MAGNETIC HORNS
for CERN neutrino beams
from the sixties to 2003

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OUTLINE

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1. INTRODUCTION

CNGS neutrino beam project is entirely in AB’s hands
( NPA, TCL, EF, ECP, EP, \( \rightarrow AB \) )
Only exception is the EP horn construction project.
This peculiarity needs now to be corrected.
Progressive transfer of activity from EP to AB is starting and should end in 2006.
2. TECHNICAL BASICS

2.1 Magnetic horn is a focusing device.

Invented in 1961 by S. Van der Meer for collection of charged particles emerging from a target. Used mainly for focusing:
- Pion / kaon beams for neutrino generation
- Antiproton beams for p p^- storage rings
S. Van der Meer in 1961
HORN FOCUSING PROPERTIES

Target produces charged particles: positively charged pions and kaons are emerging at various energies and angles.

\[ F = q (v \land B) \]
\[ B = \mu_0 \frac{I}{2\pi R} \]

CNGS → I=150 kA, R =15.4 mm B = 1.95 Tesla
Usually 2 horns are needed to produce a parallel wide band beam where a much larger number of particles emerging at various energies and angles are collected.
HORN/REFLECTOR – positive particle focusing of CNGS horn

Reflectors Focusing:
- \( p = 50 \text{ GeV} \)
- \( p_t = 180-780 \text{ MeV} \)
(horn under-focused)

Horns Focusing:
- \( p = 35 \text{ GeV} \)
- \( p_t = 80-680 \text{ MeV} \)
Horn-target distance = 2.7m
Reflectors-target dist. = 43m

Reflectors Focusing:
- \( p = 22 \text{ GeV} \)
- \( p_t = 100-400 \text{ MeV} \)
(horn over-focused)

F- Pietropaolo – INFN-Padova
CNGS focusing optics (positively charged particle trajectories)

Radial distribution of positively charged particles at the end of the target chamber TCC4
(total number of trajectories from the target: 10000)
Horn function in neutrino beam production summarized

protons hit target (450 Gev in WANF & CNGS)

$\pi^+ / K^+$ produced in solid angle corresponding to acceptance

magnetic horns to focus $\pi^+ / K^+$

$\pi^+$ and $K^+$ decay to $\mu^+ + \nu$ in long evacuated pipe

left-over hadrons shower in hadron absorber

rock shield ranges out $\mu^+$

$\nu$ beam travels through earth to experiment
**Inner conductor profile**

Fluka Monte-Carlo simulations produce best shape of magnetic volume → best inner conductor profile

( current ranging from 100kA to 400kA )

**Functional requirements for physics**

- transparency of current sheet → thin Al alloy sheet

  → minimum supporting material within magnetic volume

- high magnetic field → high current
Efficiency of horn system

Data from F. Pietropaolo – INFN / April 2003

CNGS reference beam

Nu\textsubscript{mu} CC interactions (<100GeV) at LNGS (%)

Horn\textsubscript{Refl.} zero-current : 10%
Reflector zero-current : \sim 50%
Standard configuration : 100%
Horn-Refl. half thickness : 111%
Horn-Refl. zero thickness : 123%
Perfect focusing : \sim 200%
2.2 How is a horn powered?

Horn is a short circuit i.e. small inductance 0.1 to 3 \( \mu \text{H} \) and small resistance 100 to 1000 \( \mu \Omega \)

Current is produced by discharge of a capacitor bank into horn in resonant mode (resonant L C R circuit)
High currents $\rightarrow$ pulsed mode

(reduced heating and power consumption)

Pulse length can vary from the 10µs range up to the 10ms range.

\[ T/2 \approx \pi \left( L C \right)^{1/2} \]
Typical horn capacitor discharge circuits

Charging Supply

Thyristors

Transformer

1 km line

Charging Supply

Thyristors

Transformer

1 km line

Recuperation circuits not shown
voltage reducing pulse transformer

Use of voltage reducing pulse transformer near horn is envisaged when distance between capacitor bank and horn has to be long. (WANF and CNGS)

\[ V_2 = \frac{V_1}{m} \]

Simplifies also the thyristor switch
( since \( I_1 = \frac{I_2}{m} \) )

Disadvantage:
- pulse length is longer by factor \( m \)
\[ \frac{T}{2} \approx m \pi (L C)^{1/2} \]
- addition of parasitic impedance
2.3 Operating voltage?

Exposure to very high radiation doses

→ insulation with mineral material and/or air

→ preferably low voltage on horn (and busbars)

\[ V \approx I (L/C)^{1/2} \]

If heating is not critical, pulse can be long. Low voltage on horn is possible (i.e. < 1000V):

-→ high C

or -→ voltage reducing transformer

Ex. LV horns:

- low voltage capacitors without transformer
  ex. : NUMI at Fermi lab

- high voltage capacitors with transformer
  ex. : WANF, CNGS, KEK
If heating is critical, short pulse lengths are compulsory. Pulse transformer cannot be used. HV on horn cannot be avoided.

- MiniBoone at Fermilab (4 kV range)

- Neutrino Factory prototype (4 kV range)

- PS neutrino beam with heavy liquid bubble chamber and Gargamelle in the 60's (12 kV range)
2.4 Flat top requirements

Particles cross magnetic volume when field is maximum. Duration of ejection fixes flat top requirement and pulse length needed.
2.5. Cooling

Secondary circuit is vapor tight

Demineralised cooling water 17°C

Primary circuit

Radioactive area

~ 50°C

Demineralised closed water circuit
2.6 Simulations

Electricity

Circuit is simple.

But main difficulty is correct evaluation of all inductive and resistive components. Few are negligible since horn is somehow a short-circuit.

Skin effect has to be taken in account for short pulses.

(For Al alloy 6082, $\delta = 1.6$ mm for 2500Hz i.e. 200 $\mu$s pulse)
Mechanics

Requirement for CNGS horn: 95% probability to survive $2 \times 10^7$ pulses

- Magnetic forces are cyclic \( p = \left( \frac{\mu_0 I^2}{8 \pi^2 R^2} \right) (1 - \tau/6) \)
  \( \tau = t/R \) with \( t = \) wall thickness

- Thermal effects due to current are also cyclic with addition of beam energy deposition

  \( \Rightarrow \) Repetition rate must not hit a natural frequency of horn system

Calculations are made using ANSYS

  \( \Rightarrow \) static FE analysis to estimate thermal stresses
  \( \Rightarrow \) modal analysis to estimate natural frequencies
  \( \Rightarrow \) ANSYS FE dynamic stress calculations
  \( \Rightarrow \) fatigue analysis (evaluation of maximum equivalent completely reversed stress \( \sigma_{ecrs} \))

  \( \Rightarrow \) measurements on BA7 test circuit of natural frequencies and displacements due to vibrations
Fatigue strength

vibration mode 1 (140 Hz)

Pt 1 (mode 1; 1+2)

vibration mode 2 (360 Hz)

Pt 2 (mode 2; 1+2)

σ_{ecrs} = 54 MPa (mode 2)

Pt 3 (mode 1+2)

Beam
Fatigue strength

we are below this limit

**Mechanical studies and measurements**

- **HORN** 150 kA
- **REFLECTOR** 180 kA

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Fig. 70 6061-T6 notched (radius at notch root <0.001 in.) and unnotched rotating beam fatigue at room temperature. Solid symbols indicate runout (no failure). Longitudinal and transverse specimens from extruded bar (5/8 x 3.5 in.), rolled- and drawn rod (0.75 in.), and rolled plate (1.25 in. thick). R.R. Moore specimens with 9-7/8 in. surface radius and 0.300 in. minimum diameter for unnotched specimens. Notched specimens had a 0.330 in. diameter at the notch and a 0.480 in. diameter outside the 60° notch. Source: Alcoa, 1960
2.7 Summary of engineering constraints

**Radiation**

- target - in front of - or into horn
- heating by particle absorption
- beam effects on material strength (dislocations in metal)
- radiation resistance of materials
- insulation problems
- access problems - remanent dose rates

**Corrosive environment**

**Minimum thickness**

- light Al alloy inner conductor  "10 kg"
- robust Al alloy outer conductor  "400 kg"
Cyclic heat load
  by Joule effect
  by particle absorption
  \rightarrow cyclic heat effect dilatation
  \rightarrow cooling
  sprayed water along inner conductor

Cyclic magnetic forces
  \rightarrow cyclic mechanical strain
  \rightarrow induced vibrations
  \rightarrow all effects produce mechanical fatigue

Pulsed electric system
  \rightarrow special capacitors

High current discharges
  \rightarrow thyristor assemblies
Goal:  
→ improve reliability and life time of horn  
→ inner conductor as thin as possible  

pushes mechanics close to the limit  
Fatigue is thus the limiting factor  

Enormous progress on electrical part  
since thyristors replaced ignitrons
2.8 Handling problems linked to radiation

On site repairs are impossible due to high remanent dose rates. (10 mS intervention allowed/month/person, provided dose rate < 20 mS/h)

- Replacement of a damaged horn
- Transport and storage of irradiated horns
- Re-Alignment of the horn

remain difficult constraints

A Fast Coupling System is under development at LAL/Orsay which may relieve of the necessity to use a robot for CNGS horn replacement.

Automatic procedures without human intervention should prevail.
3. 40 YEARS of HORN PROJECTS at CERN

3.1 PS neutrino beams from 61 -> 75

2s cycle with fast extraction from the PS of 2 µs proton burst at 25 GeV (up to 10E12 protons on target)
One of the first horns (63-64 PS neutrino experiment)
First horn on test in 1962-63
1 - 3 Gev neutrinos

PS Sout East Area neutrino beam constructed in 65-66 up to 26 Gev protons

Gargamelle after 1970

TARGET CENTER

96m

Gargamelle

iron shield 22 m
decay length 70m

R1 340 kA
R2 400 kA
R3 400 kA

24 April, 2003.
South East Area of PS

Target

Gargamelle
Horn on beam in 1967
12 parallel circuits

CAPACITOR DISCHARGE CIRCUIT with CROWBAR 10.10.68
R2 reflector

R3 reflector
Logbook of 9 years neutrino runs ( 66-75 )

Difficult runs (insulation problems, cable fire in 69, bad firing of ignitrons, bad electrical contacts,..) but big reward

**Discovery at Gargamelle in 1973**

The first observation of weak neutral current interactions was made in 1973 at the Gargamelle bubble chamber that was recording neutrino interactions at the CERN neutrino beam.

*(Gargamelle et les courants neutres – André Rousset Témoignage sur une découverte scientifique Collection Sciences de la Matière, 1996)*

This was the first (indirect) evidence of the existence of the W and Z particles which were explicitely discovered 10 years later also at CERN by the UA1 and UA2 experiments

*(Carlo Rubbia and Simon van der Meer obtained Nobel prizes for this discovery).*

**End of runs in South West Area ”1975**
3.2 SPS neutrino beams from 77 to 98

BEBC, WA1, Gargamelle

CHARM 1&2, CHORUS, NOMAD experiments
fast/slow extraction from the SPS: two 6 ms long spills at 450 GeV

(1 - 1.5)X10E13 protons on the target
DETECTORS
WEST AREA  822 m

124 m  290 m  185 m

450 Gev protons

mean energy 27 Gev after 94
( first iron shield )

110 kA  120 kA

West Area Neutrino Facility (WANF)
No service gallery
(local shielding along beam)
First horn in 76

Reflector positioning base
2 reflectors in serie with remote plug-in systems
CHORUS-NOMAD horn (110 kA) installed in 1993
CHORUS-NOMAD reflector (120 kA) installed in 1993
New TESLA transformer installed in 93
-transformer ratio 32-
WANF 17 cells delay line
6ms flat top on horn/reflectors pulse

Each cell $L = 220 \ \mu \text{H}$
$C = 234 \ \mu \text{F}$

$I = 110 \ \text{kA}$

1976

CHARGING POWER SUPPLY
12 kV - 25A
(Nominal 5.9 kV)

BA7

CAVE

TESLA m32

FLEXIBLE GRIDS

ONHEXION PLATES

STRIPLINES

27.5 kA
27.5 kA
27.5 kA
27.5 kA
27.5 kA

V2 = 184.47 kV nominal

I2 = 110 kA

High Voltage Primary

I = 3.47 kA
Measured horn current

6ms beam spill

100 kA  
V = 5.4 kV

Measured reflector current

6ms beam spill

120 kA  
V = 5.2 kV
Horn and reflector capacitor banks in BA7
Logbook of 21 years neutrino runs at WANF

High operational reliability

Current on horn kept low \(110\,\text{kA}\)
  - to ensure run stability
  - to avoid accidental horn replacement in very high radiation area

Several horn/reflectors configurations have been operating for the succeeding group of experiments.
No accidental horn exchange had to be faced after 77.

Complete refurbishment of target chamber took place in 92-93 for installation of CHORUS-NOMAD beam.

Impressive number of neutrino experiments based on WB beam, NB beam in 1984, “beam dump” beams, also oscillation experiment at PS in 81-82.
3.3 CNGS to operate in 2006

Goal of the CNGS project  (F- Pietropaolo - INFN-Padova)

“Long Base-Line” $\nu_\mu \rightarrow \nu_\tau$ oscillation experiments

- build an intense high energy $\nu_\mu$ beam at CERN-SPS
- optimized for $\nu_\tau$ appearance search at Gran Sasso laboratory (730 km from CERN)
CNGS Layout - F- Pietropaolo - INFN-Padova
450 Gev protons

Gran Sasso 730 km

100 m
Helium bags

1000 m
Decay tube

67 m
Hadron stop
Muon detectors

150 kA
180 kA

2.7 m
43 m

CNGS

mean energy
26.7 Gev

-F- Pietropaolo - INFN-Padova
Main design criteria of CNGS horns project

safety

savings  maximum re-use of WANF equipment

reliability
Charging supply to be adapted to AB/PO standards

CNGS + Fixed target
Horn electrical circuit layout for CNGS
Charging supply

Reflector capacitor bank

Horn capacitor bank

Controls

BB4

BHA4
CNGS HORN

Length : 6.65 m
Diameter : 70 cm
Material : Al alloy 6082
Pulsed : 150 kA , 8ms
Water cooled : distributed nozzles

First prototype successfully tested (WANF reflector outer conductor with WANF horn modified inner conductor)
5 $10^5$ pulses at 150 kA in 2001 in single pulse
$10^3$ pulses at 150 kA in 2003 in double pulse

LAL-Orsay picture - S. Wallon
BA7 horn test area (CNGS prototype testing in 2000-2001) horn with modified waf inner conductor
Inner conductor electron beam welded supported with 3 spiders
Each spider made of 3 cables

Water supply in
Water supply out

Electrical connections - 4 pairs of plates

LAL-Orsay picture - S. Wallon
Inner conductor: "10 kg

Length: 6.65 m
Min. thickness: 1.8 mm
Diameter: 30.8 à 136 mm
made up of 9 conical parts
electron beam welded
and 2 flanges
(delivered)

LAL-Orsay picture - S. Wallon
striplines

Adjustable supports

LAL-Orsay picture - S. Wallon
Horn connected to striplines

LAL-Orsay picture - S. Wallon
Fast coupling system
Striplines 4 X 37.5 kA peak

FAST COUPLING SYSTEM and HORN

TRANSF.
Recuperated WANF TESLA transformers
- transformer ratio 16 (2&2 secondary couplings not mounted)
## Operation parameter table updated April 2003

<table>
<thead>
<tr>
<th>Updated 15 April 2003</th>
<th>Unit</th>
<th>HORN SYSTEM</th>
<th>REFL. SYSTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duty cycle</td>
<td></td>
<td>2 pulses 50 ms apart all 6 s</td>
<td></td>
</tr>
<tr>
<td>Peak current in horn</td>
<td>kA</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Transformer ratio</td>
<td></td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Primary current peak</td>
<td>kA</td>
<td>9.375</td>
<td>6.646</td>
</tr>
<tr>
<td>Total capacitance for two switching sections</td>
<td>µF</td>
<td>45.4 x 90 x 2 = 8172</td>
<td>45.4 x 90 x 2 = 8172</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>ms</td>
<td>7.5</td>
<td>10</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>V</td>
<td>7700</td>
<td>6300</td>
</tr>
<tr>
<td>Total stored energy</td>
<td>kJ</td>
<td>2 x 119 = 238</td>
<td>2 x 80 = 160</td>
</tr>
<tr>
<td>Max. voltage on element</td>
<td>V</td>
<td>280</td>
<td>150</td>
</tr>
<tr>
<td>Mean power dissipated in element by current only (2 pulses)</td>
<td>kw</td>
<td>16</td>
<td>10.5</td>
</tr>
<tr>
<td>Mean power dissipated in element (inner + outer conductor) for 7.2 x 10**13 pot per 6s cycle</td>
<td>kw</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Total power dissipated in element (2 pulses)</td>
<td>kw</td>
<td>26</td>
<td>16.5</td>
</tr>
<tr>
<td>Waterflow for δθout- δθin = 5°C</td>
<td>l/min</td>
<td>75</td>
<td>48</td>
</tr>
</tbody>
</table>
**Status of CNGS horn project in April 2003**

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
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<tbody>
<tr>
<td>Production of horns at Orsay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New capacitors</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable order</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Reconditioning of electric circuits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Testing of LAL horns</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Installation in BHA4/ECA4</td>
<td></td>
<td></td>
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<tr>
<td>Installation in target chamber</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Commissioning and tests</td>
<td></td>
<td></td>
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</tbody>
</table>
### 3.5 Neutrino Factory studies for future

Prototype developed at CERN in 2001

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Maximum current</td>
<td>300 kA</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Waist diameter</td>
<td>80 mm</td>
</tr>
<tr>
<td>Length</td>
<td>1030 mm</td>
</tr>
<tr>
<td>Life time</td>
<td>6 weeks or $2 \times 10^8$ pulses for the prototype</td>
</tr>
<tr>
<td></td>
<td>(six months or $8 \times 10^8$ pulses for a final horn)</td>
</tr>
<tr>
<td>Pulse length</td>
<td>$\leq 100$ µs</td>
</tr>
<tr>
<td>r.m.s current</td>
<td>15 kA (CMS – 20 kA)</td>
</tr>
<tr>
<td>Voltage on horn</td>
<td>$\sim 4000$ V</td>
</tr>
<tr>
<td>Skin depth</td>
<td>1.25 mm</td>
</tr>
<tr>
<td>Joule losses</td>
<td>40 kW</td>
</tr>
</tbody>
</table>
Main technical problems: Cooling, vibrations, irradiation, fatigue

Toroidal water cooling channel
Studies of NUFACT horn are taken over by LAL/Orsay in the frame of European Neutrino Group created in 2003

CERN prototype under test
4 CNGS HORN PROJECT TODAY

CERN groups AB/PO with the support of AB/CO
AB/ATB
EP/TA3

collaborate in the frame of the newly created Joint Horns & their Power supplies Construction project for CNGS (JHPC-CNGS)

- EP Division is responsible to deliver the horn systems in 2006 as turnkey systems to AB division.

- AB division will take over full responsibility for the future operation and maintenance.
  Joint interdivisional efforts and AB standardised approaches will help to ensure a smooth transition to the operation phase.
Production of horns including water cooling systems, striplines and supports has been outsourced to IN2P3 – LAL/Orsay as inkind contribution according to:

MoU of 4 August 2000 between CERN and IN2P3 – LAL/Orsay

LAL/Orsay will:

- Produce horn/reflector and striplines including water circuits and supports as inkind contribution.
  
  (Outsourcing organised by EP/TA3)

- Take part in electrical testing, final installation and running-in.
5. SUMMARY

Magnetic horns are a fundamental instrument in the generation of accelerator neutrino beams.

- **Numi**: 200 kA, 0.5 Hz, 6M pulses
  - 1 year
  - [Diagram: NuMi horn 1, NuMi horn 2]

- **MinibooNe**: 170 kA, 5 Hz, 11M pulses
  - 1 year
  - [Diagram: MiniBooNE, KEK horn 1, KEK horn 2]

- **K2K**: 250 kA, 0.5 Hz, 11M pulses
  - 1 year
  - [Diagram: CERN/NeuFact horn prototype]

- **NuFact**: 300 kA, 50 Hz, 200 M pulses
  - 6 weeks
  - [Diagram: CNGS horn 1, CNGS horn 2]

- **CNGS**: 150 kA, 2 pulse/6s, 42 M pulses
  - 4 years

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6. CONCLUSION

What has changed in 40 years?

- electronbeam welding, less supporting material
- power thyristors
- computer controls
- elaborate calculations with computer programs
- distance of detectors

How does future look?

AB division goes into a nice heritage in 2006. Let's wish that neutrino hunting goes on successfully with the expected $\tau$ appearance ($\tau$ lepton detection).

On the longer future, development of fast cycling horns for neutrino factories opens a new field of developments. (neutrino oscillations proposals with a Superbeam and Beta-beam?)
Problems with neutrinos ??... (see recent novel from F. Vanucci)

Many thanks to all from the sixties to now