CNGS Horns: Repair and Improvements

Ans Pardons, CERN
Outline

• Introduction
  – Overview of horns
  – Lessons learnt from previous horns
  – CNGS horn features

• CNGS operation: memorable moments
  – 2006: Reflector (2nd horn) water outlet leak
  – 2007: Broken stripline cable
  – 2008: Cooling water demineralisation issues

• Conclusions
Introduction: Overview horns

1963: horn from CERN PS neutrino experiment
300kA, 25GeV, $<<0.1$Hz
$10^{12}$ protons per pulse

K2K

MiniBoone

NuMI

CNGS
Introduction: Overview horns

<table>
<thead>
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</thead>
<tbody>
<tr>
<td>Number of horns</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Current (kA)</td>
<td>250</td>
<td>170</td>
<td>185</td>
<td>150 / 180</td>
<td>320</td>
</tr>
<tr>
<td>Nr pulses/beam</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Pulse width (ms)</td>
<td>2.5</td>
<td>0.15</td>
<td>2.3</td>
<td>6 / 10</td>
<td>0.7 / 2 / 2</td>
</tr>
<tr>
<td>Avg. freq. (Hz)</td>
<td>0.5</td>
<td>5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Target included?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Design life-time ($10^6$ cycles or eqv. years)</td>
<td>10 ~1 yr</td>
<td>100(*) ~1yr</td>
<td>10 ~1yr</td>
<td>20 ~4yr</td>
<td>20 ~5yrs</td>
</tr>
<tr>
<td>Beam energy (GeV)</td>
<td>12</td>
<td>8</td>
<td>120</td>
<td>400</td>
<td>50</td>
</tr>
<tr>
<td>Protons on target (per cycle)</td>
<td>$6 \times 10^{12}$</td>
<td>$5 \times 10^{12}$</td>
<td>$3 \times 10^{13}$</td>
<td>$4.8 \times 10^{13}$</td>
<td>$3 \times 10^{14}$</td>
</tr>
</tbody>
</table>

(*$)$ 264 $10^6$ pulses reached!
Introduction: Lessons from the past

Lessons from pre-CNGS era:

- We can design conductors to resist fatigue
- Concentrate on accessory systems (electric, hydraulic)
  - Galvanic corrosion kills! (drainage & choice of materials)
  - Vibration can fatigue rigid structures (e.g. water lines)
  - Magnetic forces between stripline conductors are important
- Even with careful design, in-situ work reaches a RP limit
- For higher number of POT there is the need to:
  - Design with remote handling in mind
  - Foresee full set of spares
- Understanding of failure harder as POT increase
- Foresee camera, work cell facility, tools to investigate...
Introduction: CNGS Horn features

- 150/180kA, 0.3Hz (20Hz inst.)
- 400GeV/c, $2.4 \times 10^{13}$ ppp (x2)
- Design lifetime: 20 $10^6$ double pulses
Introduction: CNGS Horn features

**Designed for remote exchange (not remote repair!)**

<1mSv total personnel dose after 1 year beam, and 1 month cooldown

Alignment between target hall frame & horn

Plug-in water connector

From water collector
Introduction: CNGS Horn features

**Electrical connection**
- Local action (5 nuts)

**Shielding & horn handling**
- Remote lifting tools for shielding & horns
- Crane with coordinates & cameras

**Remaining work from trench**

Ans Pardons, CERN
Introduction: CNGS Horn features

**Horn removal**
- Target hall frame
- Using cameras & guiding line, bring horn to storage place

**In-situ spare water circuit**
- Switch at ~1m from shielding

**Transformer & cooling unit in side gallery**
2006: Water outlet leak

Observations from control room:
• Increased water levels in sumps
• High refill rate of reflector closed water circuit

→ Access: Observations from target area
• Water running under reflector (downstream)
• Flexible tubes & connections OK

→ Remove roof shielding: Water inlets OK
→ Remove side shielding: Leak found!
Water outlet leak

Function of water outlet:
- Drain water
- Electrically insulate outer conductor from water circuit
- Transition from aluminium to stainless steel

Realisation through brazed ceramic muffs, titanium flanges and stainless steel bellows

Ceramic muff is machined for better fit and therefore better brazing – but this is the location of the failure!
Why the outlet broke

Failure because sum of (mainly shear) stresses from brazing procedure & machining reaches rupture limit of ceramic

Stresses coming from
1. Cool-down after brazing
2. Machined internal edge
3. Geometry: thin muff
4. Assembly:
   (No pure compression)
   Misalignment forces
5. Vibrations
6. Accident (?)

→ Needs new design
→ Exchange on horn & reflector!

Destructive tests confirm that outlet ceramic stress is at ~95% of rupture limit!
New water outlets

Stress in ceramic reduced:

- No brazing (but airtight)
- Soft graphite seal
- No machined internal edges
- Under compression
- Larger cross-section
New inlets & validation

Water inlets: different geometry but also brazed ceramic → replace

Laser vibrometer measurements to estimate vibration amplitudes and frequencies

Finite element calculations: all OK

Rigorous leak tests on spare horn
Exchange work

Important factors to success:

- Work executed upstream in target chamber (1µSv/hr)
- Remote horn handling procedure very well documented (<50µSv!)
- Adapted additional shielding
- Dose planning, training & development of tools
Exchange work

Water outlets
- Disconnect conductor from frame
- Lift conductor to allow margin
- Dismount old outlet, install new
- Lower and reconnect conductor to frame

Water inlets
- Use shielded cabin
- Dismount old cooling ramp
- Install new cooling ramp
- When horns in place: water tests (repair)

→ Total personnel dose exchange inlets & outlets = 1.6mSv
2007: Broken stripline cable

Transformer-to-stripline link

Silver plated copper, brazed cables, twisted strands
(WANF extrapolation)
• Compromise between flexible (installation) and rigid (magnetic forces)
• Clamping system to reduce vibration amplitude
• Silver plated for better electrical contact (Cu-Al)
2007: Broken stripline cable

Observations

- In August 2007, a cut in a cable of the outer plate of the flexible strip line section of the reflector is detected.
- The reflector striplines have seen ~150000 double pulses.
- The horn striplines are identical to the reflector, but see less current than the reflector and have all cables intact.
- The cable broke at the edge of the region where the brazing metal rigidifies the strands.
- The broken cable was removed entirely to avoid short-circuit with the neighbouring cables. A by-pass system and insulating sheets were installed to ensure a safe 2007 run.

Dye penetrant shows many cracks in reflector outer stripline plate cables, both on stripline and transformer side

For run 2007 only
2007: Broken stripline cable

Observation & analysis

- The cut cable was inspected by the CERN metallurgical lab and shows **fatigue** cracks near ruptured section
- **Brazing** significantly weakens the copper cable (40%)
- Measuring the **vibration** of the plate during electrical pulsing shows an **amplitude of 2 mm** under magnetic forces between conductor plates

(courtesy of A. Gerardin, G. Arnau Izquierdo, CERN)

➤ Needs new design
Horn & Reflector stripline link improvement

New design
- Plates instead of twisted cables
- No brazing
- Full-height clamps

Validation & installation
- Extended FE calculations (Seqv<50MPa)
- New vibration amplitude measured: <0.2mm
- Installed on both horn and reflector in May 2008
2008: Water demineralization issues

Hydraulic diagram & characteristics of horn cooling

Demineralisation avoids sparks and reduces corrosion in horns

<table>
<thead>
<tr>
<th></th>
<th>Horn</th>
<th>Refl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure to H/R (bar)</td>
<td>2.2</td>
<td>1.6</td>
</tr>
<tr>
<td>Flow to H/R (l/min)</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Flow in demin. loop (l/min)</td>
<td>45</td>
<td>20</td>
</tr>
</tbody>
</table>
Configuration 2006-2008

- Cartridges bought in industry
- 40 litres of resin per cartridge
- 1 cartridge in circuit, 1 spare
- Quick connectors for rapid exchange without water spill

Disadvantages
- Limited time to saturation:
  \(~7.5 \times 10^{18} \) pot for horn \( \rightarrow \) 6x per year
  (Exchange = ~2 days of beam stop)
- No possibility to recycle the cartridges \( \rightarrow \) large quantities of radioactive waste
- Some essential pieces made of plastic
New design

- All-metal cartridges (304L & 316L)
- Optimised for easy recycling, i.e. exchanging the resin
- Connections that allow up to three cartridges to be put in the circuit in parallel
- Downstream filter for resin beads
  (Lesson learnt from NuMi)

Advantages

- Significantly less radioactive waste
- Time to saturation doubles or triples
- Reliable since only radiation resistant materials
New design

Production and tests (considered as pressurized vessel)

Strainers
Internal tubes
MIG&BE(*) welding
Inlet distribution tube

Assembly
Pressure test
Flow test
Recycling

(*) Metal Inert Gas & Beam Electron
New design

Handling and installation

Installation 18/6/2009 on horn circuit

Main circuit characteristics remain unchanged
Ideas for future improvements (2011)

- There are still electronics in the conductivity probe
  → New probe with electronics at ~100m
- Pump works at full speed, over-dimensioned
  (95% feed-back line) → Frequency variator
- Flow meters keep on failing (radiation, rust?) → New type
- Local purge system (cartridge exchange) → Remote
Conclusions

Nothing new, but is worth repeating...

• Design accessory systems as sturdy as possible
  – Careful choice of materials & techniques
    (e.g. think twice before you braze!)
  – Everything vibrates (& everything sees radiation)
  – Test entire horn system without beam (~$5 \times 10^5$ cycles)

• There will always be bad surprises!
  – Design for remote exchange, but also optimise of remote repair (for early surprises)
  – Build spares (you’ll sleep much better at night)

• Learn from others & share your experience!
Thank you!

And special thanks to NBI-ers Larry Bartoszek, Sam Childress, Jim Hylen, Atsuko Ichikawa and Kazuhiro Tanaka for their valuable input over the last +5 years...
(and for moral support during CNGS horn problems)
Extra Slides
# CNGS Proton Beam Parameters

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Nominal CNGS beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal energy [GeV]</td>
<td>400</td>
</tr>
<tr>
<td>Normalized emittance [µm]</td>
<td>H=12 V=7</td>
</tr>
<tr>
<td>Emittance [µm]</td>
<td>H=0.028 V=0.016</td>
</tr>
<tr>
<td>Momentum spread ∆p/p</td>
<td>0.07 % +/- 20%</td>
</tr>
<tr>
<td># extractions per cycle</td>
<td>2 separated by 50 ms</td>
</tr>
<tr>
<td>Batch length [µs]</td>
<td>10.5</td>
</tr>
<tr>
<td># of bunches per pulse</td>
<td>2100</td>
</tr>
<tr>
<td>Intensity per extraction</td>
<td>2.4 \times 10^{13}</td>
</tr>
<tr>
<td>Bunch length [ns] (4σ)</td>
<td>2</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>5</td>
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<tr>
<td>Beta at focus [m]</td>
<td>hor.: 10; vert.: 20</td>
</tr>
<tr>
<td>Beam sizes at 400 GeV [mm]</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Beam divergence [mrad]</td>
<td>hor.: 0.05; vert.: 0.03</td>
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## CNGS Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Phase</th>
<th>Location</th>
<th>CERN</th>
<th>Event Details</th>
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<tbody>
<tr>
<td>2000-2005</td>
<td>Civil Engineering &amp; Installation</td>
<td>CERN</td>
<td></td>
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<tr>
<td>2006:</td>
<td>Beam Commissioning</td>
<td>CERN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 July-27 Oct</td>
<td>Detector electronics commissioning</td>
<td>Gran Sasso</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2006-2007:</td>
<td>Reflector Water Leak Repair/Improvement</td>
<td>CERN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shutdown</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007:</td>
<td>Beam Commissioning at high intensity</td>
<td>CERN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 Sept-20 Oct</td>
<td>Detector commissioning with 60000 bricks</td>
<td>Gran Sasso</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007-2008:</td>
<td>Additional shielding and electronics re-arrangement</td>
<td>CERN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shutdown</td>
<td>Finishing OPERA bricks</td>
<td>Gran Sasso</td>
<td></td>
<td></td>
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<tr>
<td>2008:</td>
<td>CNGS Physics Run</td>
<td></td>
<td></td>
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<tr>
<td>18 June-3 Nov</td>
<td></td>
<td></td>
<td>1.78·10^{19}pot</td>
<td></td>
</tr>
<tr>
<td>2009:</td>
<td>CNGS Physics Run</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 June-today</td>
<td></td>
<td></td>
<td>2.4·10^{19}pot</td>
<td></td>
</tr>
</tbody>
</table>
Total Integrated Intensity Since CNGS Start in 2006

Total today: 8E19 pot
(Approved for 22.5E19 pot)

- 2006: 0.08E19 pot
- 2007: 0.08E19 pot
- 2008: 1.78E19 pot
- 2009: 3.52E19 pot
- 2010: 2.52E19 pot

Start-up Issues → Physics run

Month/Year:
- 12/06
- 07/07
- 01/08
- 07/08
- 12/08
- 07/09
- 12/09
- 07/10
CNGS Physics Run: Comparison of Yearly Integrated Intensity

Integrated Intensity

Nominal: 4.5E19 pot

2008

1.78E19

2009

3.52E19

2010

1.78E19

2008

2010