Performance and Operational Experience of the CNGS Facility

Edda GSCHWENDTNER, Dario AUTIERO, Karel CORNELIS, Ilias EFTHYMIOPOULOS, Alfredo FERRARI, Alberto GUGLIELMI, Ans PARDONS, Paola SALA Heinz VINCKE, Joerg WENNINGER

(October 20, 2009)

Outline

- Introduction
- Layout and Main Parameters
- Operational Experience and Performance
- Summary

CERN Neutrinos to Gran Sasso (CNGS)

long base-line appearance experiment:

- Produce muon neutrino beam at CERN
- Measure tau neutrinos in Gran Sasso, Italy (732km)

→ ν_τ interaction in the target produces a τ lepton

→ Identification of tau lepton by characteristic kink

2 detectors in Gran Sasso:

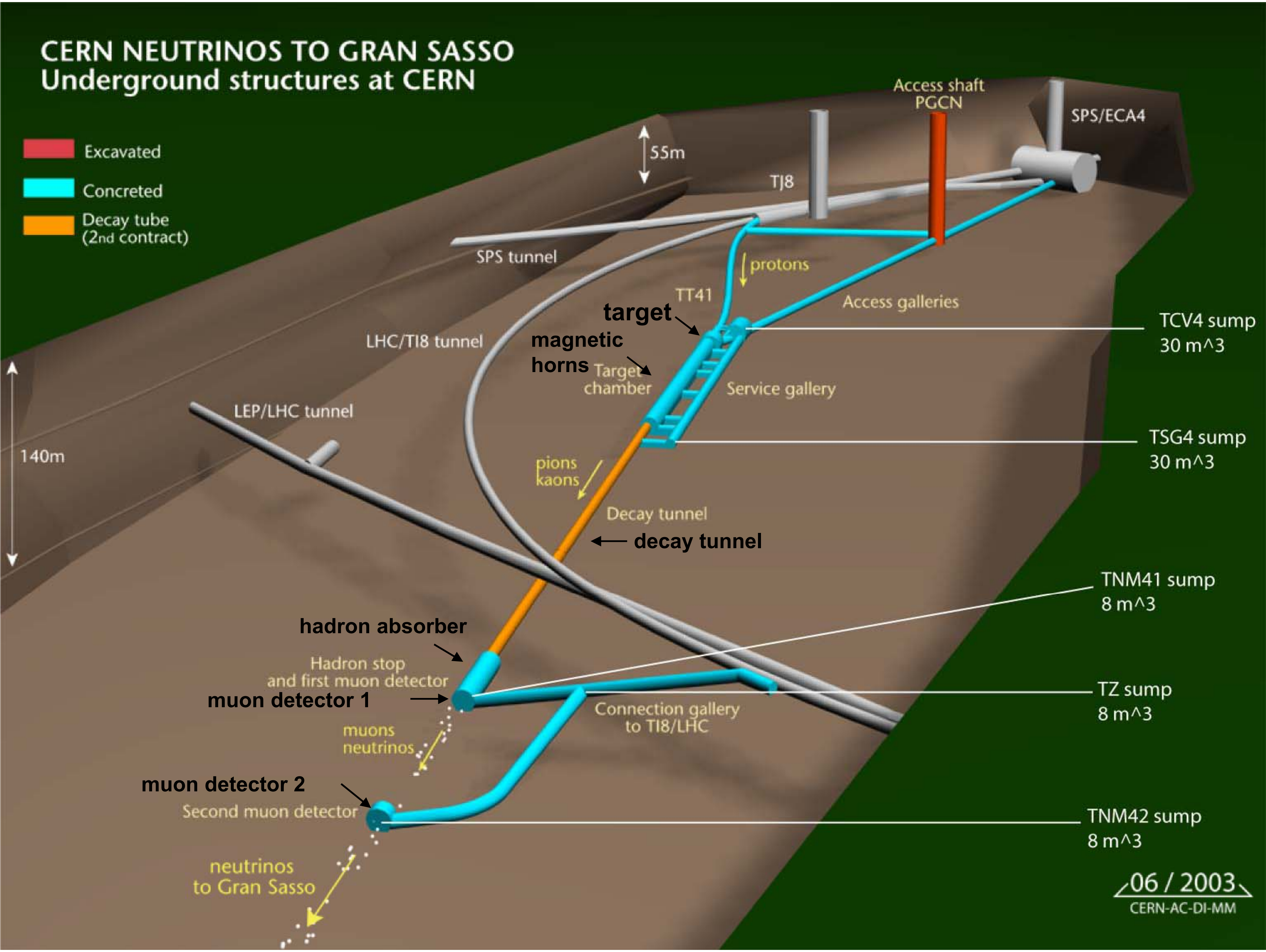
• OPERA
(1.2kton) emulsion target detector
~146000 lead-emulsion bricks

• ICARUS
(600ton) liquid argon TPC

CNGS: Conventional Neutrino Beams

→ **Produce pions and Kaons to make neutrinos**

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

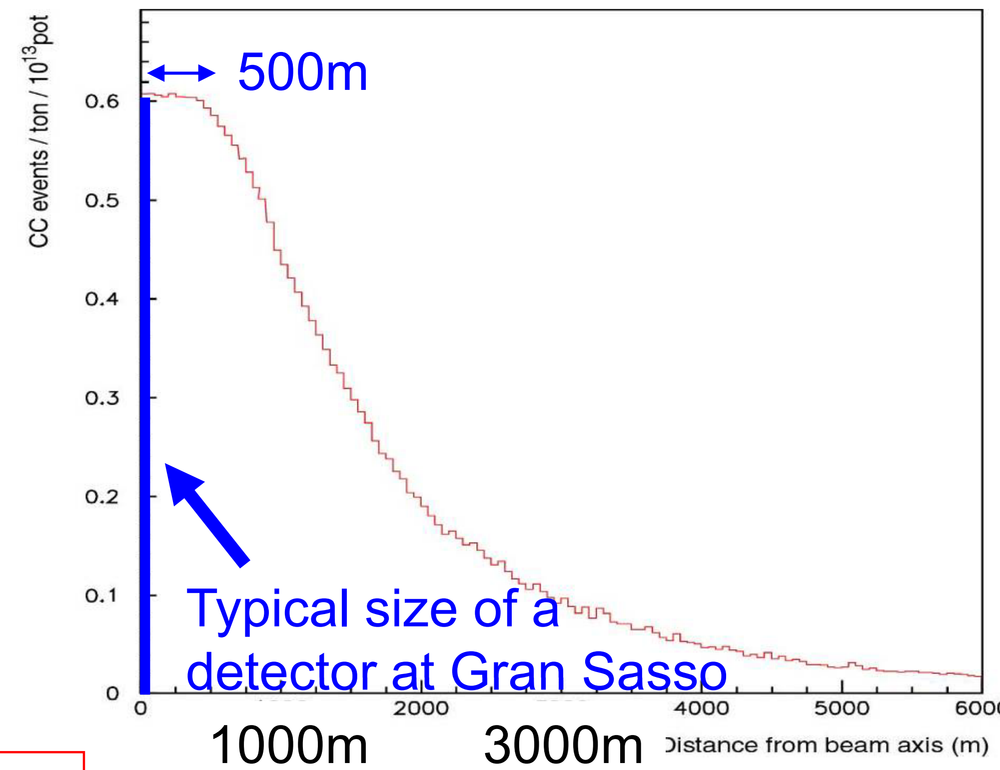

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN
Excavated
Concreted
Decay tube
(2nd contract)
55m
140m
Access shaft
PGCN
SPS/ECA4
TJ8
SPS tunnel
protons
TT41
Access galleries
target
TCV4 sump
30 m^3
magnetic
horns
Target
chamber
LHC/TI8 tunnel
Service gallery
LEP/LHC tunnel
TSG4 sump
30 m^3
pions
kaons
Decay tunnel
decay tunnel
TNM41 sump
8 m^3
hadron absorber
Hadron stop
and first muon detector
muon detector 1
TZ sump
8 m^3
Connection gallery
to TI8/LHC
muons
neutrinos
muon detector 2
Second muon detector
TNM42 sump
8 m^3
neutrinos
to Gran Sasso
06 / 2003
CERN-AC-DI-MM

CERN Neutrinos to Gran Sasso

Approved for 22.5 $\cdot 10^{19}$ protons on target
i.e. 5 years with $4.5 \cdot 10^{19}$ pot/ year
(200 days, nominal intensity)

→ $2.2 \cdot 10^{17}$ pot/day
→ ~10^{17} ν_μ /day
→ ~10^{11} ν_μ /day at detector in Gran Sasso

→ 3600 ν_μ interactions/year in OPERA
(charged current interactions)
→ 2-3 ν_τ interactions detected/year in OPERA



~1 ν_τ observed interaction with $2 \cdot 10^{19}$ pot

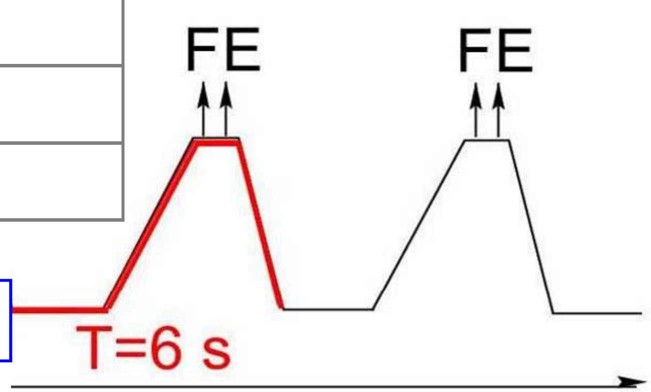
CNGS Run 2008: $1.78 \cdot 10^{19}$ pot

Run 2009 today: $2.53 \cdot 10^{19}$ pot

CNGS Proton Beam Parameters

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

500kW beam power



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

CNGS Challenges

- High Intensity, High Energy Proton Beam (500kW, 400GeV/c)
  - Induced radioactivity
    - In components, shielding, fluids, etc…
  - Intervention on equipment 'impossible'
    - Remote handling by overhead crane
    - Replace broken equipment, no repair
    - Human intervention only after long 'cooling time'
  - Design of equipment: compromise
    - E.g. horn inner conductor: for neutrino yield: thin tube, for reliability: thick tube
- Intense Short Beam Pulses, Small Beam Spot (up to 3.5×10^{13} per 10.5 μs extraction, < 1 mm spot)
  - Thermo mechanical shocks by energy deposition (designing target rods, thin windows, etc…)

→ **Proton beam: Tuning, Interlocks!**

→ **most challenging zone: Target Chamber (target–horn–reflector)**

CNGS Layout and Main Parameters

CNGS Primary Beam Line

100m extraction together with LHC, 620m long arc to bend towards Gran Sasso, 120m long focusing section

Magnet System:

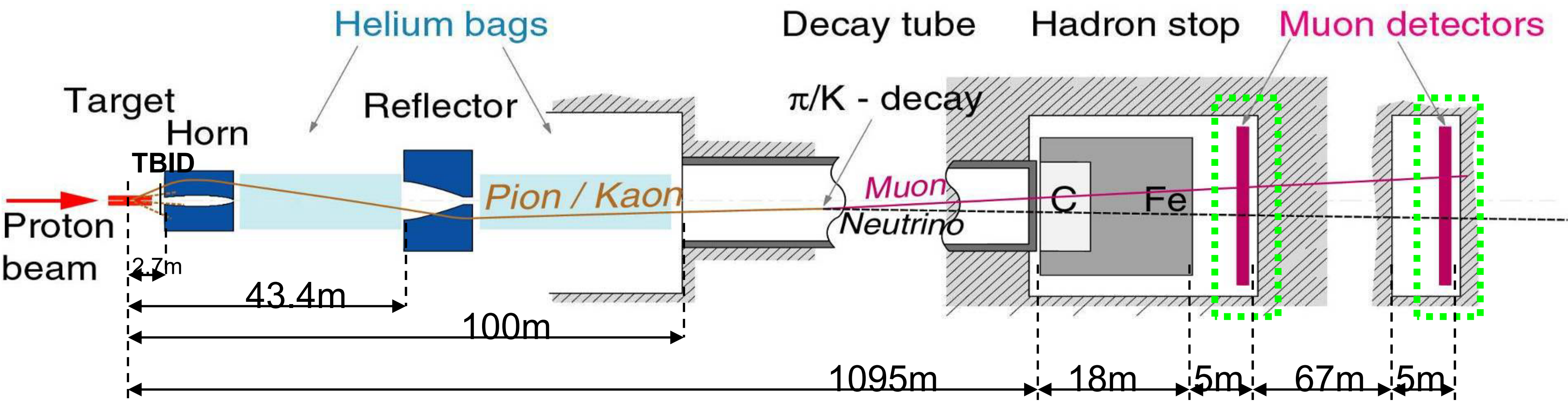
- 73 MBG Dipoles
  - 1.7 T nominal field at 400 GeV/c
- 20 Quadrupole Magnets
  - Nominal gradient 40 T/m
- 12 Corrector Magnets

Beam Instrumentation:

- 23 Beam Position Monitors (Button Electrode BPMs)
  - recuperated from LEP
  - Last one is strip-line coupler pick-up operated in air
  - mechanically coupled to target
- 8 Beam profile monitors
  - Optical transition radiation monitors: 75 μm carbon or 12 μm titanium screens
- 2 Beam current transformers
- 18 Beam Loss monitors
  - SPS type N_2 filled ionization chambers

Primary Beam Line

CNGS Secondary Beam Line



Air cooled graphite target

- Target table movable horizontally/vertically for alignment

- Multiplicity detector: TBID, ionization chambers
- 2 horns (horn and reflector)
  - Water cooled, pulsed with 10ms half-sine wave pulse of up to 150/180kA, remote polarity change possible
- Decay pipe:
  - 1000m, diameter 2.45m, 1mbar vacuum, 3mm Ti entrance window, 50mm carbon steel water cooled exit window.
- Hadron absorber:
  - Absorbs 100kW of protons and other hadrons
- 2 muon monitor stations: muon fluxes and profiles

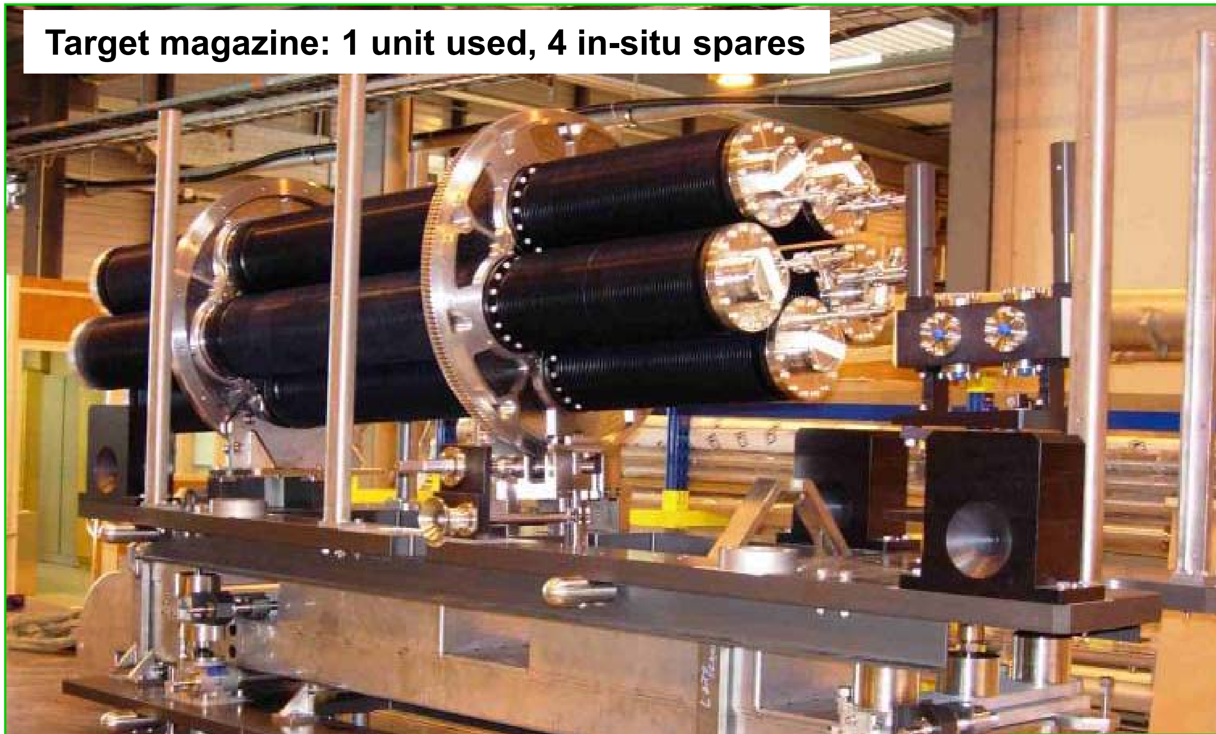
CNGS Target

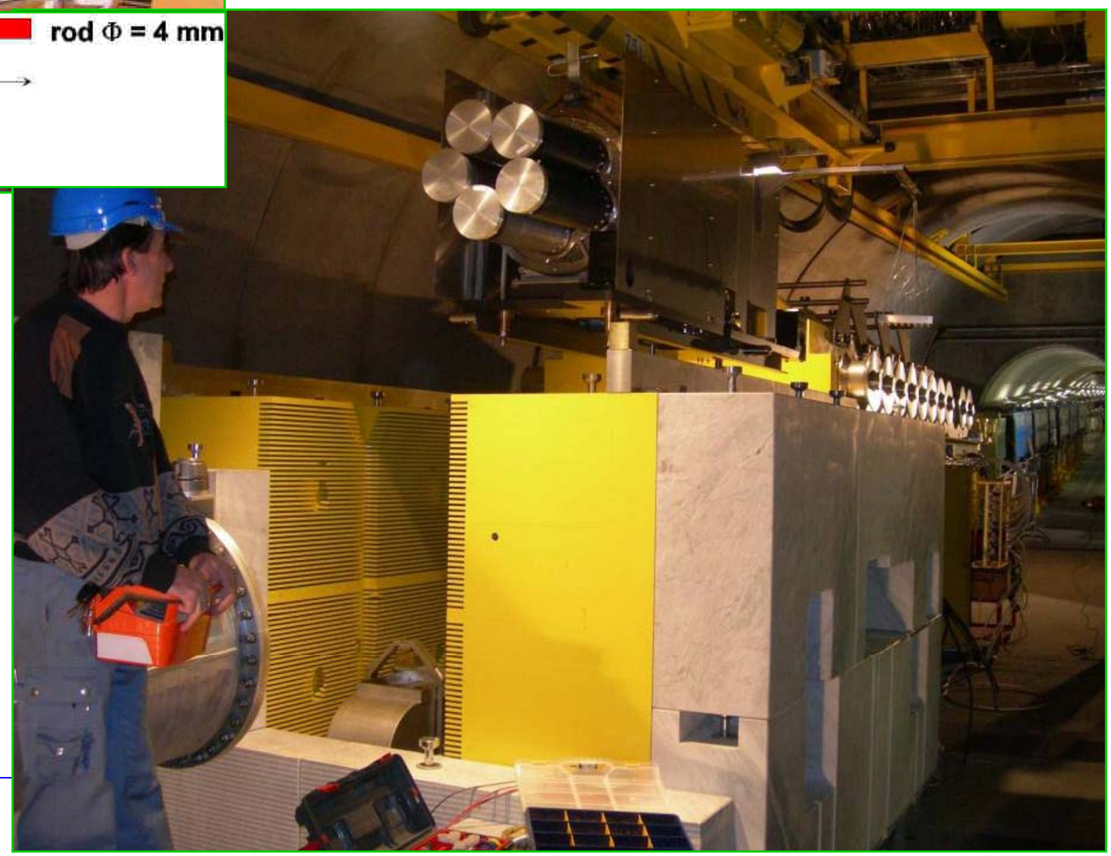
13 graphite rods, each 10cm long,

Ø = 5mm and/or 4mm

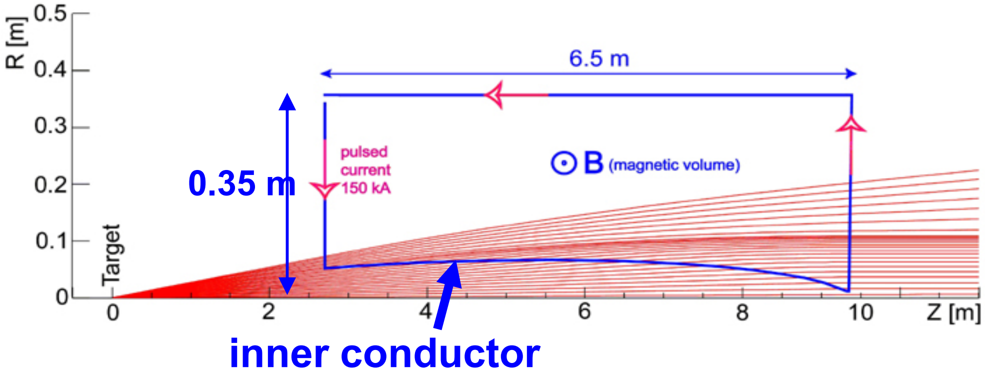
2.7mm interaction length

Ten targets (+1 prototype) have been built. → Assembled in two magazines.

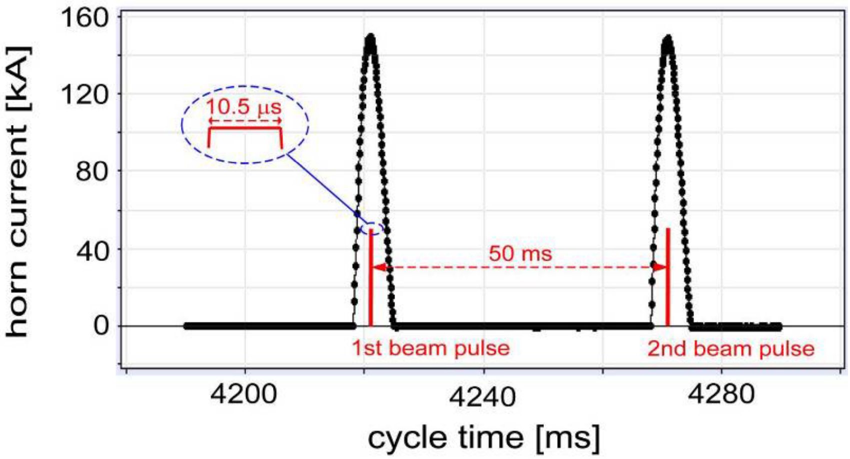




CNGS Horn and Reflector

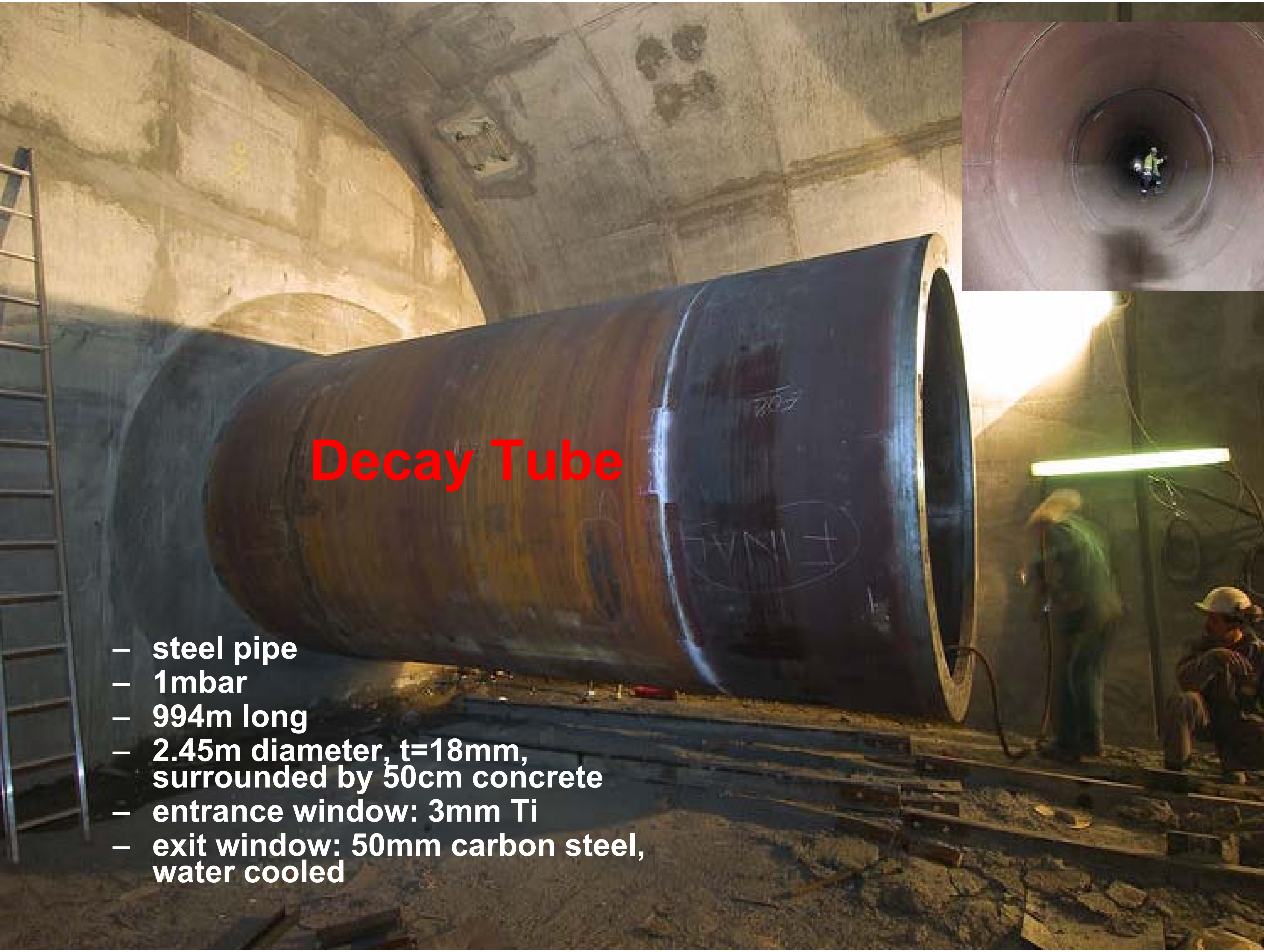


- 150kA/180kA, pulsed
- 7m long, inner conductor 1.8mm thick
- Designed for $2 \cdot 10^7$ pulses
- Water cooling to evacuate 26kW
- 1 spare horn (no reflector yet)



Design features

- Water cooling circuit
  - In situ spare, easy switch
    - <<1mSv total dose after 1y beam, 1w stop
  - Remote water connection
- Remote handling & electrical connections
  - << 1mSv total dose after 1y beam, 1m stop
- Remote and quick polarity change



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

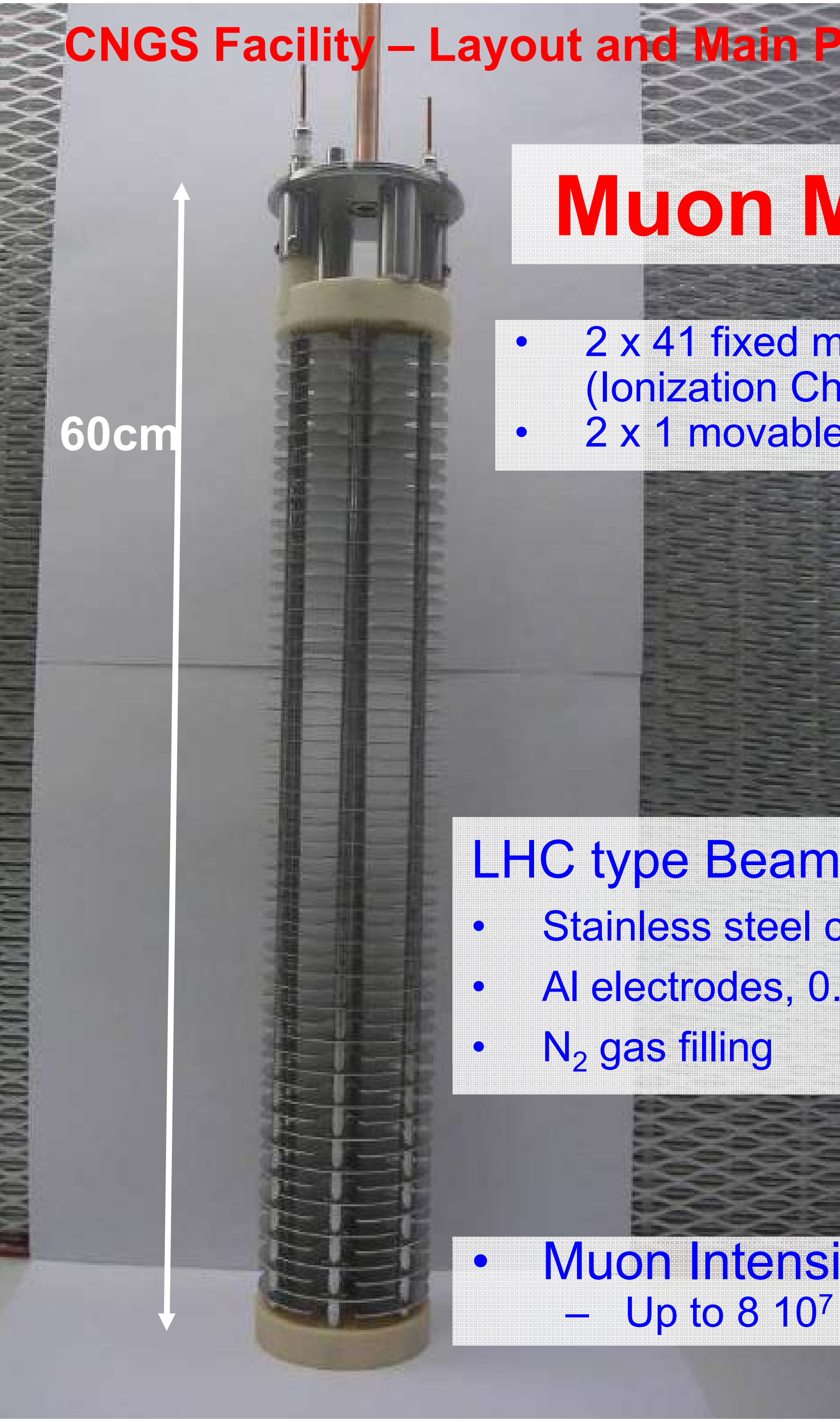
Muon Monitors

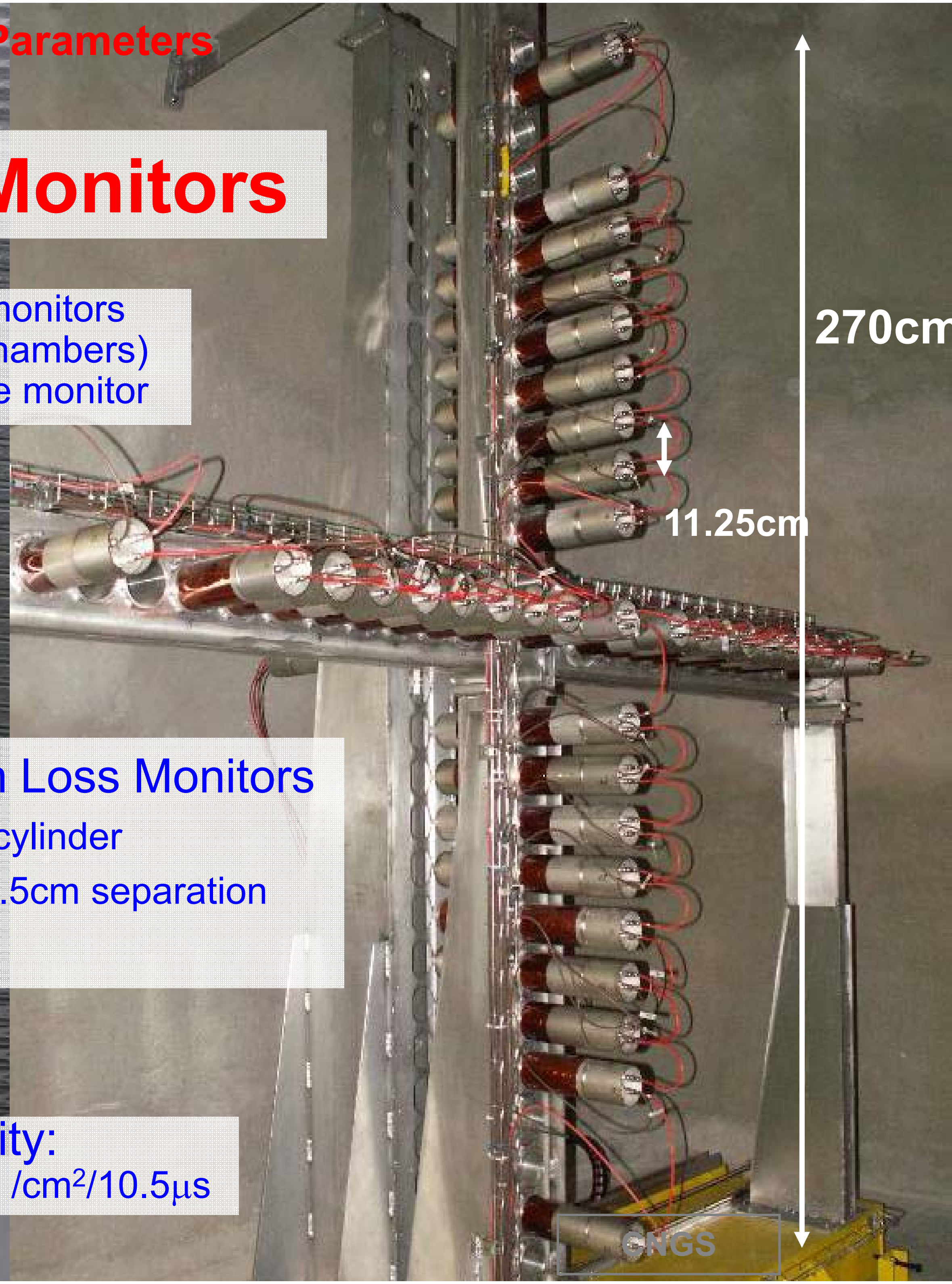
- 2 x 41 fixed monitors (Ionization Chambers)
- 2 x 1 movable monitor

LHC type Beam Loss Monitors

- Stainless steel cylinder
- Al electrodes, 0.5cm separation
- N_2 gas filling

- Muon Intensity:
  – Up to 8 10^7 $/cm^2/10.5\mu s$





Operational Experience and Performance

CNGS Timeline

2000-2005	Civil Engineering & Installation	CERN	
2006: 10 July-27 Oct	Beam Commissioning Detector electronics commissioning	CERN Gran Sasso	$0.08 \cdot 10^{19}$ pot
2006-2007: Shutdown	Reflector Water Leak Repair/Improvement	CERN	
2007: 17 Sept-20 Oct	Beam Commissioning at high intensity Detector commissioning with 60000 bricks	CERN Gran Sasso	$0.08 \cdot 10^{19}$pot
2007-2008: Shutdown	Additional shielding and electronics re-arrangement Finishing OPERA bricks	CERN Gran Sasso	
2008: 18 June- 3 Nov	CNGS Physics Run		$1.78 \cdot 10^{19}$pot
2009: 1 June-today	CNGS Physics Run		$2.4 \cdot 10^{19}$pot

CNGS Performance

2008: 18 June – 3 November 2008

- Excellent performance of the CNGS Facility
- CNGS modifications finished successfully
- Beam line equipment working well and stable

→ $1.78 \cdot 10^{19}$ protons on target

→ OPERA experiment:

- 10100 on-time events
- 1700 candidate interaction in bricks

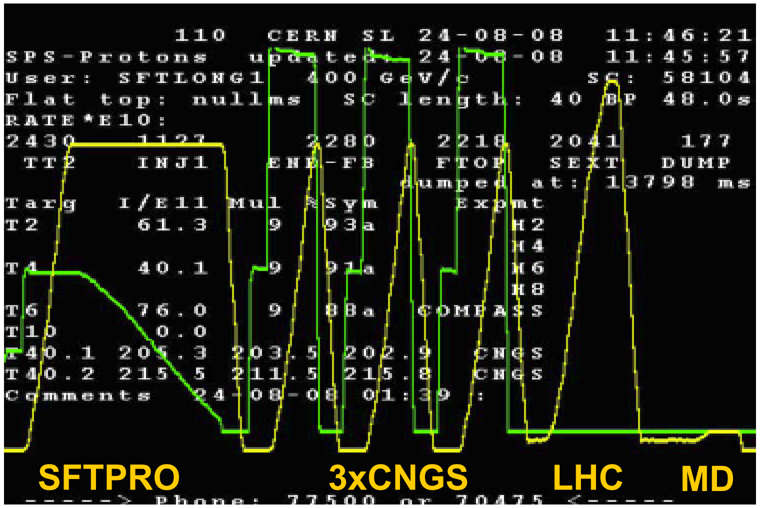
2009: 28 May – 23 November 2009

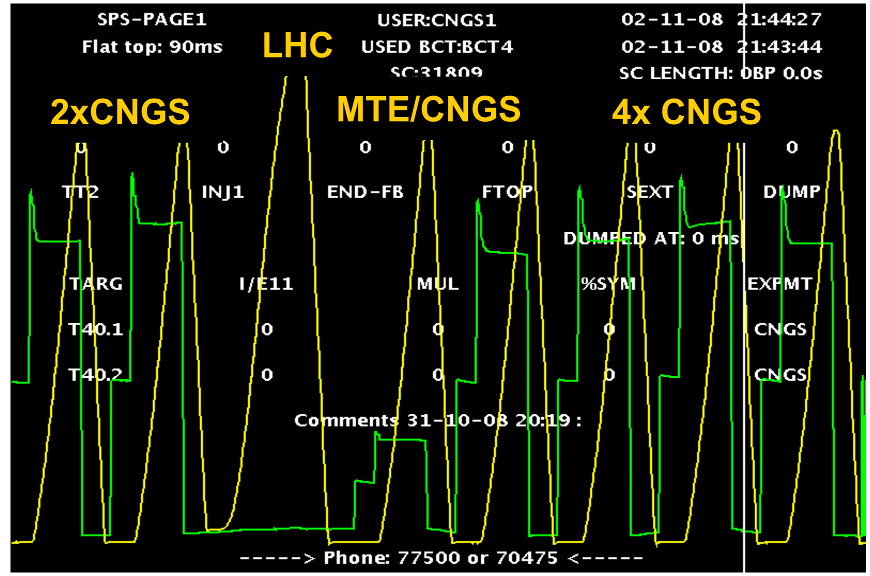
→ 16nd October 2009: $2.53 \cdot 10^{19}$ protons on target

→ OPERA experiment:

- >15500 on-time events
- >2500 candidate interaction in bricks

Supercycle 2008



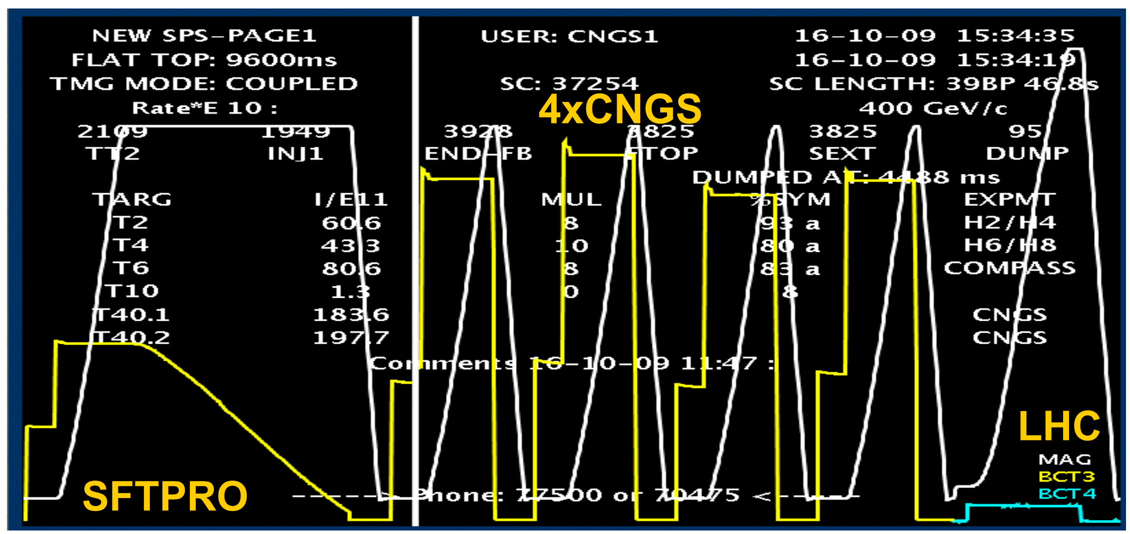


48s supercycle:
North Area, 3 CNGS, 1LHC,1MD
→ 37.5% CNGS duty cycle

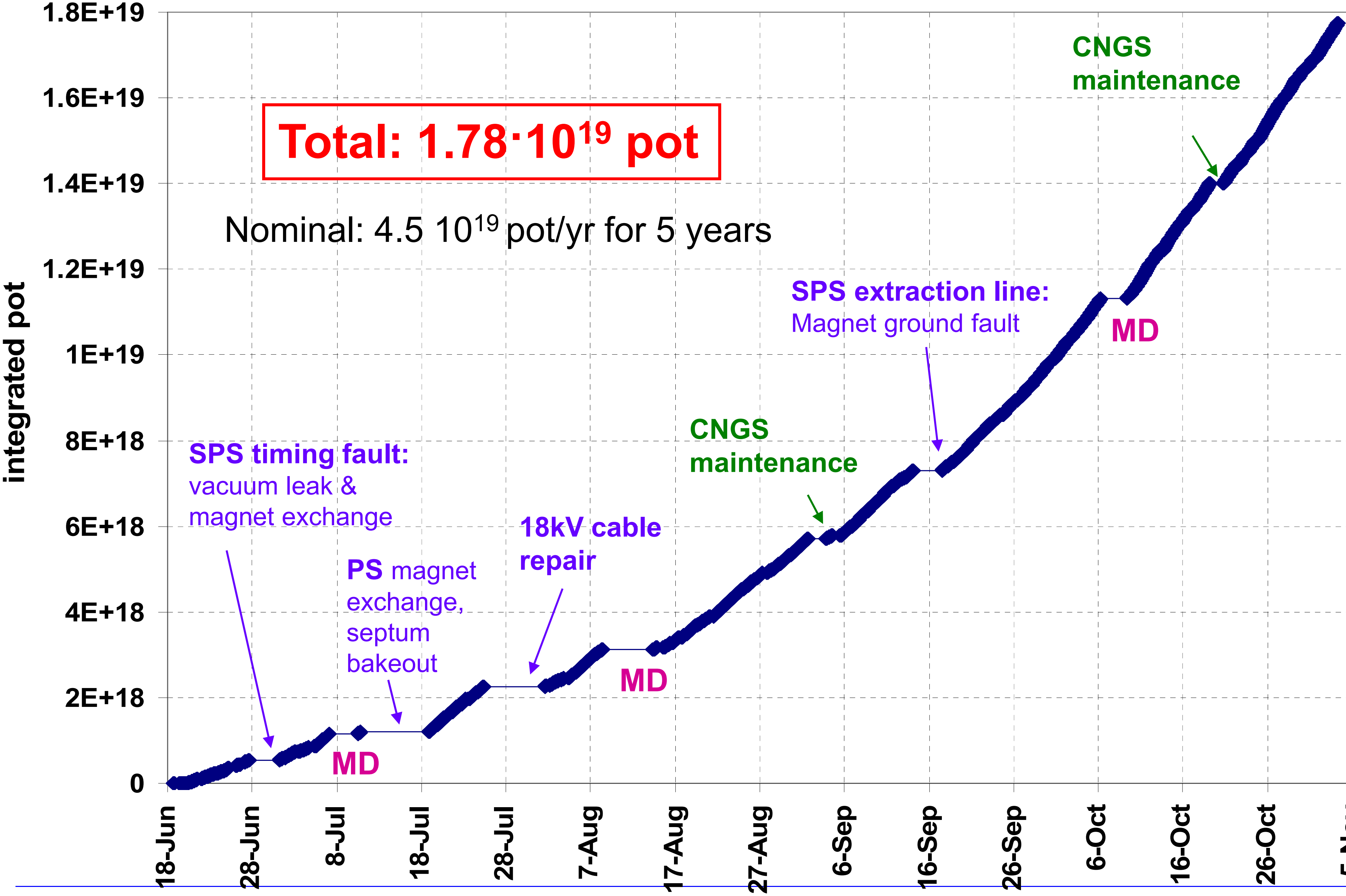
50.4s supercycle: 7 CNGS, 1 LHC
→ 83% CNGS duty cycle

Supercycle 2009

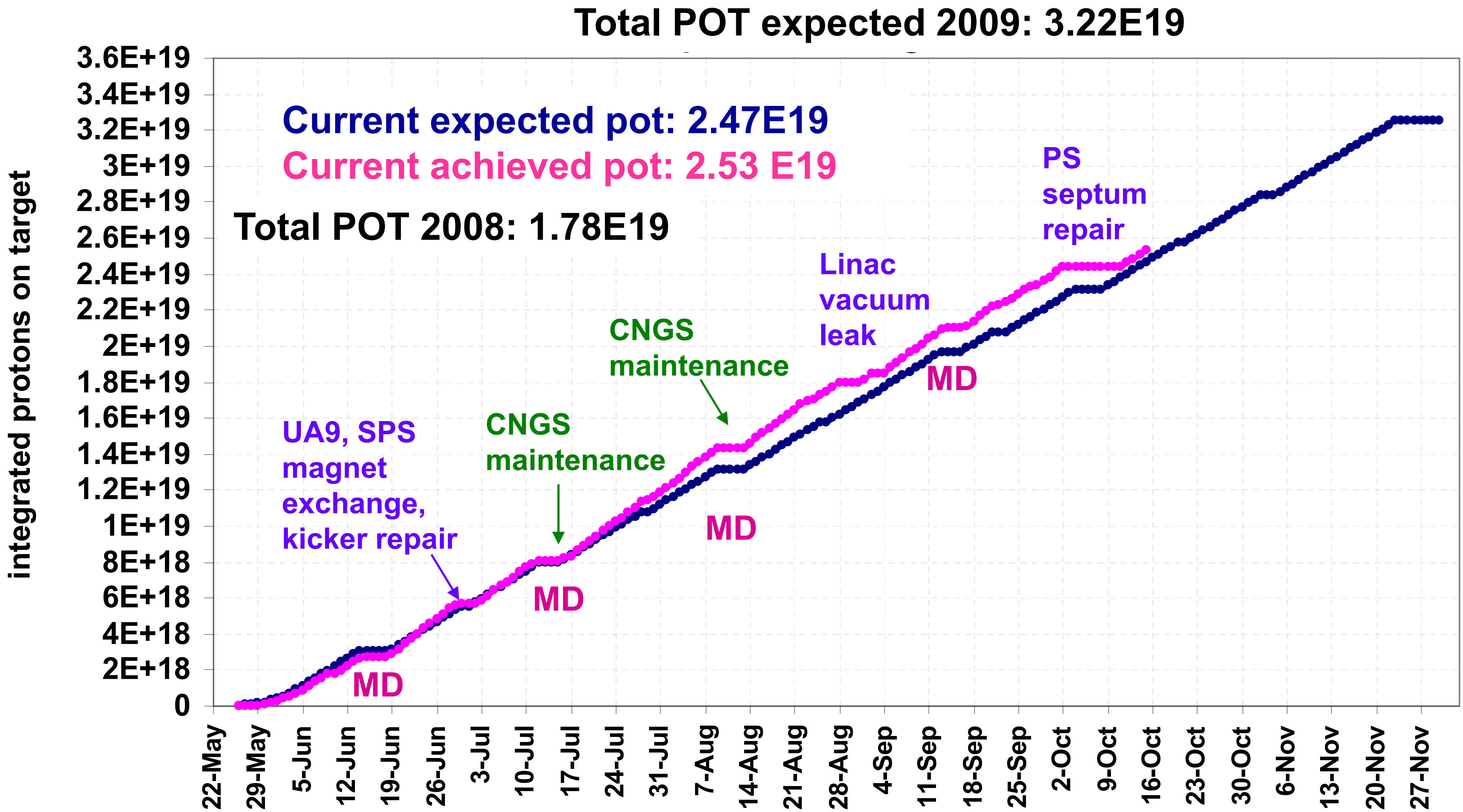
46.8s supercycle:
North Area, 4 CNGS, 1LHC
→ 51.3% CNGS duty cycle



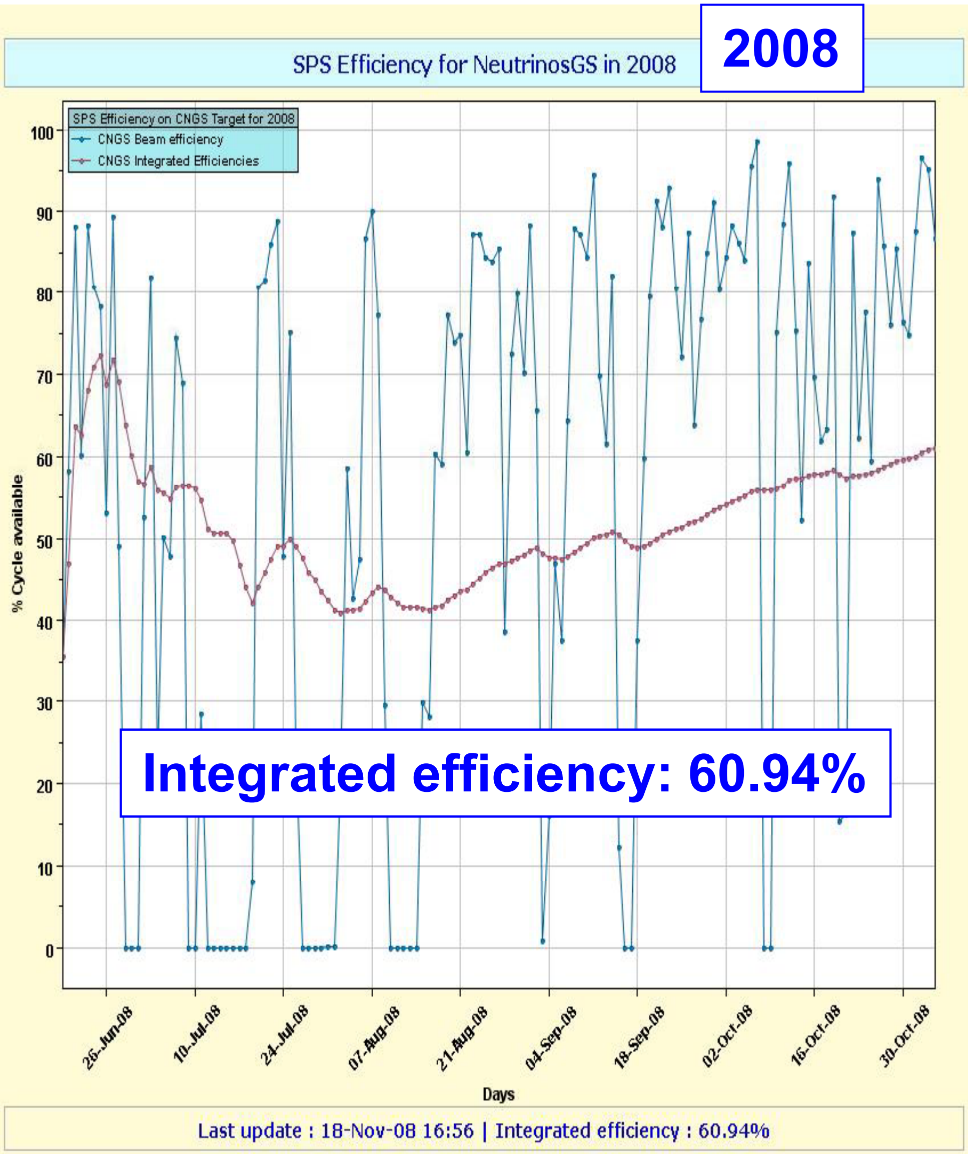
CNGS Run 2008: 18 June- 03 Nov 2008

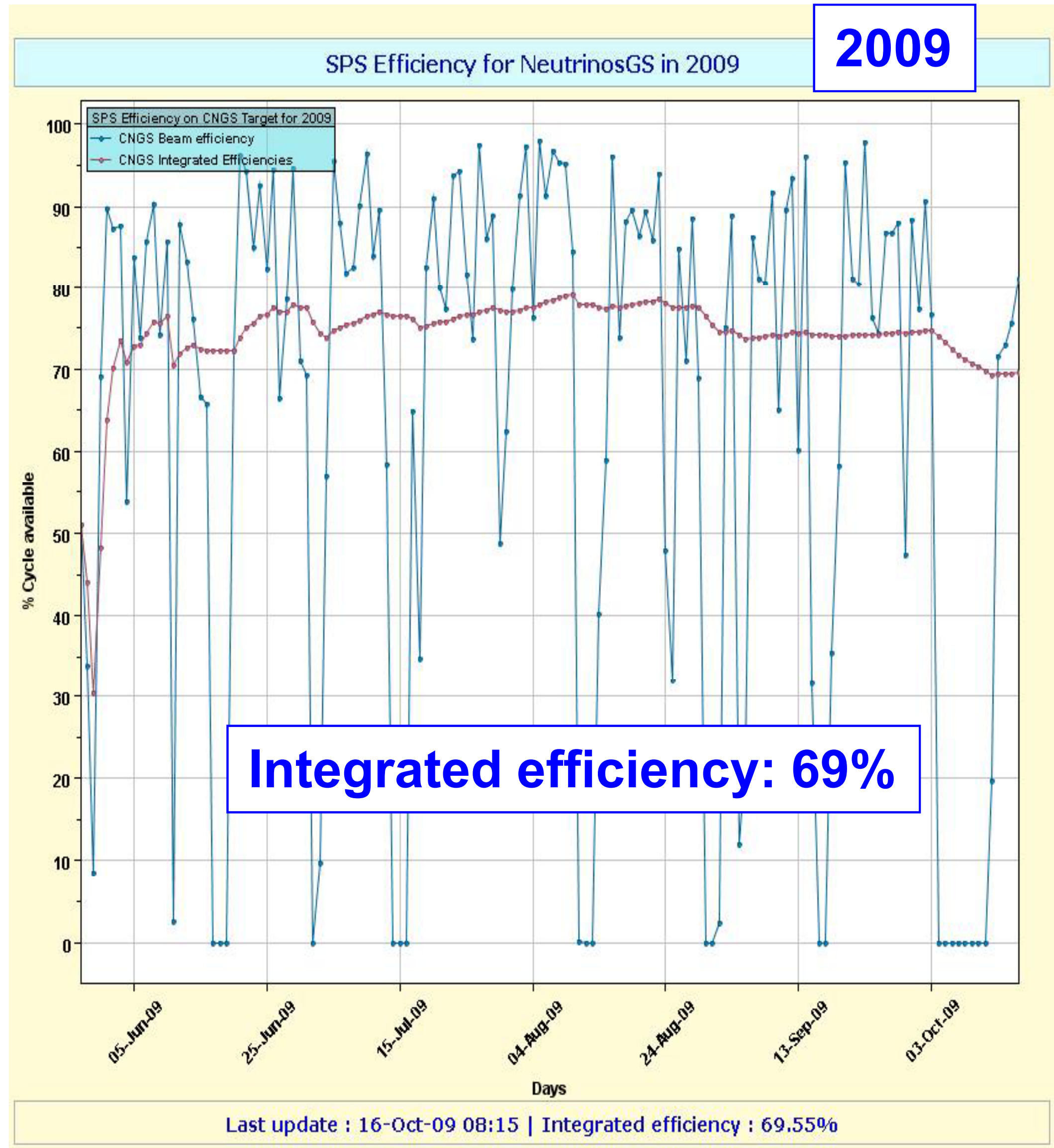


2009 Protons on Target

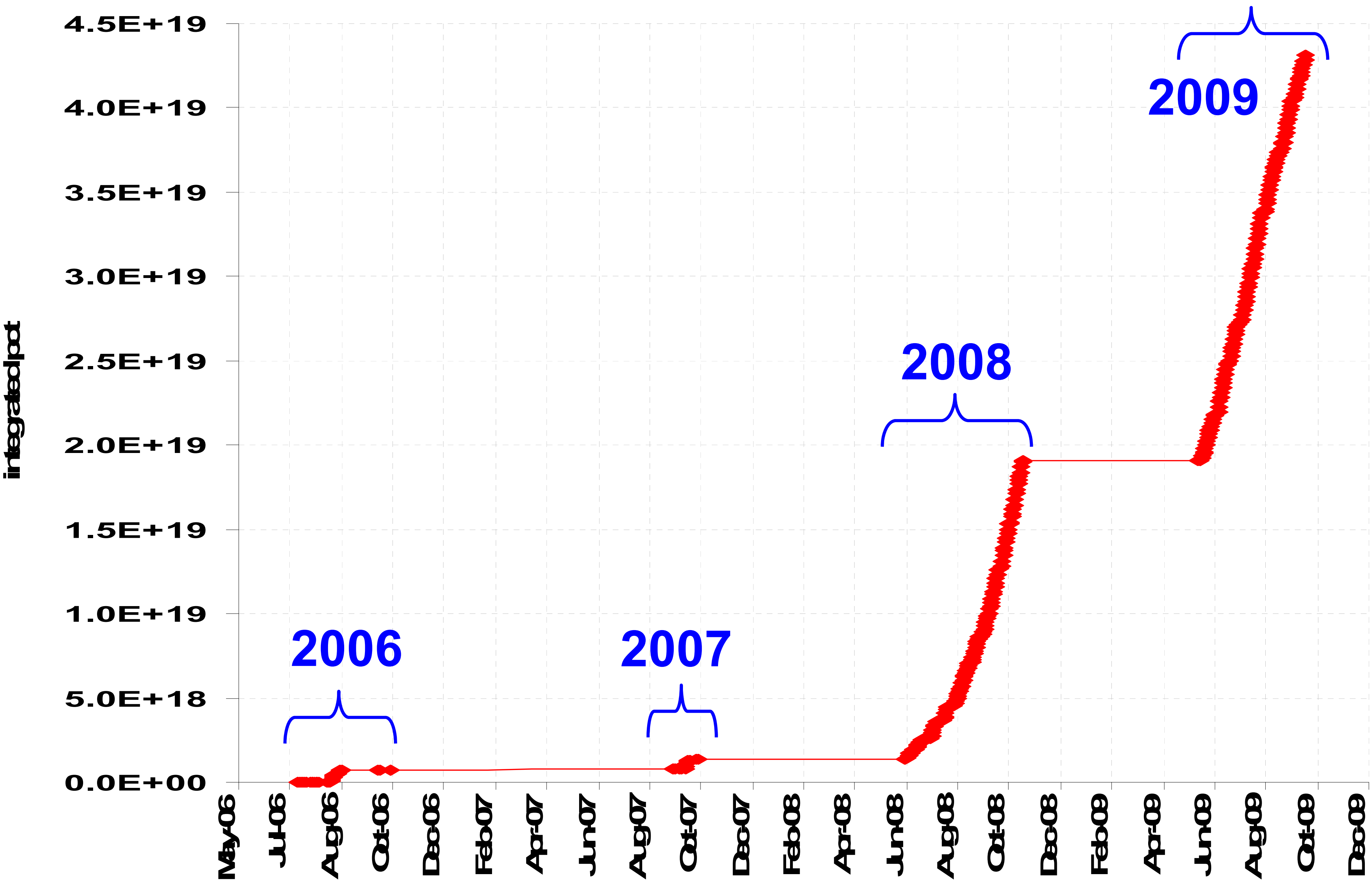


SPS Efficiencies for CNGS



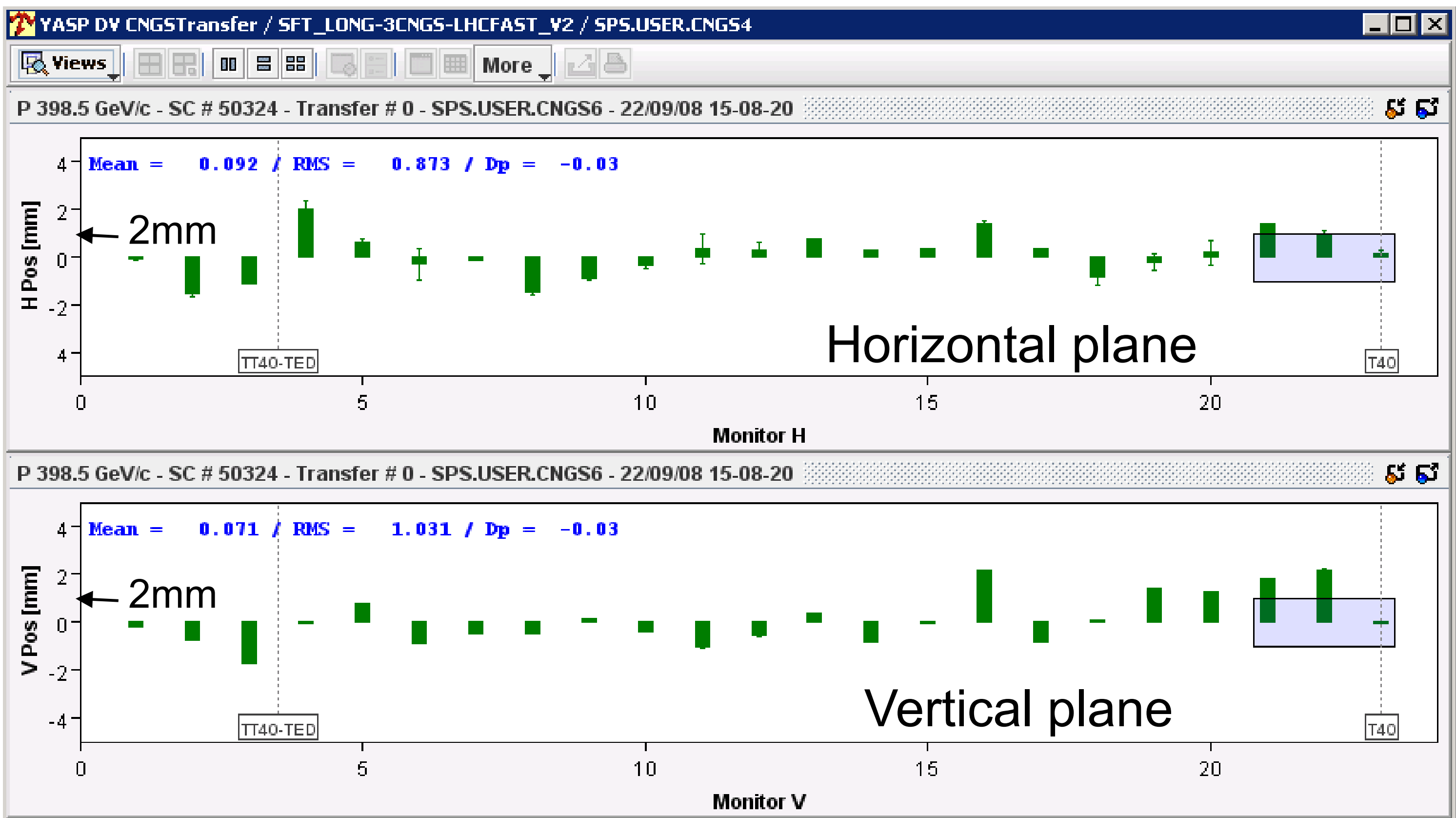


Total Protons on Target



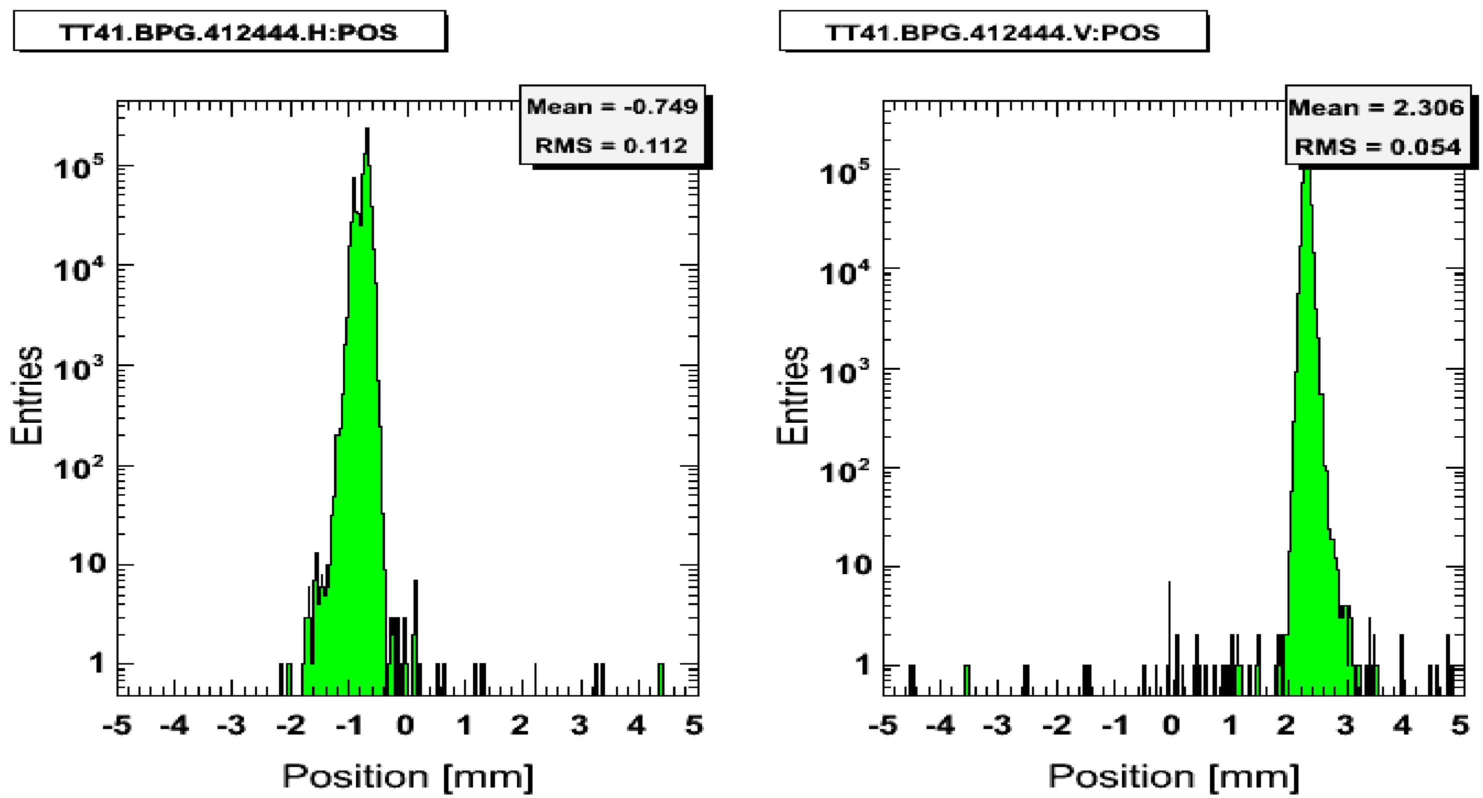
Primary Beam

- Extraction interlock in LSS4 modified to accommodate the simultaneous operation of LHC and CNGS
  - Good performance, no incidents
- No extraction and transfer line losses
- Trajectory tolerance: 4mm, last monitors to +/-2mm and +/- 0.5mm (last 2 monitors)
  - Largest excursion just exceed 2mm
- Total trajectory drift over 2008 is ~1mm rms in each plane

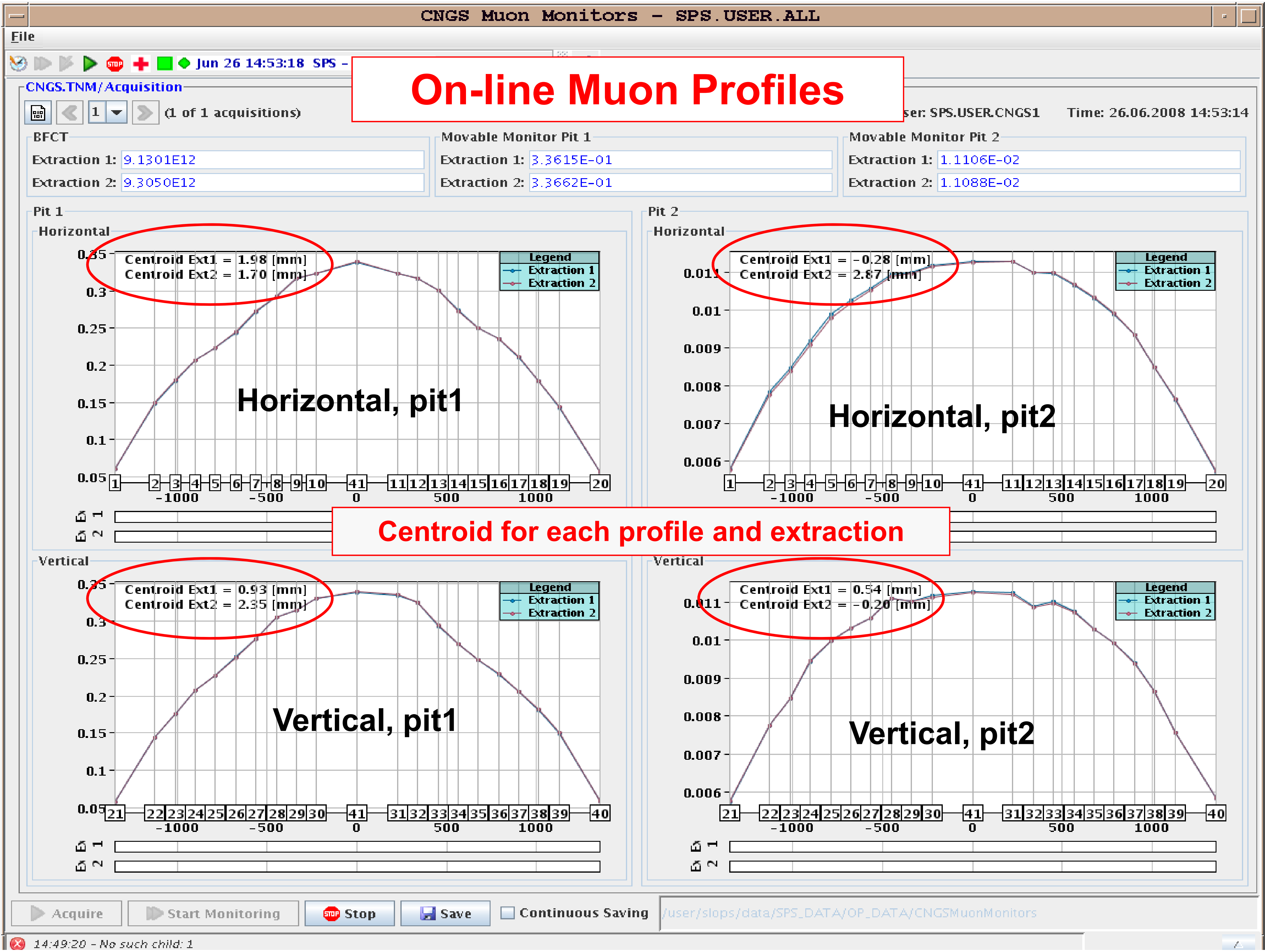


Target Beam Position

- Excellent position stability; ~50 (100) μm horiz(vert) over entire run.
- No active position feedback is necessary
  - 1-2 small steerings/week only



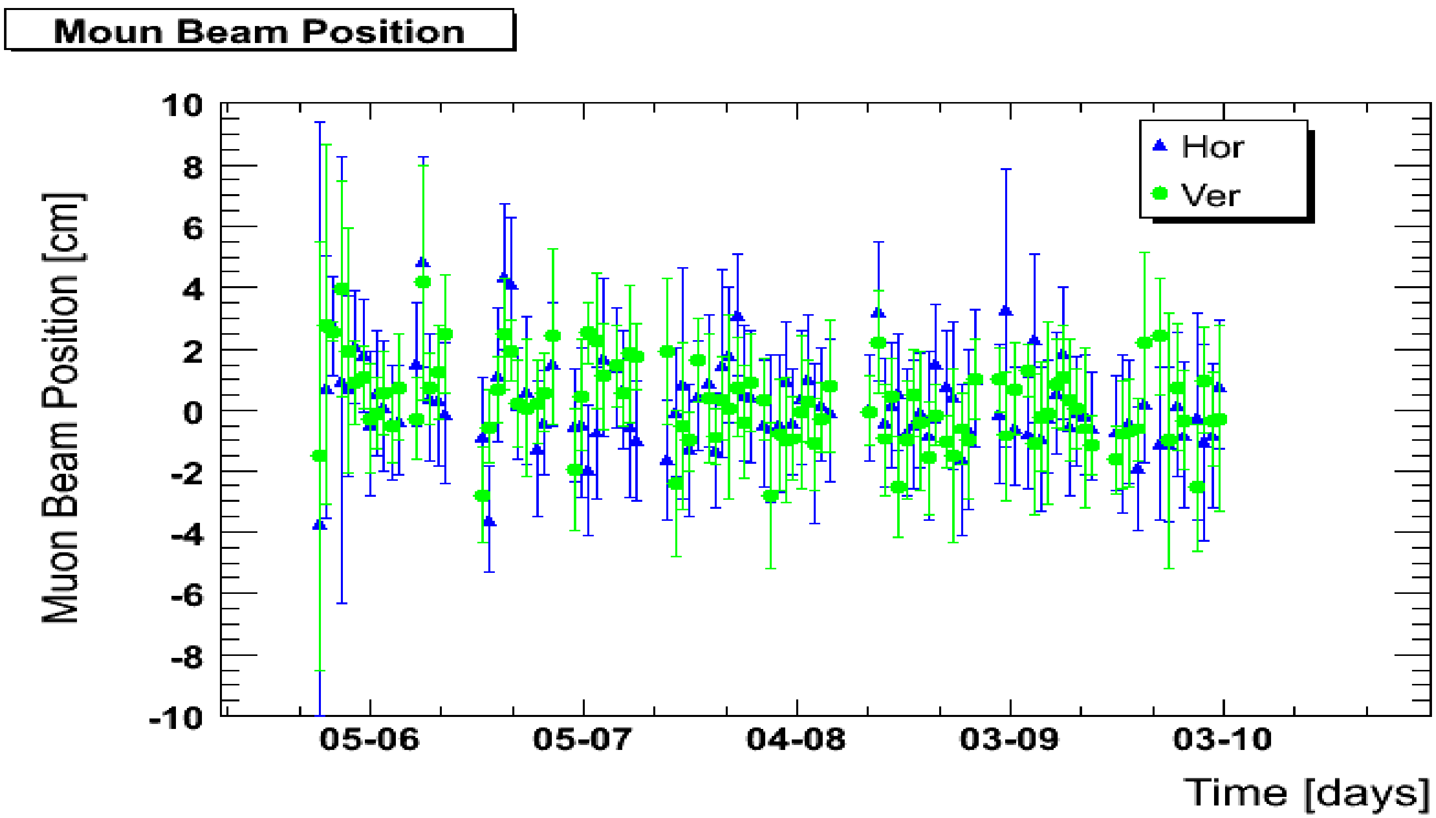
Horizontal and vertical beam position on the last BPM in front of the target



CNGS Muon Monitors - SPS.USER.ALL
On-line Muon Profiles
Jun 26 14:53:18 SPS -
CNGS.TNM/Acquisition
(1 of 1 acquisitions)
ser: SPS.USER.CNGS1
Time: 26.06.2008 14:53:14
BFCT
Extraction 1: 9.1301E12
Extraction 2: 9.3050E12
Movable Monitor Pit 1
Extraction 1: 3.3615E-01
Extraction 2: 3.3662E-01
Movable Monitor Pit 2
Extraction 1: 1.1106E-02
Extraction 2: 1.1088E-02
Pit 1
Horizontal
Centroid Ext1 = 1.98 [mm]
Centroid Ext2 = 1.70 [mm]
Horizontal, pit1
Pit 2
Horizontal
Centroid Ext1 = -0.28 [mm]
Centroid Ext2 = 2.87 [mm]
Horizontal, pit2
Centroid for each profile and extraction
Vertical
Centroid Ext1 = 0.93 [mm]
Centroid Ext2 = 2.35 [mm]
Vertical, pit1
Vertical
Centroid Ext1 = 0.54 [mm]
Centroid Ext2 = -0.20 [mm]
Vertical, pit2
Legend
Extraction 1
Extraction 2
Acquire
Start Monitoring
Stop
Save
Continuous Saving
/user/slops/data/SPS_DATA/OP_DATA/CNGSMuonMonitors
14:49:20 - No such child: 1

Beam Stability seen on Muon Monitors

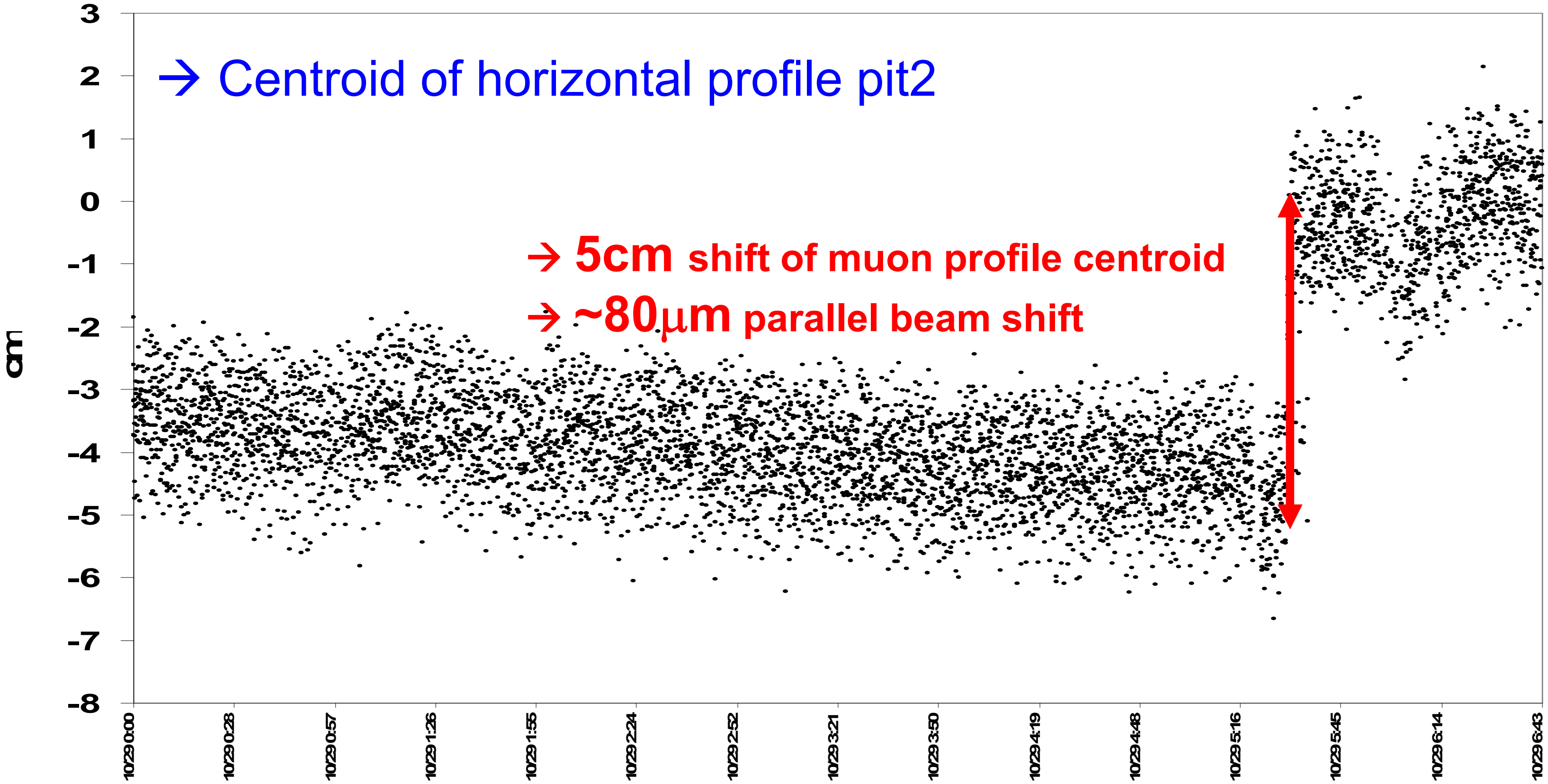
- Position stability of muon beam in pit 2 is ~2cm rms
- Beam position correlated to beam position on target.
  - Parallel displacement of primary beam on T40



Muon Monitors

Very sensitive to any beam changes !

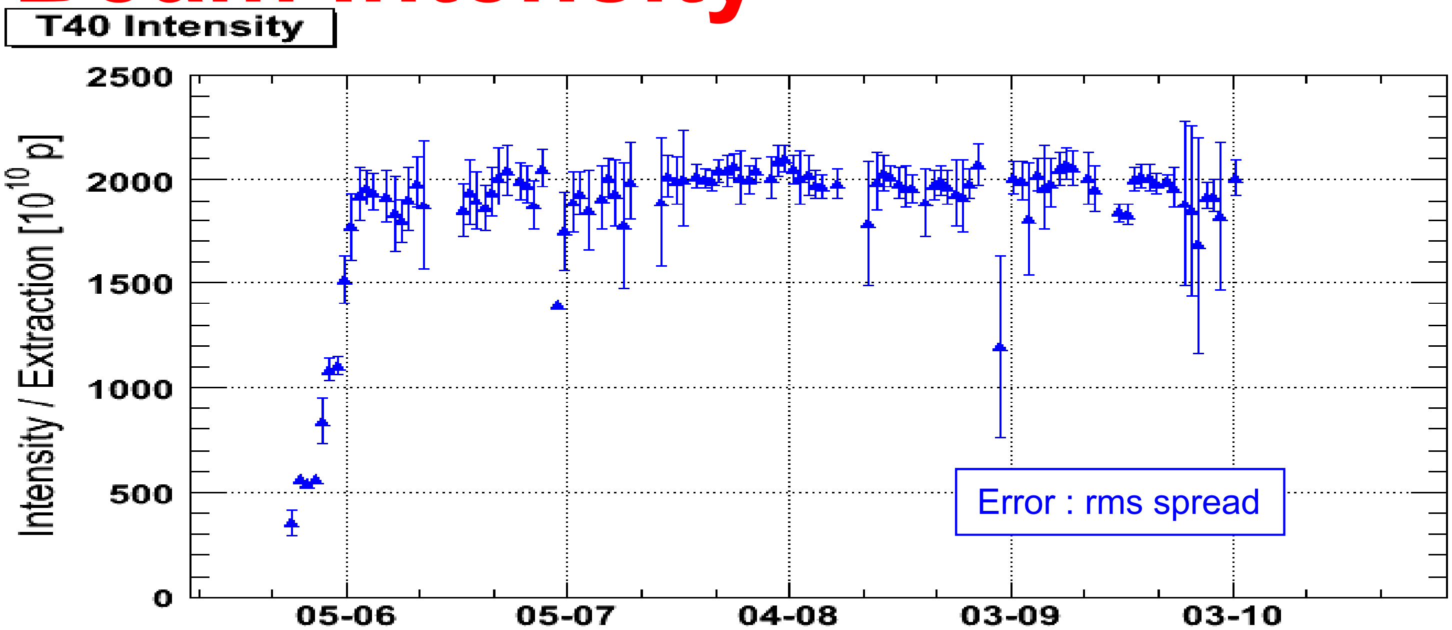
– Offset of beam vs target at 0.05mm level → Muon Profiles Pit 2



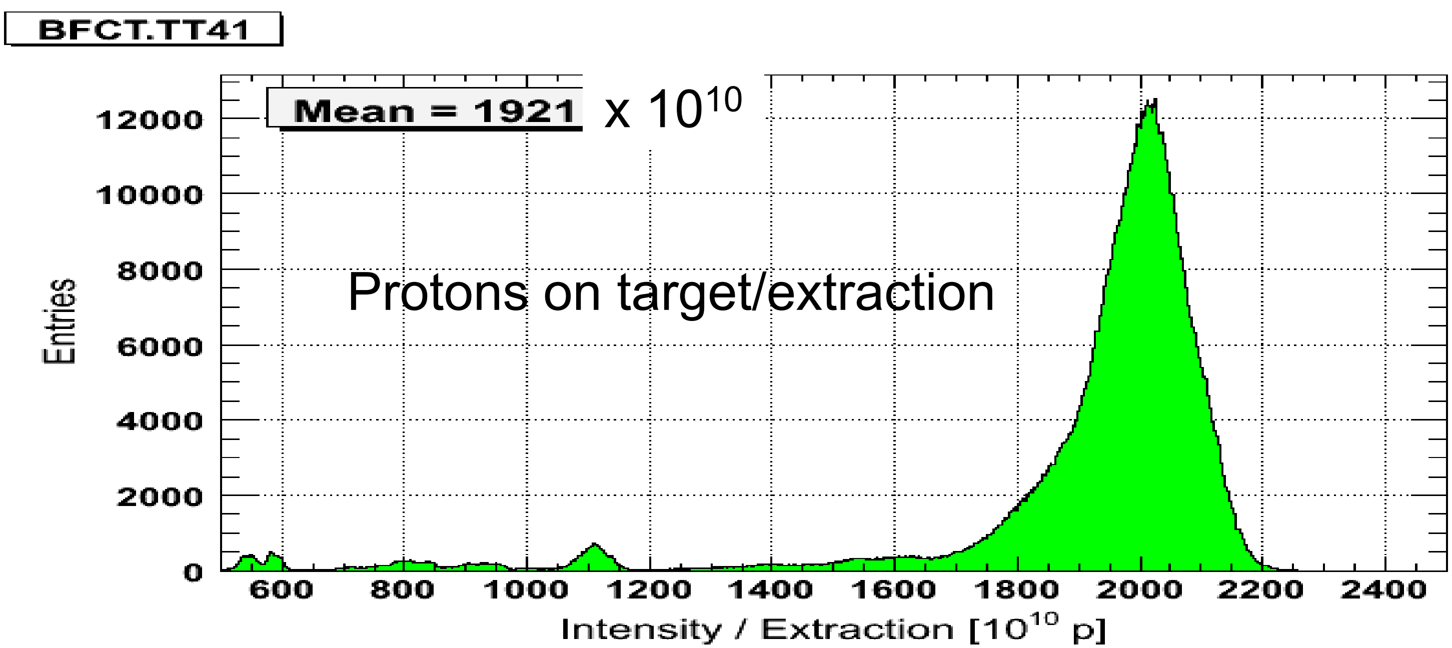
– Offset of target vs horn at 0.1mm level
  - Target table motorized
  - Horn and reflector tables not

→ Muon Profiles Pit 1

Beam Intensity

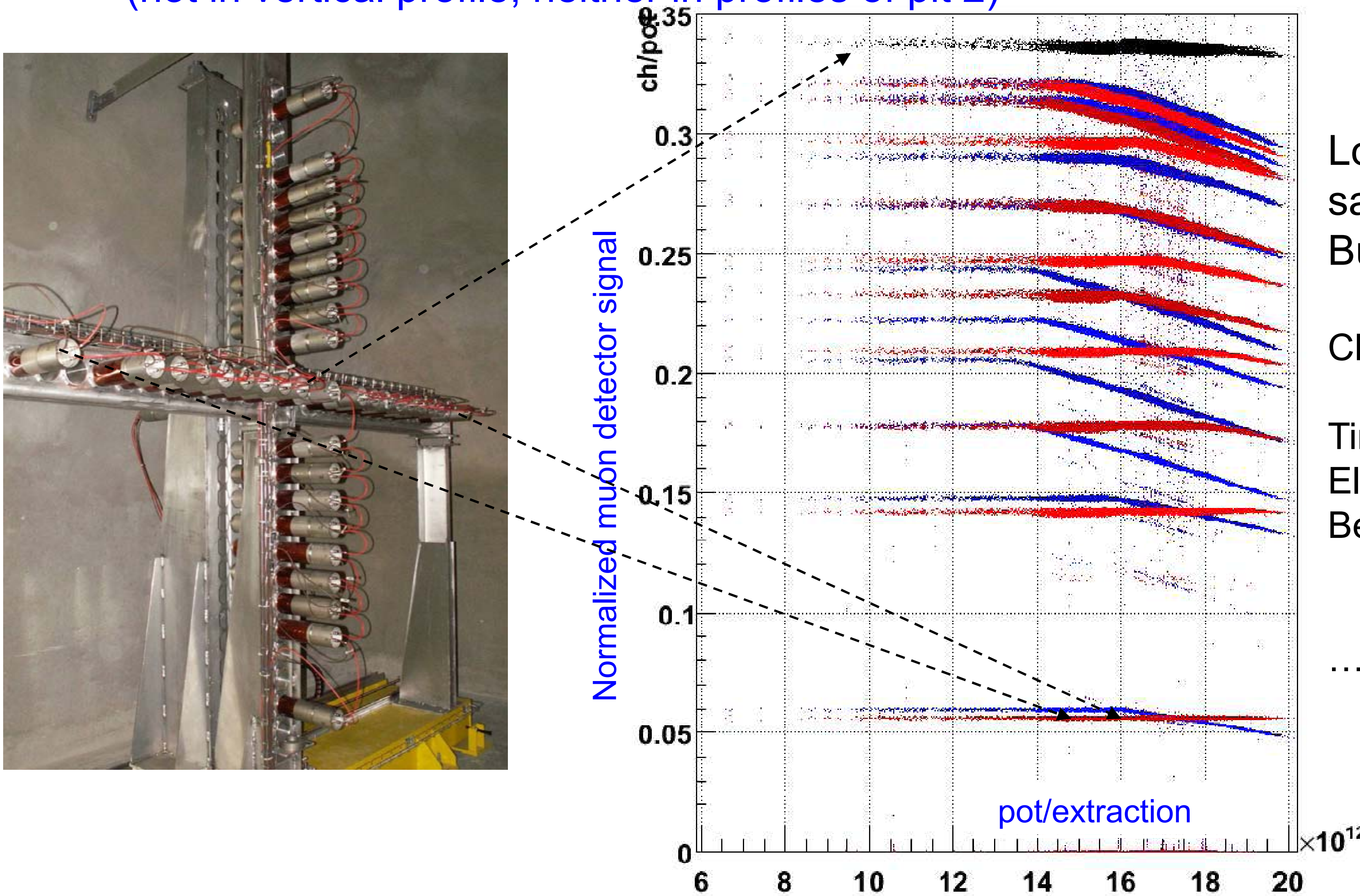


Typical transmission of the CNGS beam through the SPS cycle ~ 92%. Injection losses ~ 6%.



Muon Detector Non-Linearity Puzzle

2007: observation: non-linear muon detector signal in horizontal profile of pit 1
(not in vertical profile, neither in profiles of pit 2)



A. Marsili et al, AB-2008-044-BI

Looks like saturation effect
But:

Check:

Timing?
Electronics cards?
Beam intensity?

…

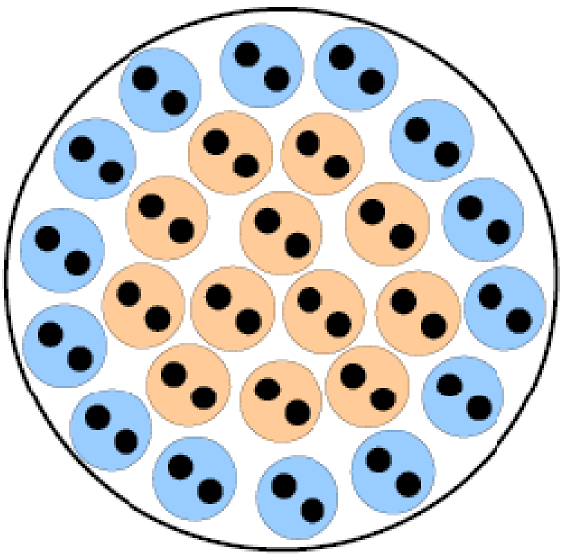
Muon Detector Non-Linearity Puzzle

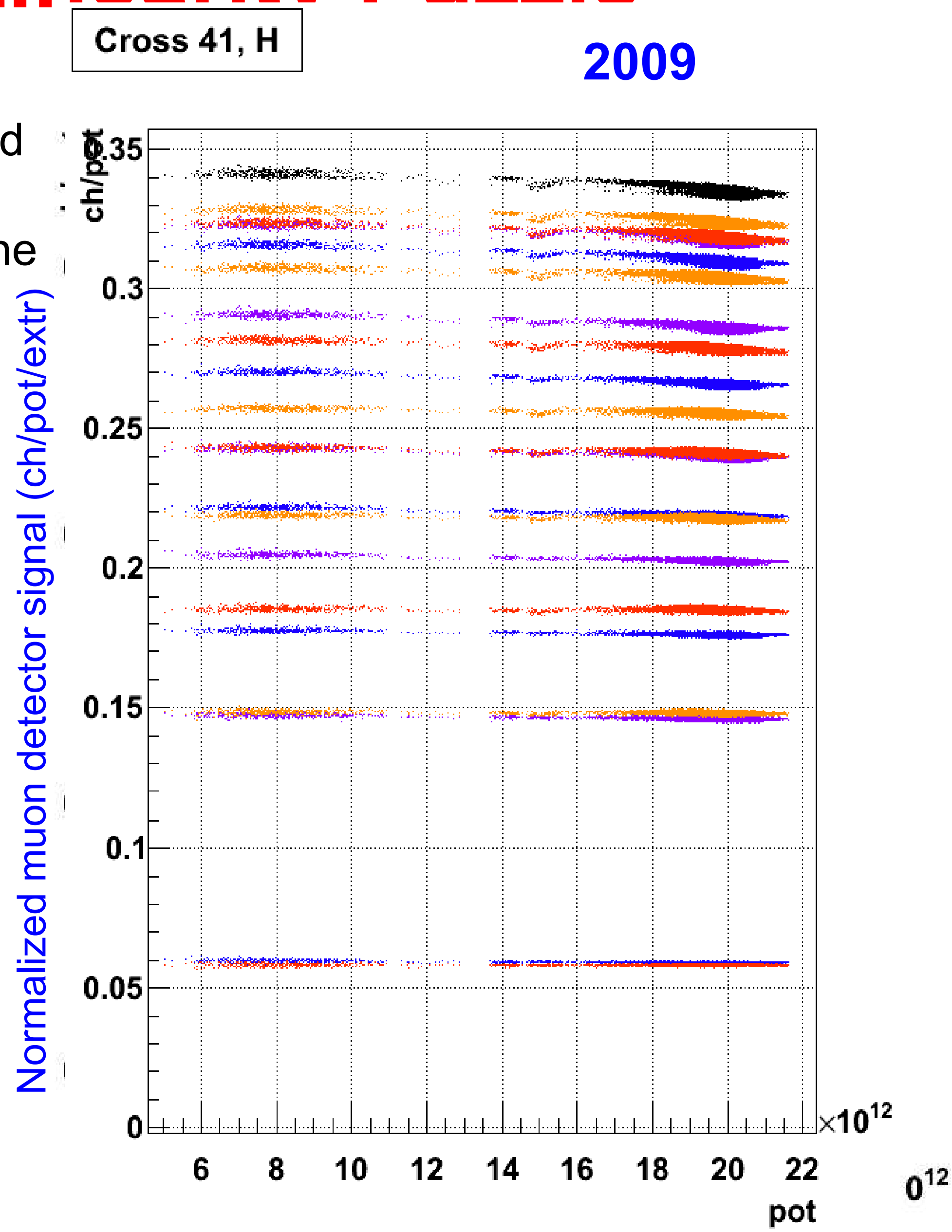
Wire topology:

All detectors are connected to readout card via a 750m long twisted multi-wire cable.

→ Horizontal profile detectors are inside the multi-wire cable

→ See different capacitances!



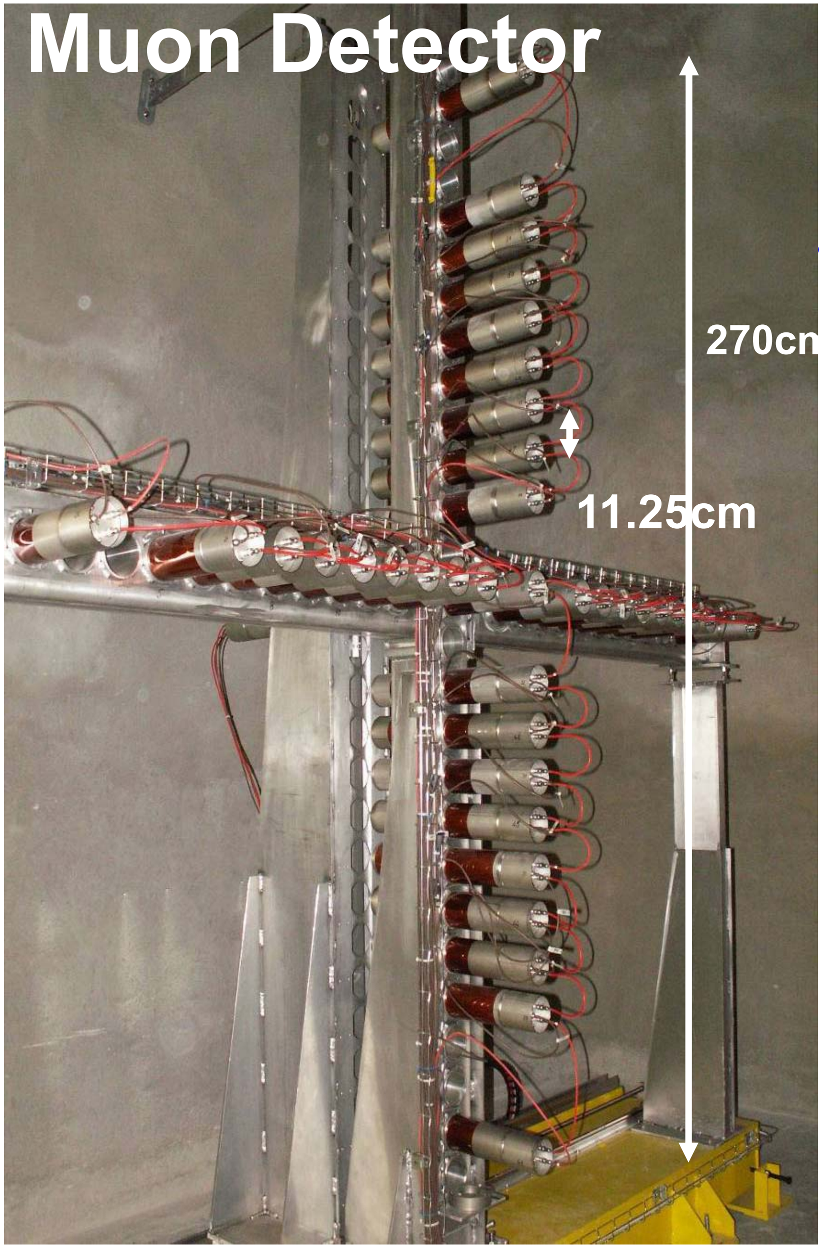


Remedy:

Increase capacitance of all wires to a fixed value:

→ adding 220nF capacitor between each wire and shielding.

CNGS Polarity Puzzle

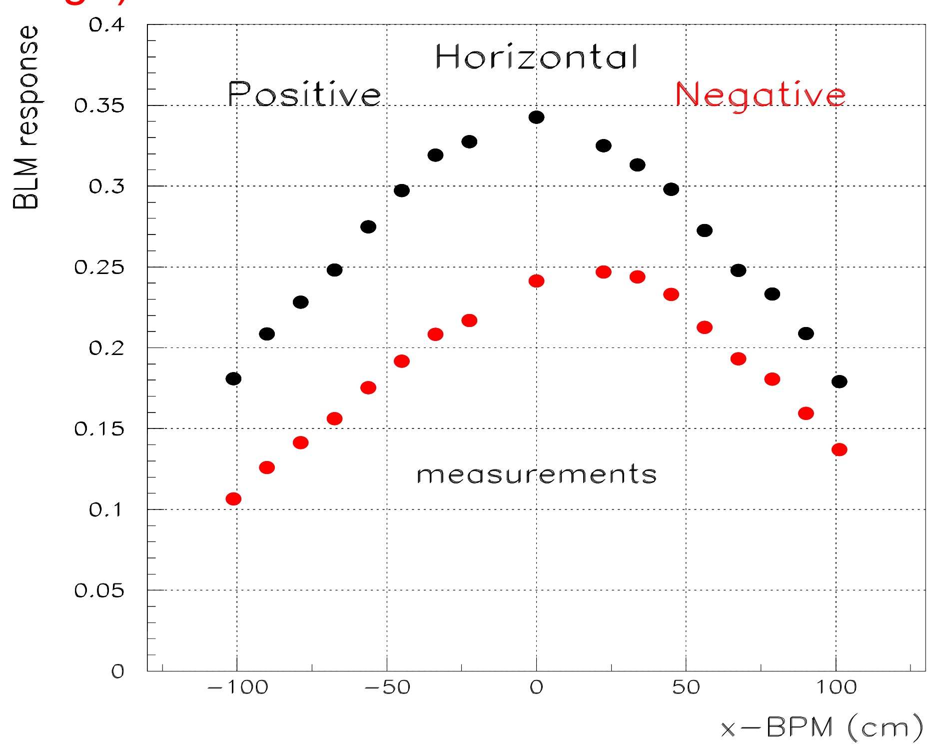


Sensitive to any beam change (e.g. offset of beam vs target at 50μm level)

→ Online feedback on quality of neutrino beam

Observation of asymmetry in horizontal direction between

- Neutrino (focusing of mesons with positive charge)
- Anti-neutrino (focusing of mesons with negative charge)



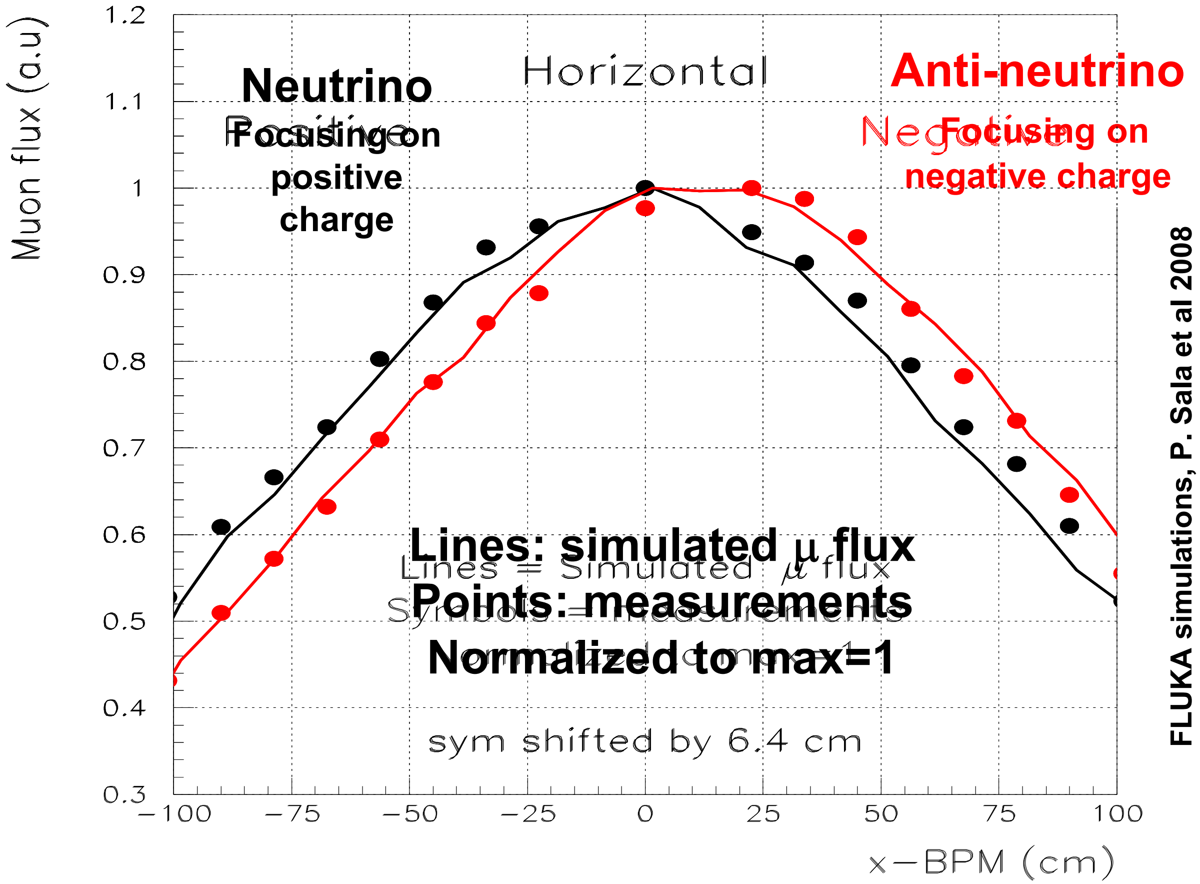
CNGS Polarity Puzzle

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

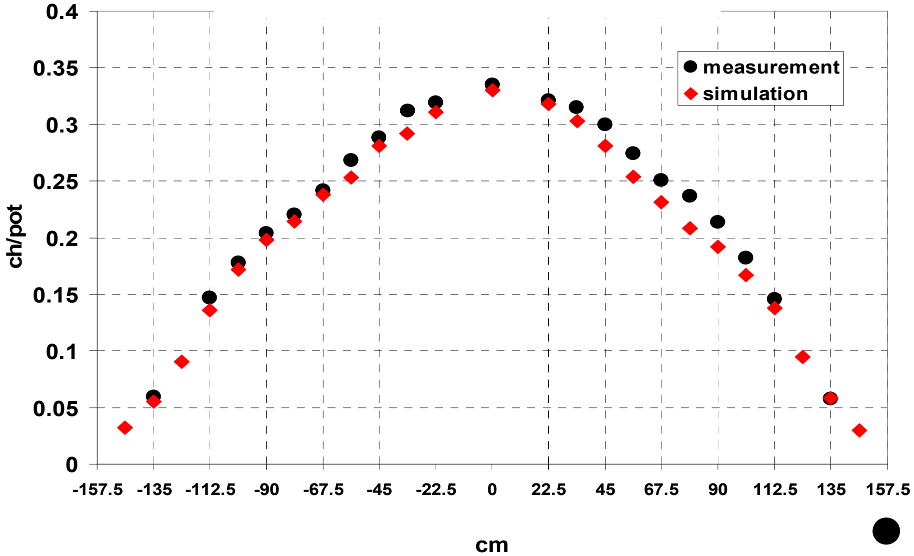
→ Results in shifts of the observed magnitude

→ Measurements and simulations agree very well (absolute comparison within 5% in first muon pit)

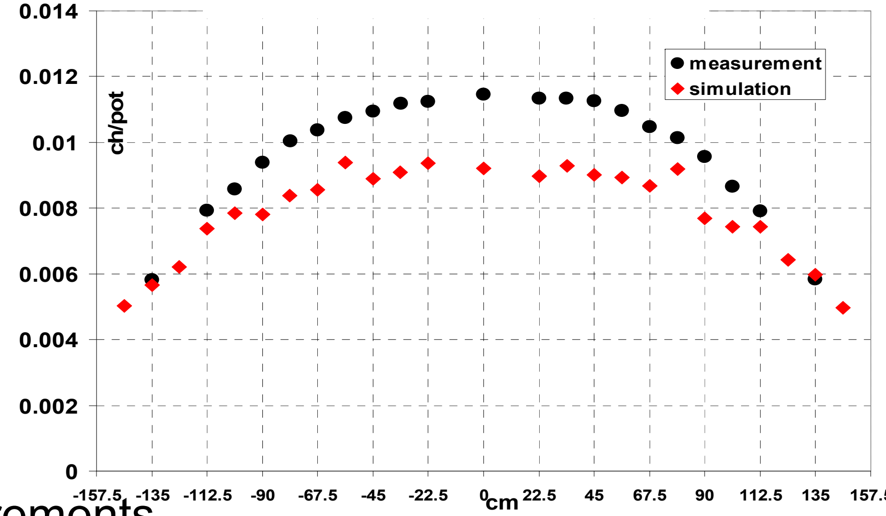


Muon Monitors: Measurements vs. Simulations

Horizontal Profile Pit 1



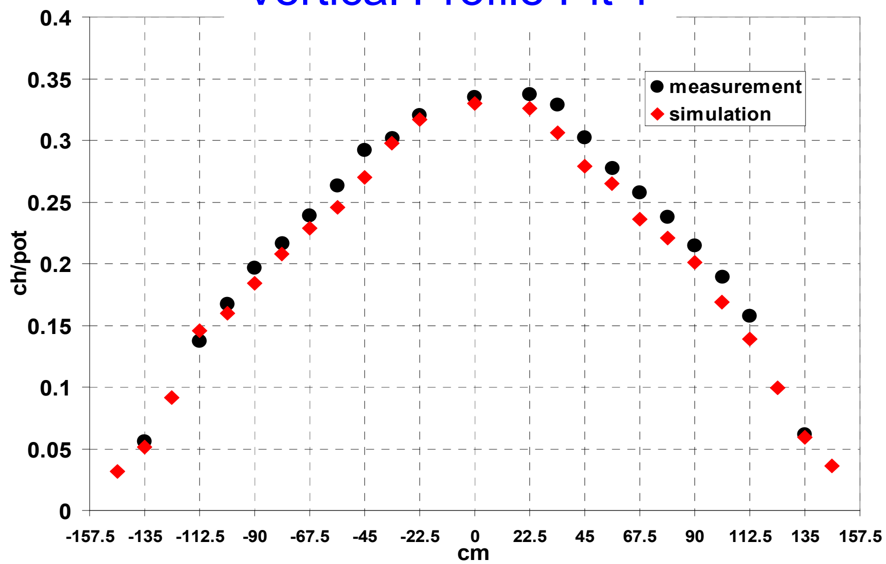
Horizontal Profile Pit 2



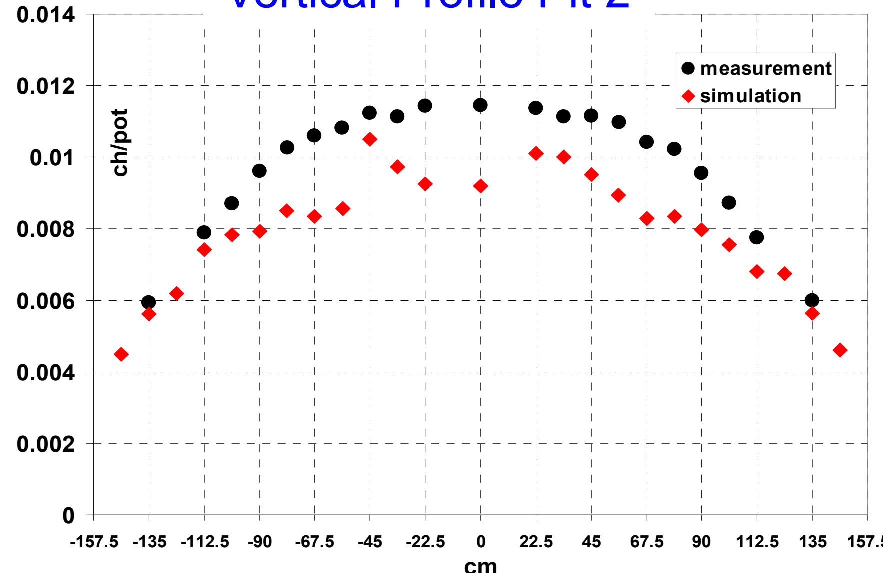
● Measurements

♦ Simulations

Vertical Profile Pit 1



Vertical Profile Pit 2



P. Sala et al, FLUKA simulations 2008

→ Excellent agreement!

Summary

- CNGS commissioned in 2006
- Successful modifications in the CNGS facility and completion of the OPERA Detector
- Physics run since 2008
  - 2008:
    - 1.78 10^{19} protons on target total
  - 2009:
    - Expect 3.2 10^{19} protons on target total
    - Today (16 October 2009): 2.53 10^{19} protons on target

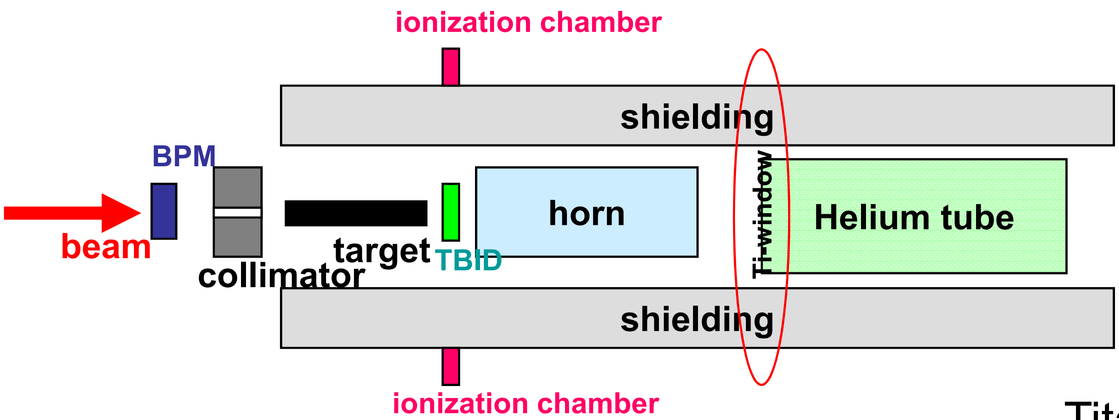
→ Waiting for tau neutrino results!!

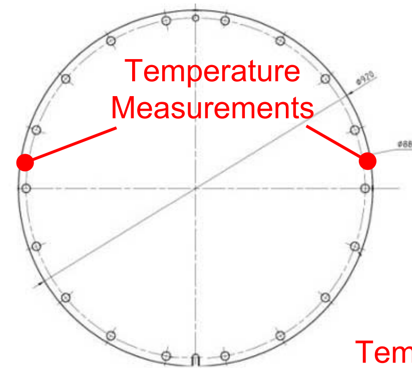
- Additional Slides

CNGS Performance - Reminder

Examples:	effect on ν_τ cc events
horn off axis by 6mm	< 3%
reflector off axis by 30mm	< 3%
proton beam on target off axis by 1mm	< 3%
CNGS facility misaligned by 0.5mrad (beam 360m off)	< 3%

Helium Tube Entrance Window

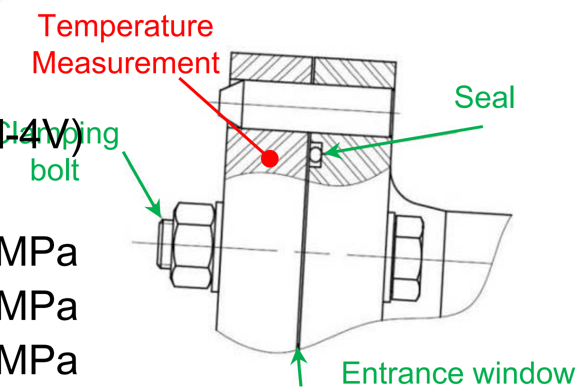


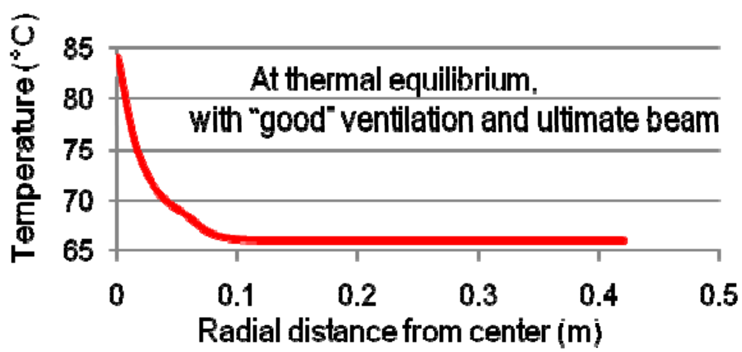


- 0.3mm thick
- 0.8m inner diameter
- Clamped with seal between flanges

Titanium Grade (Ti-6Al-4V)

- Ultimate stress:
  - @20°C: >900MPa
  - @100°C: >870MPa
  - @150°C: >850MPa





From calculations:

- When ventilation vs. beam is such that temp. at flange = 66°C:

→ Window: Temp. <100°C & Stress <250MPa → Safety factor 3 ensured.

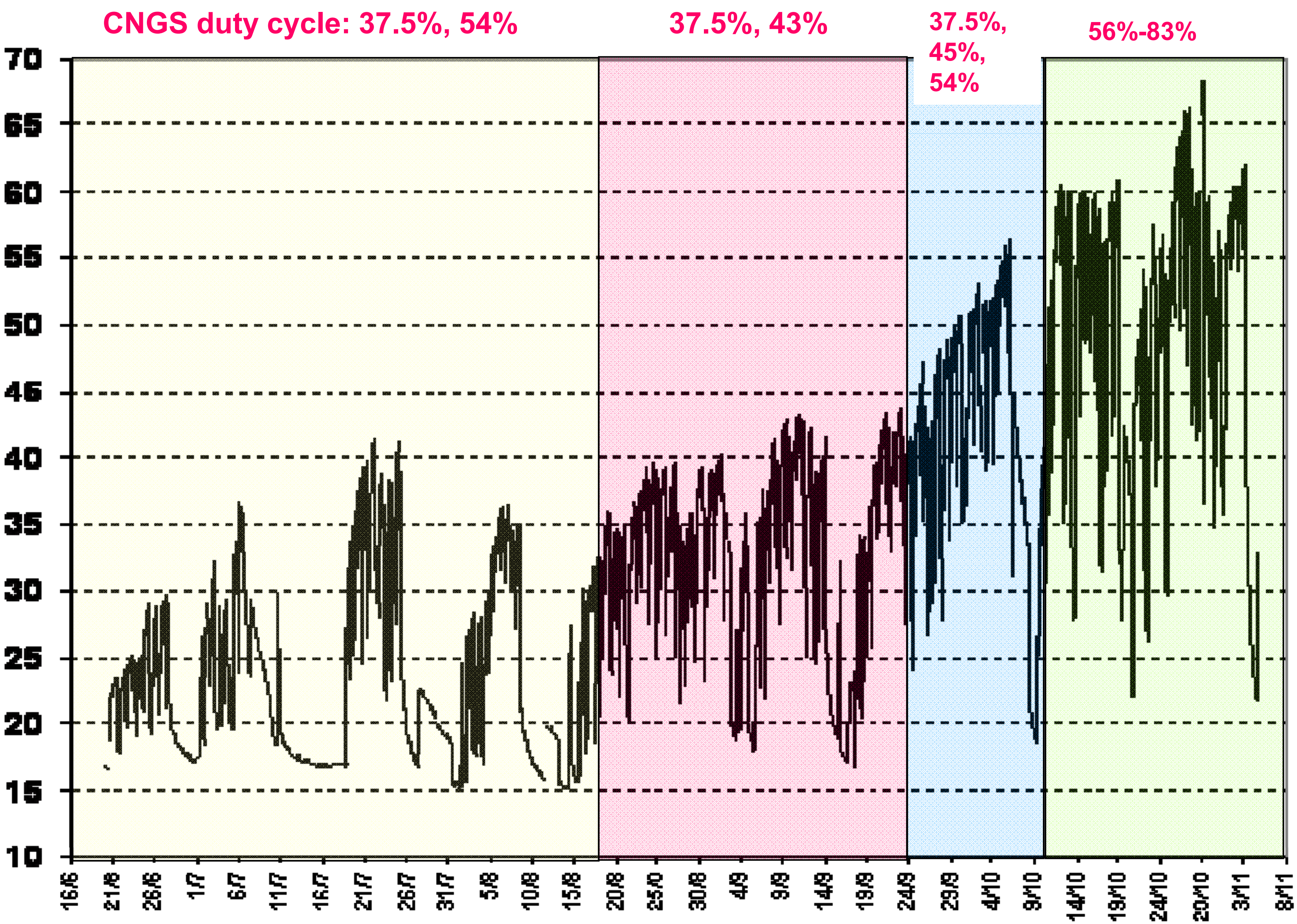
From temperature measurements during operation (extrapolate):

- If temp. measured < 85°C

→Window: Temp. <150°C & Stress <300MPa → Safety factor 2.5 ensured.

Courtesy of A. Pardons

Helium Tube Entrance Window Temperature

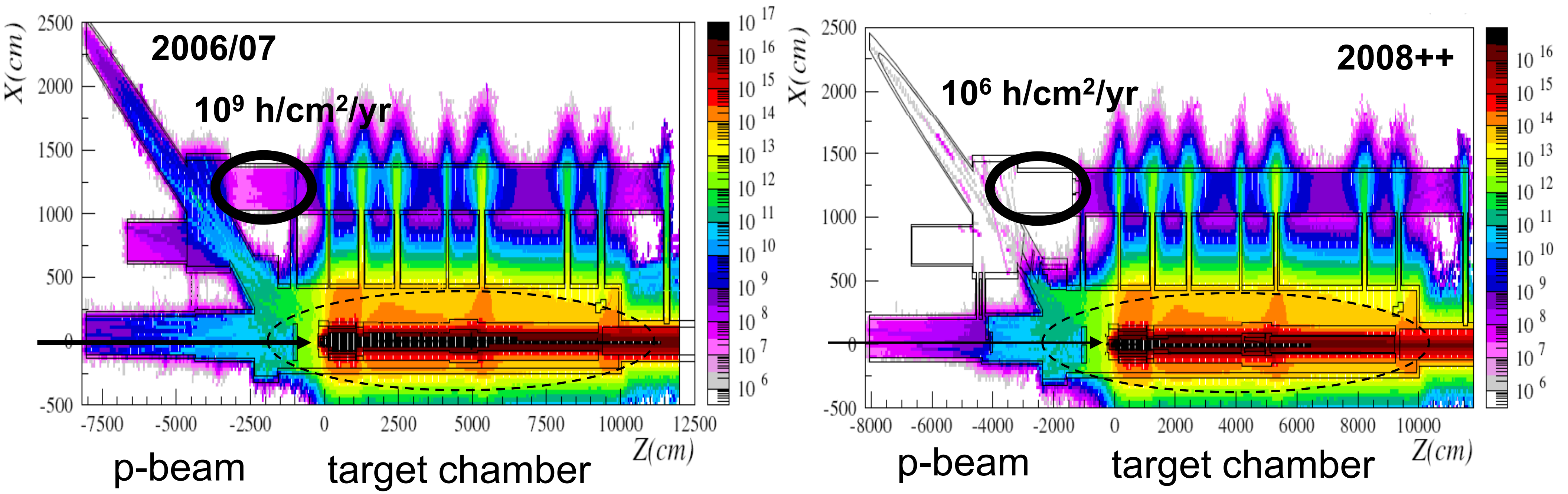


CNGS Radiation Issues

CNGS: no surface building above CNGS target area

→ many electronics in tunnel area

- During CNGS run 2007:
  - Failure in ventilation system installed in the CNGS tunnel area due to radiation effects in electronics (SEU due to high energy hadron fluence).
- modifications during shutdown 2007/08:
  - Move most of the electronics out of CNGS tunnel area
  - Create radiation safe area for electronics which needs to stay in CNGS
  - Add shielding → 53m³ concrete → up to 6m³ thick shielding walls



Neutrino Parameter Status: July 2008 Review of Particle Physics

If flavor eigenstates and mass eigenstates are different (mixing) and if masses are different
→ neutrino oscillation

Mass states: $|\nu_1\rangle \quad |\nu_2\rangle \quad |\nu_3\rangle$ Flavor states: $|\nu_e\rangle \quad |\nu_\mu\rangle \quad |\nu_\tau\rangle$

$m_1, m_2, m_3 \qquad \Delta m_{12} = m_2 - m_1, \quad \Delta m_{23} = m_3 - m_2$

Mixing of the three neutrinos: unitary 3x3 matrix → 4 parameters like the CKM matrix for Quarks.
CP violating phase not yet accessible → currently 3 mixing angles θ.

$$|\nu_\alpha\rangle = \sum_{n=1}^{3} U^*_{\alpha i}\,|\nu_i\rangle \quad \sim \quad \begin{pmatrix} |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$\boxed{P_{\mu\to\tau} = \sin^2(2\theta_{23})\,\sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)}$$

$\Delta m^2_{21} = 8 \pm 0.3 \times 10^{-5}\ eV^2$ $\Delta m_{21} = 9 \pm 0.17\ meV$ solar and reactor Neutrinos

$\Delta m^2_{32} = 2.5 \pm 0.5 \times 10^{-3}\ eV^2$ $\Delta m_{32} = 50 \pm 5\ meV$ Atmospheric and long Baseline

$\sin^2 2\theta_{23} > 0.93$ → θ_{23}=35.3 degrees compatible with max. mixing θ=45 degrees

Neutrinos

Weakly interacting leptons ν_e, ν_μ, ν_τ, no charge

- Solar Neutrinos:
  - $6 \cdot 10^{14}$ neutrinos/s/m^2
    - → Every 100 years 1 neutrino interacts in human body
    - → 10^{16} meter lead to stop half of these neutrinos
- Natural radioactivity from earth:
  - $6 \cdot 10^{6}$ neutrinos/s/cm^2.
- ^{40}K in our body:
  - $3.4 \cdot 10^{8}$ neutrinos/day
- Cosmic neutrinos:
  - 330 neutrinos/cm^3

- CNGS
  - Send ~10^{17} neutrinos/day to Gran Sasso

Neutrino Introduction

$$P_{\mu\rightarrow\tau} = \sin^2(2\theta_{23})\ \sin^2\left(\frac{\Delta m^2_{23}L}{4E}\right)$$

→ Δm^2_{32}… governs the ν_μ to ν_τ oscillation

→ Up to now: only measured by disappearance of muon neutrinos:

- Produce muon neutrino beam, measure muon neutrino flux at near detector
- Extrapolate muon neutrino flux to a far detector
- Measure muon neutrino flux at far detector
- Difference is interpreted as oscillation from muon neutrinos to undetected tau neutrinos

→ K2K, NuMI

→ **CNGS (CERN Neutrinos to Gran Sasso):**

long base-line appearance experiment:

- Produce muon neutrino beam at CERN
- Measure tau neutrinos in Gran Sasso, Italy (732km)

→ Very convincing verification of the neutrino oscillation

→ ν_τ interaction in the target produces a τ lepton

→ Identification of tau lepton by characteristic kink

2 detectors in Gran Sasso:

- OPERA (1.2kton) emulsion target detector ~146000 lead-emulsion bricks
- ICARUS (600ton) liquid argon TPC