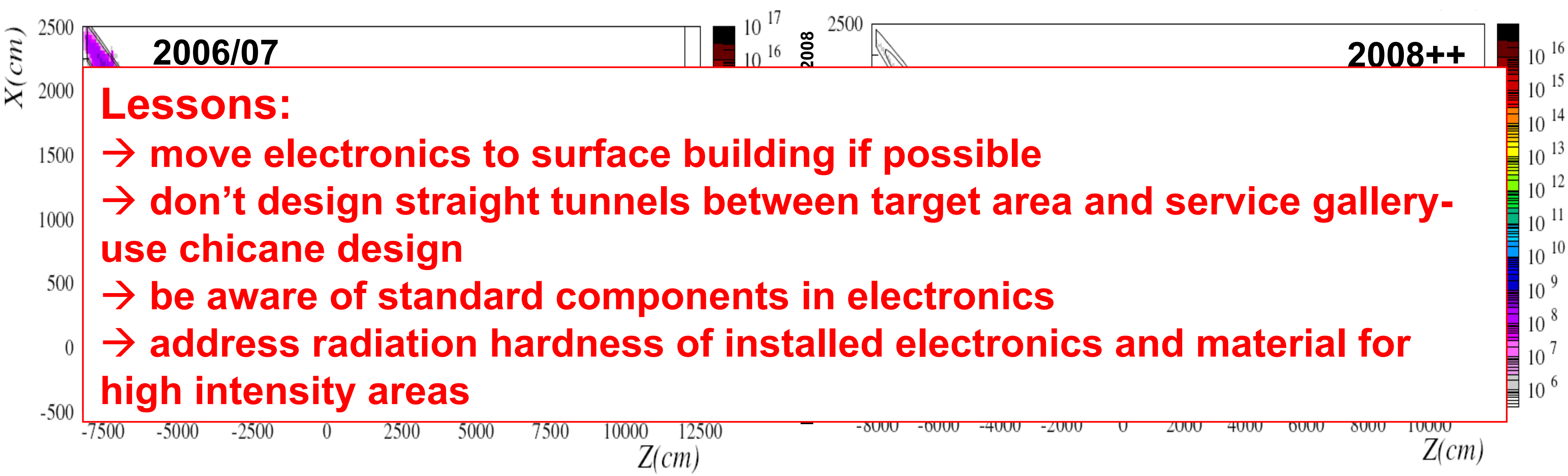
Lessons:
→ Concentrate in design on peripherals (insulating water lines)
→ Design with repair in mind; test thoroughly without beam
→Foresee tooling, training

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

Neutrino Facility at J-PARC

T2K

Long baseline neutrino oscillation experiment from Tokai to Kamioka.

Super-K: 50 kton
Water Cherenkov

J-PARC
0.75MW 50GeV PS

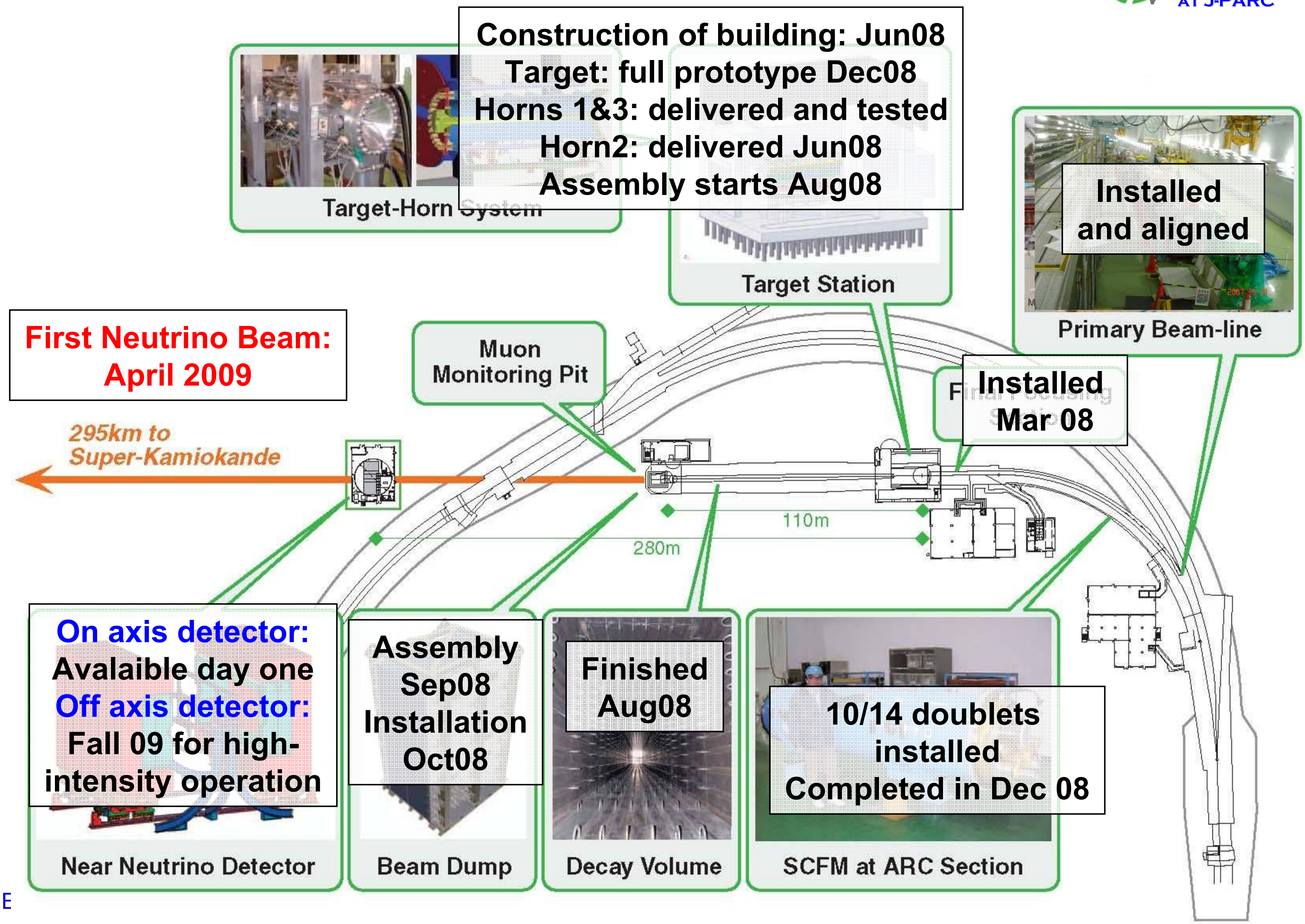
Physics goals

- 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_ν = 0.8GeV ~0.65 GeV)

T2K Beam Line

NEUTRINO FACILITY AT J-PARC



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!!

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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!