CERN Neutrinos to Gran Sasso (CNGS):
Commissioning and First Operation

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AB/ATB/EA
on behalf of the CNGS project and commissioning teams
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2. Proton Beam Line Commissioning
3. Secondary Beam Line Commissioning
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5. First Events at Gran Sasso (OPERA)
CNGS Project

CNGS (CERN Neutrinos to Gran Sasso)

- A long base-line neutrino beam facility (732km)
- send $\nu_\mu$ beam produced at CERN
- detect $\nu_\tau$ appearance in experiments at Gran Sasso

$\Rightarrow$ direct proof of $\nu_\mu$ - $\nu_\tau$ oscillation (appearance experiment)
$\nu_\tau$ – Appearance Experiment

- **Beam optimization:**
  - Intensity: as high as possible
  - Neutrino energy: matched for $\nu_\mu - \nu_\tau$ appearance experiments

- **Product of**
  1. Oscillation probability $\nu_\mu - \nu_\tau$
  2. Production cross-section $\nu_\tau$ with matter
  3. $\nu_\mu - $fluence(E)
     + Detection efficiency in the experiment
Look for the $\tau$ lepton:

- extremely difficult:

  $\tau$ travels only less than 1 mm before decaying

Approach:

- very good position resolution (see the decay ‘kink’): OPERA

  (ICARUS: see status report at the next SPSC 3 Oct. 2006)
Radial Distribution of the $\nu_\mu$-Beam at GS

typical size of a detector at Gran Sasso
CERN Neutrinos to Gran Sasso
CNGS Layout

$$\text{p} + \text{C} \rightarrow \text{(interactions)} \rightarrow \pi^+, \ K^+ \rightarrow \text{(decay in flight)} \rightarrow \mu^+ + \nu_\mu$$
## 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 Δp/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 [10^{13} p]</td>
<td>2.4</td>
</tr>
<tr>
<td>Bunch length [ns] (4σ)</td>
<td>2</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>5</td>
</tr>
<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>
</tr>
</tbody>
</table>

Expected beam performance: 4.5 x 10^{19} protons/year on target

Upgrade phase: 3.5 x 10^{13} p

500kW beam power
Schedule

<table>
<thead>
<tr>
<th>Civil Engineering</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>excavate civil engineering pit, tunnels and caverns; concrete / shotcrete tunnels and caverns</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

Install hadron stop
iron + graphite blocks, aluminum plate + water cooling

Install decay tube
lower decay tube sleeves, weld together, pour concrete

Civil Engineering - phase 2
finish concrete floors, close provisional CE pit

Install general services
electrical services, ventilation, cooling water, etc.

Install equipment
proton beam line, target, horn-reflector, shielding

Commissioning w/o beam

First beam: 10 July 2006
Proton Beam Line Commissioning
MBG (Dipoles)
- 73 magnets (5 spares)
- Gap height 37mm
- Nominal field: 1.7 T @ 400 GeV
- Magnetic length: 6.3m

QTG (Quadrupoles)
- 20 magnets (3 spares)
- Magnetic aperture: 45mm
- Nominal gradient 40 T/m, 2.2m long

MDG (Corrector Magnets)
- 12 magnets (5 spares)
- Gap height: 45mm
- Bending angle: 80mm, 0.7m long
Final focusing onto the target (recuperated magnets)
Proton beam: last beam position / beam profile monitors upstream of the target station collimator and shielding

BN collimator, d=14mm

Be window, t=100μm
Commissioning Plan

- **Hardware commissioning**  
  - Beam instrumentations
  - Power supplies
  - Magnets (polarities)
  - Vacuum system
  - (April / May: Target / Horn exchange exercises ‘real’)

- **‘Dry runs’ from CCC**  
  - Timing
  - Controls
  - Interlocks
  - Beam permit
  - Magnets (currents & polarities)

- **Commissioning with beam**  
  2006: weeks 28, 30 and 33
CNGS Commissioning:
total number of protons used: $7 \times 10^{15}$

$1 \times 10^{13}$

(equivalent to 1 hour of CNGS running with nominal beam)
1st shot down proton beam line: beam is already well centered on screens

8 profile monitors (BTVG):
Optical Transition Radiation screens:
• 75 μm carbon
• 12 μm titanium screens

E. Gschwendtner, CERN
CNGS Beam Position Monitors

18 Button Electrode BPMs in TT41
60mm Aperture
Average of two extractions. 1E13 protons per batch

Horizontal plane

Vertical plane

5mm
energy difference of $6 \cdot 10^{-5}$

Beam position stability onto the target over the 3 first days: $\sim 50 \, \mu\text{m rms}$
Stripline coupler pick-up, operated in air

very reliable position reading
Beam Losses along the Proton Line

TT41: ALL screens OUT, at the exception of the target one

CNGS BLMs with double extraction $1 \cdot 10^{13}$
Optics Check

Beta functions

good agreement with theory

Dispersion $D_x$

Dispersion $D_y$
Secondary Beam Line Commissioning
CNGS Secondary Beam Layout

TBID / 2 Ionization Chambers

TBID: Target Beam Instrumentation Downstream

Muon Detectors
10 cm long **graphite rods**, Ø = 5mm and/or 4mm

**Note:**
- target rods **thin** / interspaced to “let the pions out”
- target shall be **robust** to resist the beam-induced stresses
- target is **air-cooled** (particle energy deposition)
Ten targets (+1 prototype) have been built. They are assembled in two magazines.
Target magazine installation inside target station (25 Nov. 2005)
TBID Monitor
- Secondary emission monitor
- 12 µm Ti foils
- diameter = 145mm
- better than $10^{-4}$ mbar vacuum

TBID Monitor might not survive if high intensity beam misses the target

Ionization Chambers as back-up (SPS-type BLMs)
Target Region Layout

Ionization Chambers

BPM2  collimator  target

beam  horn

RX target 88881  PMICN403
Horizontal Beam Scan, Target Out

Intensity on TBID vs. BPM2

BPM2 [mm]

arbitrary unit

-8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10

BPM2 collimator
Intersity on TBID vs. BPM2 position

Horizontal Beam Scan, Target IN

[BPM2 vs Intensity Graph]
Installation of the horn in the target chamber
Horn/Reflector Power System

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>HORN System</th>
<th>REFLECTOR System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Peak current</td>
<td>kA</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>ms</td>
<td>6.5</td>
<td>9.8</td>
</tr>
<tr>
<td>Transformer ratio</td>
<td></td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Primary peak current</td>
<td>A</td>
<td>9375</td>
<td>5646</td>
</tr>
<tr>
<td>Charging voltage</td>
<td>V</td>
<td>6300</td>
<td>5800</td>
</tr>
<tr>
<td>Water flow for delta T=5C</td>
<td>l/min</td>
<td>75</td>
<td>48</td>
</tr>
<tr>
<td>Pressure</td>
<td>bar</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Decay Tube

- steel pipe
- 1mbar
- 994m long
- 2.45m diameter, t=18mm, surrounded by 50cm concrete
- entrance window: 3mm Ti
- exit window: 50mm carbon steel, water cooled

April 2004: vacuum tests ok
Hadron Stop completed Sept. 2003

- Cooling modules: stainless steel tubes in Al blocks
- Several temperature sensors (both in target chamber and in hadron stop)
Muon Monitors

Monitoring of:

- muon intensity
- muon beam profile shape
- muon beam profile centre

Muon energy filter due to 67m rock in between pit 1 and pit 2.
Expected Muon Signals (FLUKA)

Muon intensity:
Up to $\sim 8 \times 10^7$ per cm$^2$ and $10.5\mu$s

→ Detector choice: ionization chambers
Muon Monitor Layout

LHC type Beam Loss Monitors
- Parallel electrodes separated by 0.5 cm
- Stainless steel cylinder
- Al electrodes
- N₂ gas filling at 100 mbar over pressure
- Diameter=8.9cm, active length=34.5cm, 1.5 litre

- Dynamic range: 10⁵
- Specs accuracies: 10% absolute, 3% relative, 1% cycle by cycle, 5% per year

CNGS installation:
- 2 x 37 fixed monitors (Ionization Chambers)
- 2 x 1 movable chamber behind fixed monitors for relative calibration
- Movement by stepping motors
Horizontal Angular Scan, Target Out

horizontal muon detectors pit1, target out, horn/refl off, ~ 3E11 protons

charges/pot vs cm

-158 -146 -135 -124 -113 -101 -90 -78.8 -67.5 -56.3 -45 -33.8 -22.5 -11.3 0 11.3 22.5 33.8 45 56.3 67.5 78.8 90 101 113 124 135 146 158 cm

-0.2mrad - 0.2mrad - 0.0mrad
target vs. horn misalignment: 3 mm → 10.1 cm shift in Muon Pit1
6 mm → 19.1 cm
9 mm → 24.3 cm

simulations
Vertical Target vs. Horn Alignment

Muon pit 1: more sensitive to target vs. horn alignment

- Target with beam zero
- Target 2mm upwards

Charges/pot vs. cm

BPM2 Target Horn

BPM2 Target Horn
beam vs. target misalignment: 0.5 mm → 7.3 cm shift in Muon Pit2
1.0 mm → 14.8 cm

simulations
Muon pit 2: more sensitive to beam vs. target alignment

-1.5 mm
1 mm
nominal, 0 mm

charges/pot

cm
Final Alignment

BPM2

1.9 mm

coll. \( \Phi =14 \) mm

target

horn

target ref. system
beam ref. system

BPM2

1.4 mm

2 mm

coll. \( \Phi =14 \) mm

target ref. system
beam ref. system
“all muons” (except low E)

only highest energy muons

On-line display

Pit 1

pit 1, horizontal

pit 1, vertical

Pit 2

pit 2, horizontal

pit 2, vertical
Target Unit Tests

unit 1: polycrystalline graphite by Carbone-Lorraine 2020 PT
density 1.76 g/cm³

unit 3: carbon-carbon composite by Carbone-Lorraine A035
density >1.75 g/cm³
Comparison Unit 1 and Unit 3

Average of 2 extraction, \(\sim 1.2 \times 10^{13}\) protons

Muon pit 1

Muon pit 2
Check Horn/Reflector On/Off

Muon Signals in Pit 1

\[ \Delta \sim \text{factor 10} \]

Horn/Refl ON

Horn/Refl OFF
Comparison measurement-simulation, horizontal pit 1

Muon Monitors, Horizontal Pit 1

- Measurement
- Simulation

Fluka simulation
Muon Monitors, Horizontal Pit 2

- Measurement
- Simulation

Fluka simulation
CNGS Operation
CNGS operation: protons on target
18 - 30 August: $6.3 \times 10^{17}$ p.o.t.
Muon Monitor Stability Pit 2

proton intensity/extraction

charges/pot

+/-1%
Muon Monitor Stability Pit 1

- Proton intensity/extraction
- Charges/pot

+/-1%
Horn Cooling

trend during 8 days

Horn water Temp “in/out”

H water Temp-out

H water Temp-in

Water conductivity

4.7°C

3°C

1°C

24h
Radiation Detectors in ECA4
The monitors show maximum radiation values of 1 $\mu$Sv/h in accessible regions. Based on beam loss studies and simulations this corresponds to a beam loss of 0.05 %.
First OPERA Events
Basic unit: brick: 56 Pb sheets + 56 emulsion sheets

31 target planes / supermodule  (in total: 206336 bricks, 1766 tons)

Proposal: July 2000, installation at LNGS started in May 2003
First observation of CNGS beam neutrinos: August 18th, 2006
Scintillator planes 5900 m²
8064 7m long drift tubes

3050 m² Resistive Plate Counters
2000 tons of iron for the two magnets
Event Selection by Using GPS Timing Info

Δt first extraction (ns)

Ext1

Ext2

50 ms

Zoom on the spill peaks

Δt closest extraction (ns)

Cosmic rays background events

10 μs
Beam Events

CC event in the first magnet

Muon from CC interaction in the material in front of the detector (BOREXINO, rocks)
Summary

- CNGS construction started 2000
- Installation finished beginning 2006
- Detailed hardware commissioning
- ‘Dry runs’
  - Allowed early debugging of all systems
- CNGS has been successfully commissioned

→ CNGS is operational

- The most difficult part (high intensity operation) starts now
  - Very high radiation levels
  - Fatigue from beam impact (shocks) on equipment
  - Fatigue from pulsing
  - …
MANY THANKS

to all involved in the project’s success!