
## 4th High Power Targetry Workshop

**Malmö, Sweden, 2nd – 6th May 2, 2011**

# Design, maintenance and operational aspects of the CNGS target

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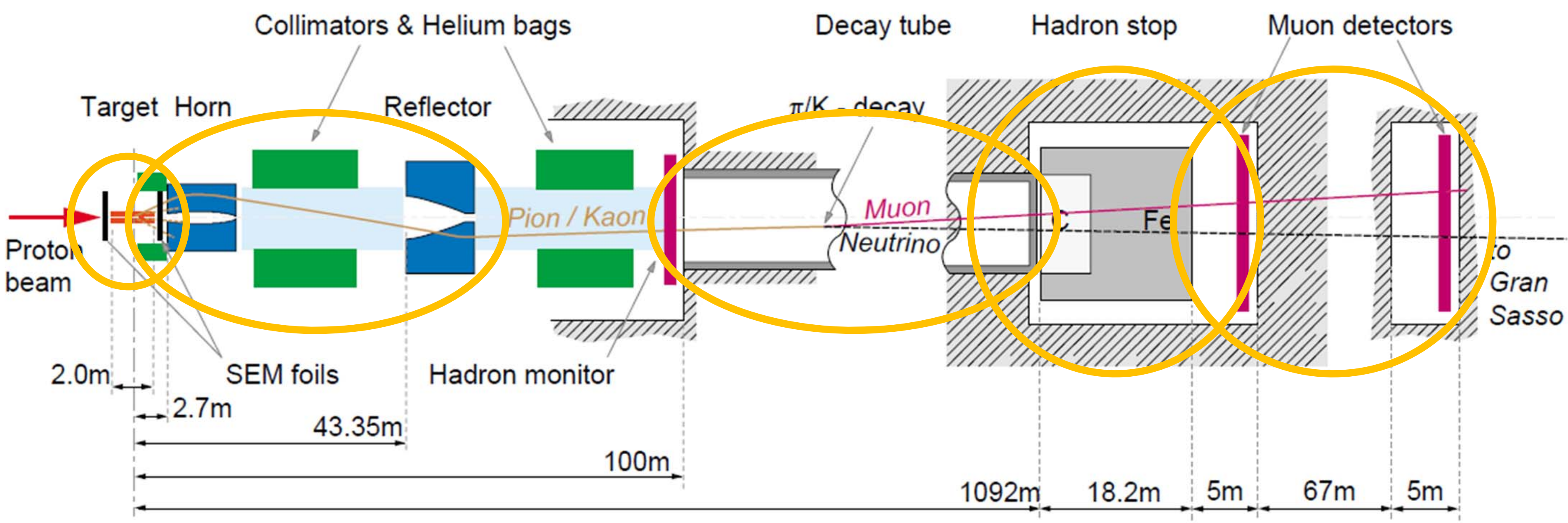
# Outline

1. Introduction to **CNGS physics case** and **design guidelines**

2. **CNGS target design**
   I. FLUKA simulation optimization
   II. Engineering design of the target and auxiliary equipment

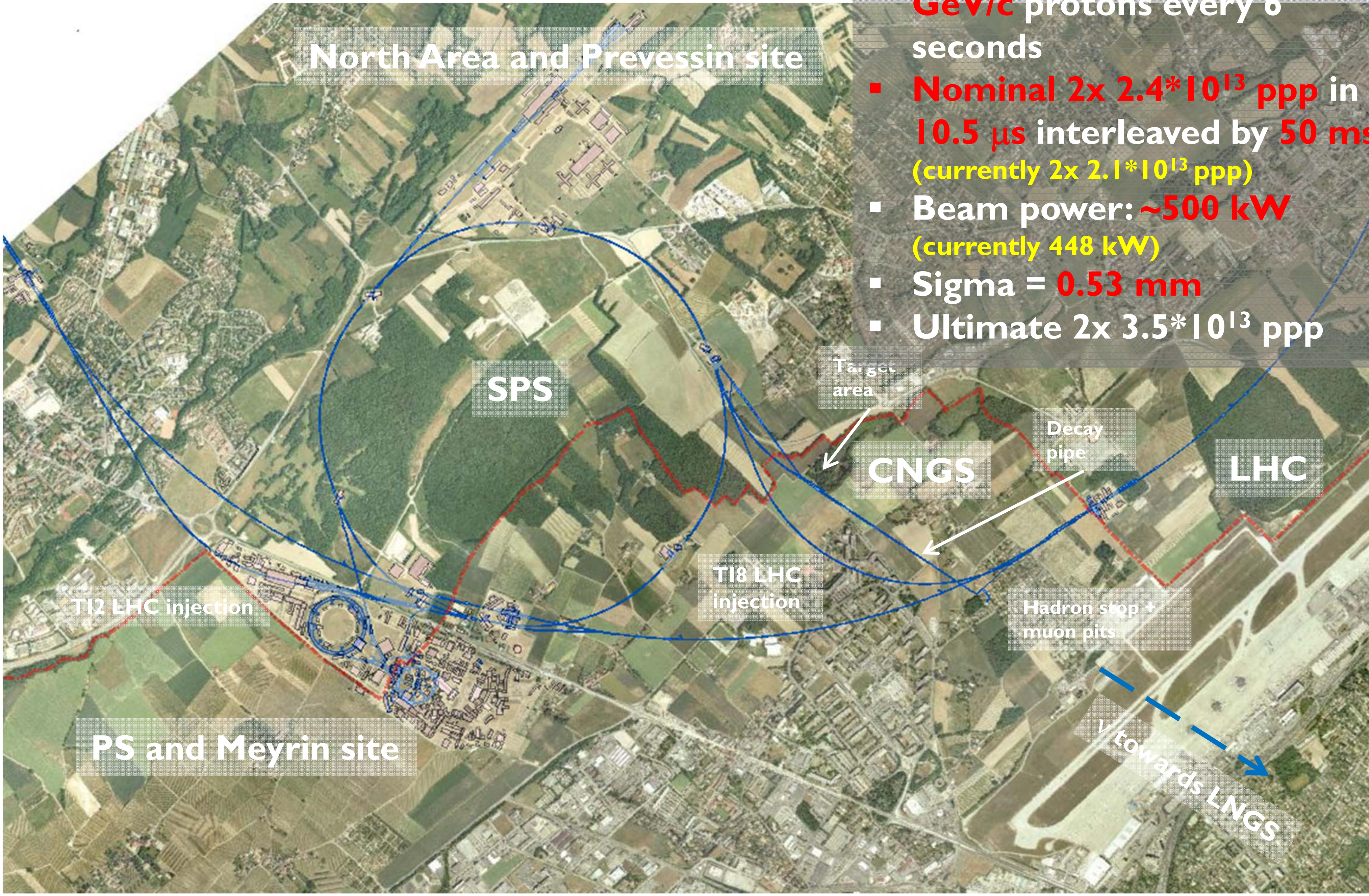
3. **Operational aspects** of the installation: selected topics
   I. Maintenance of the target system
   II. Investigation on target motorization failure

# General layout of the CNGS installation

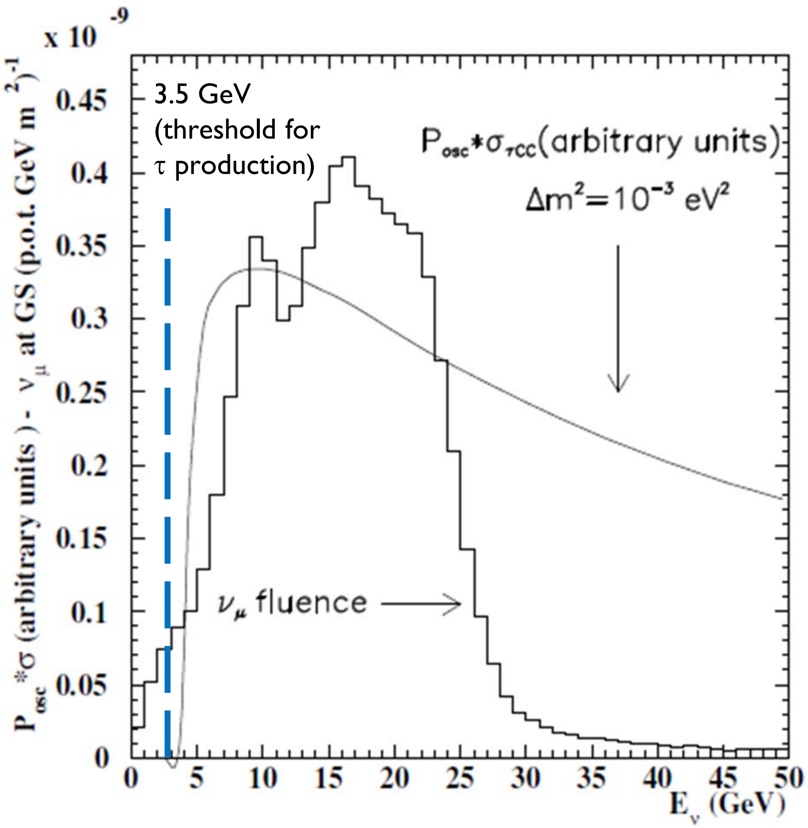



- **Air cooled graphite target** magazine (**π/K production**)
- 2 **horns** (horn + reflector) → water cooled, pulsed with 10ms half-sine wave of 150/180 kA, 0.3 Hz, remote polarity change (**focusing of charged mesons**)
- **Decay pipe** → 1000m 2.45 m Ø, 1 mbar vacuum (**decay in flight**)
- Hadron absorber → C core + Fe, ~100 kW absorption proton and other hadrons
- 2 muon monitor stations: μ fluxes and profiles (direction of the **ν beam towards LNGS**)

- SPS: 2 fast extraction of **400 GeV/c** protons every 6 seconds
- **Nominal 2x $2.4*10^{13}$ ppp** in **10.5 μs** interleaved by **50 ms**
  (currently 2x $2.1*10^{13}$ ppp)
- Beam power: **~500 kW**
  (currently 448 kW)
- Sigma = **0.53 mm**
- Ultimate 2x $3.5*10^{13}$ ppp



# Physics requirement for the CNGS beam




CNGS is a **long base-line appearance experiment**, designed for $\nu_\mu \rightarrow \nu_\tau$ oscillation search → **$\nu_\tau$ appearance in a (almost) pure $\nu_\mu$ beam**

The **energy spectrum of the $\nu_\mu$ is well matched to $R \sim \sigma_{\tau CC}/E_\nu^2$ at ~17 GeV** to maximize the signal rate ($\nu_\tau$ appearance)

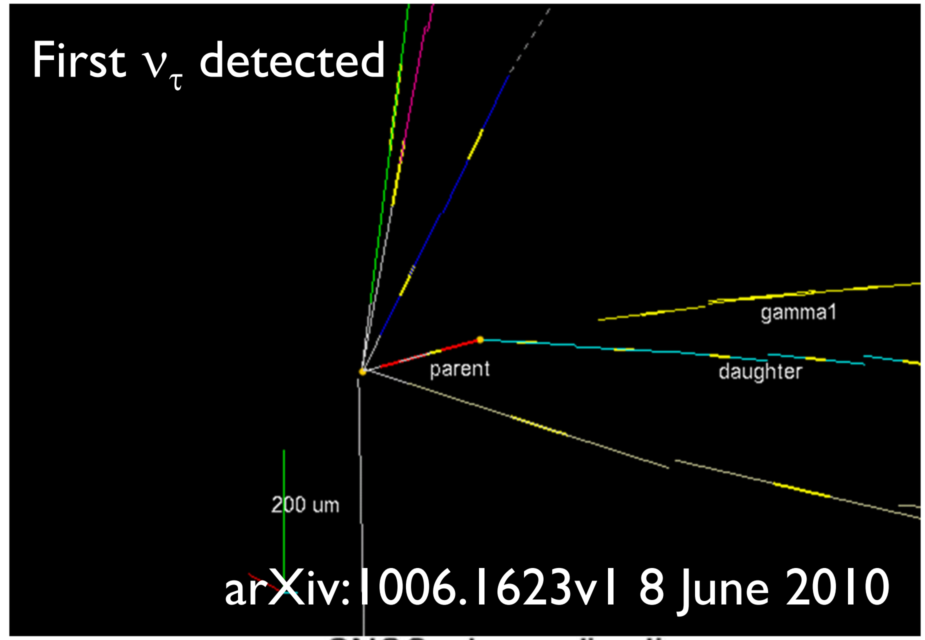
- Low anti-$\nu_\mu$ and $\nu_e$ contamination

CNGS approved for 22.5*$10^{19}$ POT (5 y with 4.5*$10^{19}$ POT/y)
→ … up to now **10.5*$10^{19}$ POT**
→ **Few $\nu_\tau$ expected in OPERA and ICARUS detectors**

# Example of neutrino events in OPERA and ICARUS

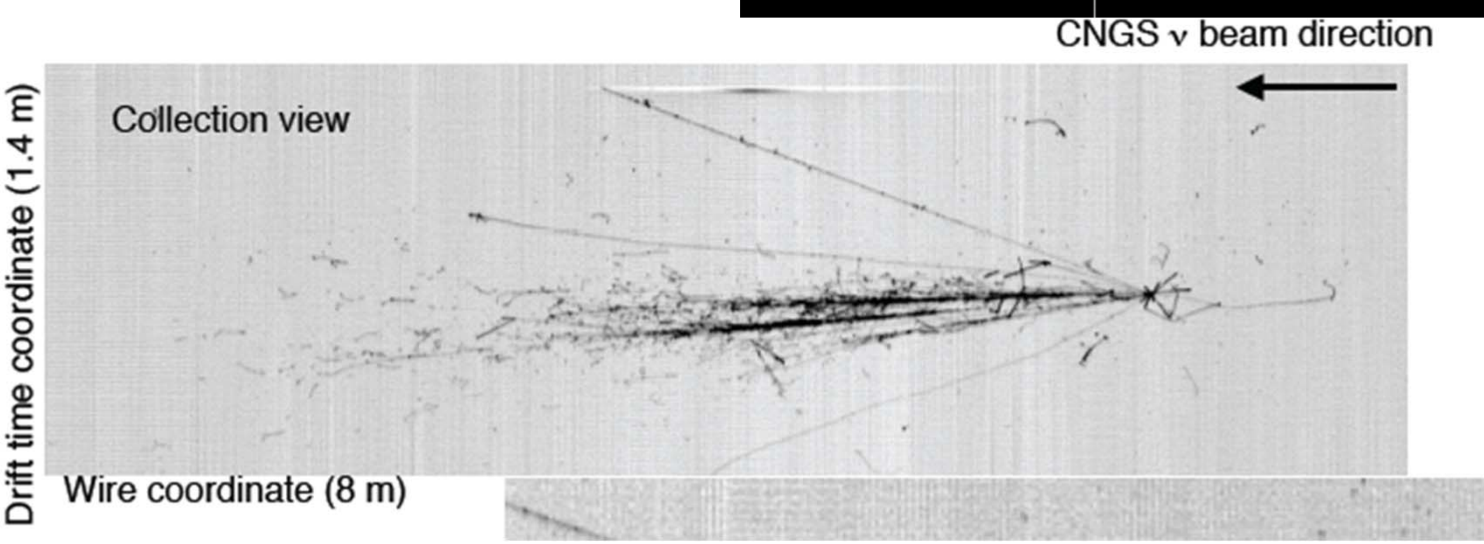
**OPERA**: 1.2 kton emulsion target detector

- 146000 lead emulsion bricks




**ICARUS**: 600 ton Liquid Argon TPC

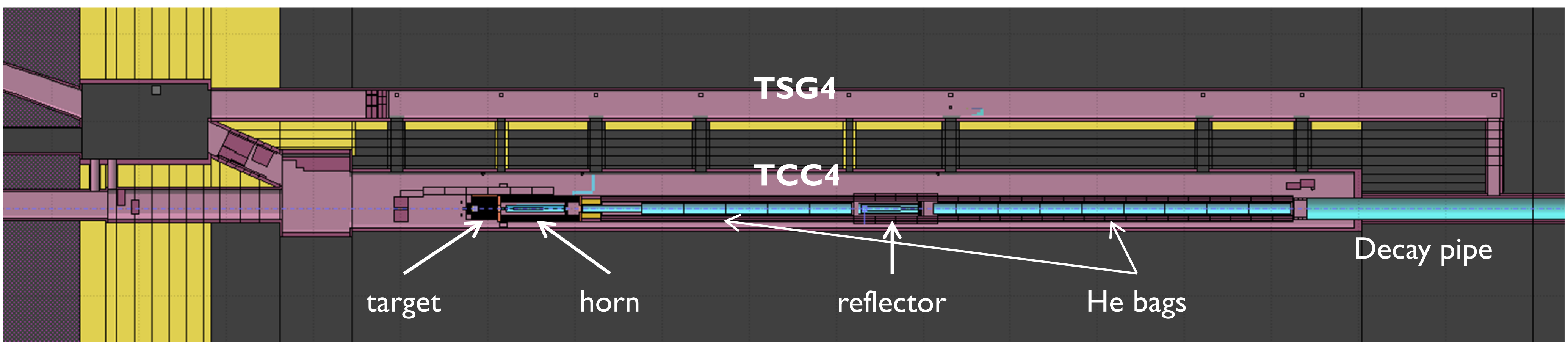
- High sensitivity and online reconstruction of tracks



# CNGS description with FLUKA

The CNGS beam-line facility **is fully described within the FLUKA Monte Carlo code** for various purposes:

1. Optimization of the **target design** in the initial project stages
2. **Energy deposition** in the secondary beam line → mechanical and thermal analysis
3. Prompt and residual **dose rate** → radioprotection
4. Monitor **beam response** → commissioning and diagnostics (μ distrib. at μ-pits)
5. Predict **neutrino beam energy spectrum/composition** at LNGS



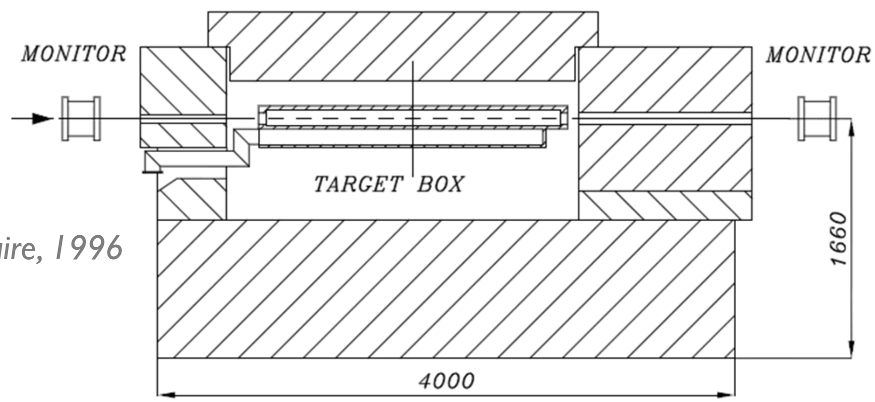
# Past experience at CERN

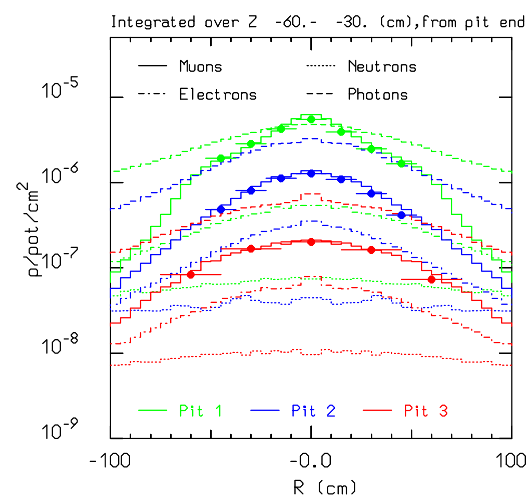
The design of the CNGS target takes advantage of the experience with previous fixed targets at CERN

→ **T9 WANF** target (CHORUS and NOMAD experiments) (~180 kW beam)
→ 11 Be rods, **3 mm Ø**, **10 cm long**, spaced every 9 cm, He cooled (forced flow)

- **Operational experience** with the target (e.g. corrosion in humid/radioactive environment)
- **FLUKA used for beam simulations and comparison** with ν-induced CC events in NOMAD

S. Peraire, 1996




- WANF muon pits good agreement for the 3 detector regions

# Physics requirement of the CNGS target

1. Provide the **highest possible proton interactions**
2. Decrease **probability of secondaries reinteraction**

→ For HE ν beams: target needs to be **segmented**, in order to allow small-angle high momentum secondaries to escape the target with less path length

I. Target need to be **robust to resist beam-induced stresses**
II. Due to particle energy deposition the target must be **cooled**

*With the following technological constraints:*

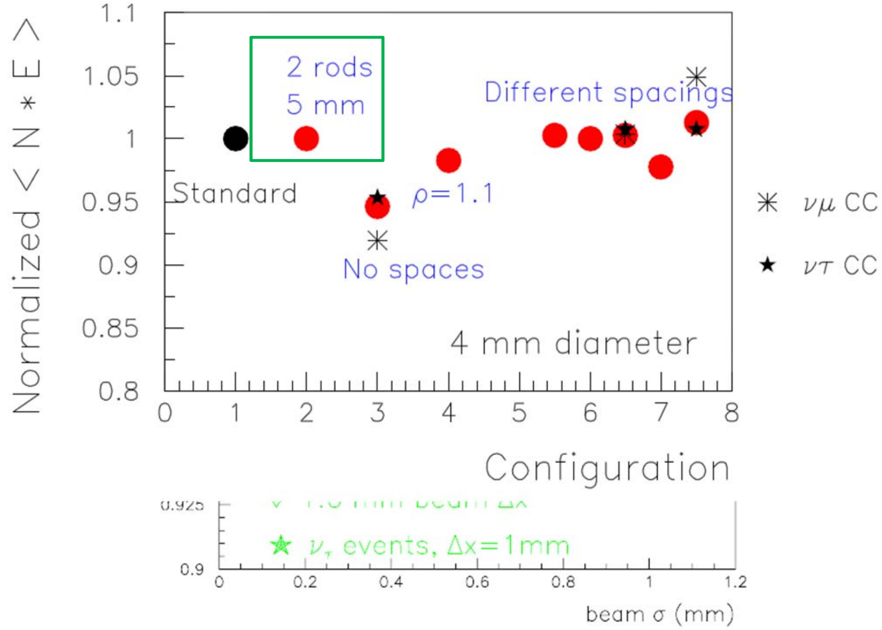
- The target **should not be cooled by water** (avoid mechanical shocks and activation/radioprotection issues)
- Material choices should **minimize the absorbed beam power** and **maximize radiation resistance**
- Target should be **replaceable**, with in-situ spares

# Design optimization of the CNGS target

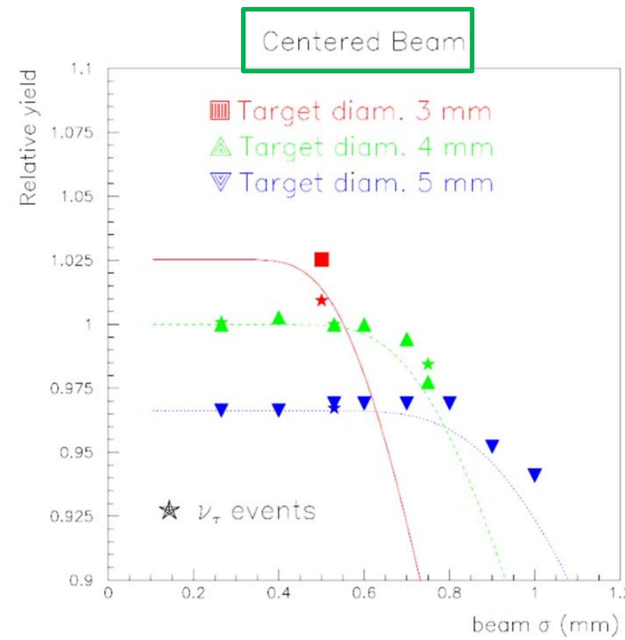
A thorough study was performed to optimize the physics and engineering of the target unit.

Effect of **target configuration on $\pi$ yield**

Effect of **beam displacement**




Effect of **beam $\sigma$** and **target diameter** of $\pi$ yield



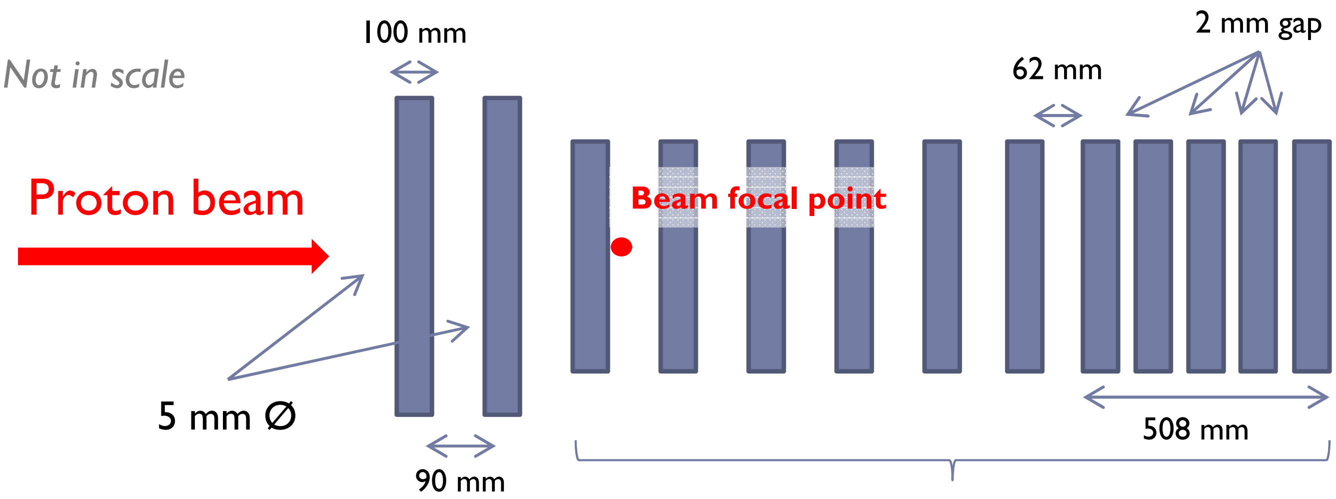

- 3mm comparison with WANF target
- $\sigma$=0.53 mm is the reference beam

→ Due to proton beam size and target configuration, **the alignment of the beam line elements is not "too much" critical for CNGS neutrino fluxes**

*P. Sala (2001)*

# CNGS target rod configuration

*Not in scale*



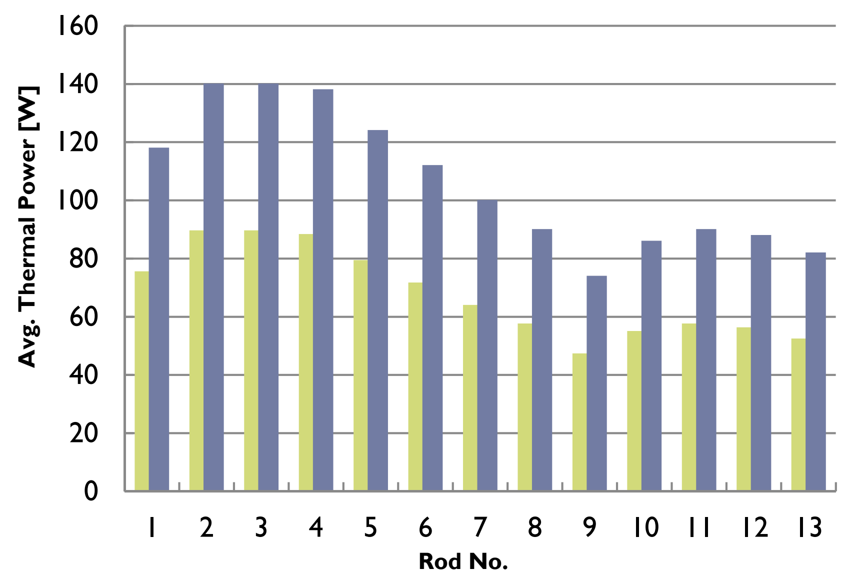

Baseline configuration

Total power in rods!
Nominal ($4.8*10^{13}$ p/6s cycle) → **886 W**
Ultimate ($7.0*10^{13}$ p/6s cycle)→ **1292 kW**

Baseline target:

- **13 graphite rods**, 10 cm each for a total of 3.3 $\lambda_I$
- **5 mm Ø** for the first two (maintain a margin of security → containment of proton beam tails), **4 mm Ø** for the others
- The first 8 are **separated by 9 cm** each to better develop meson production, with the **last 5 packed** to reduce longitudinal smearing in $\pi$ production (for a better focalization)

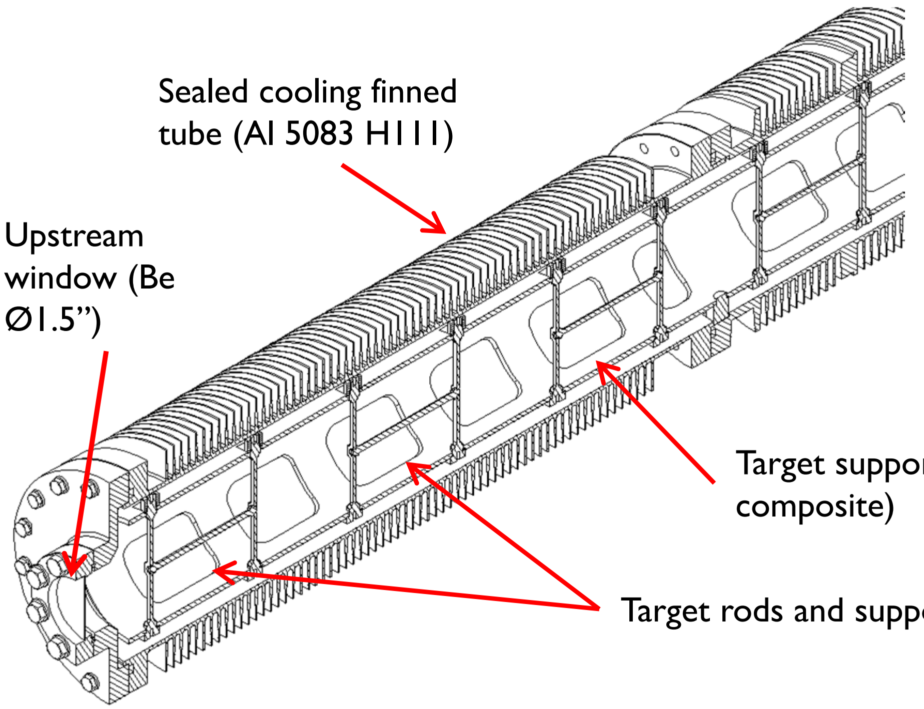
**CNGS Peak Thermal Load**



# The CNGS target unit

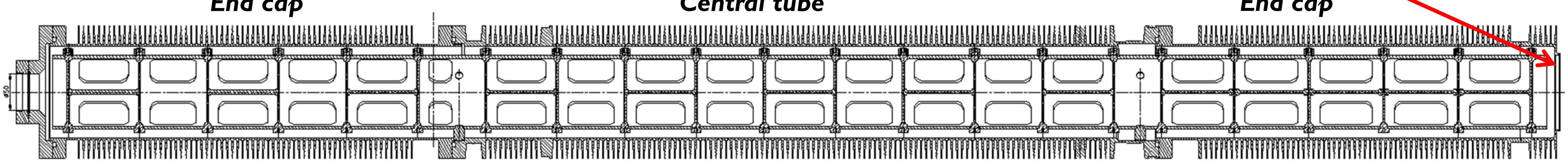
Target unit is conceived as a **static sealed system** filled with 0.5 bar of He (@cold)

- Cooling of the target rods is made by **radiation** to the Al tube and **convection**
- The target "revolver" is flushed with air which keeps the aluminum temperature <100 ˚C

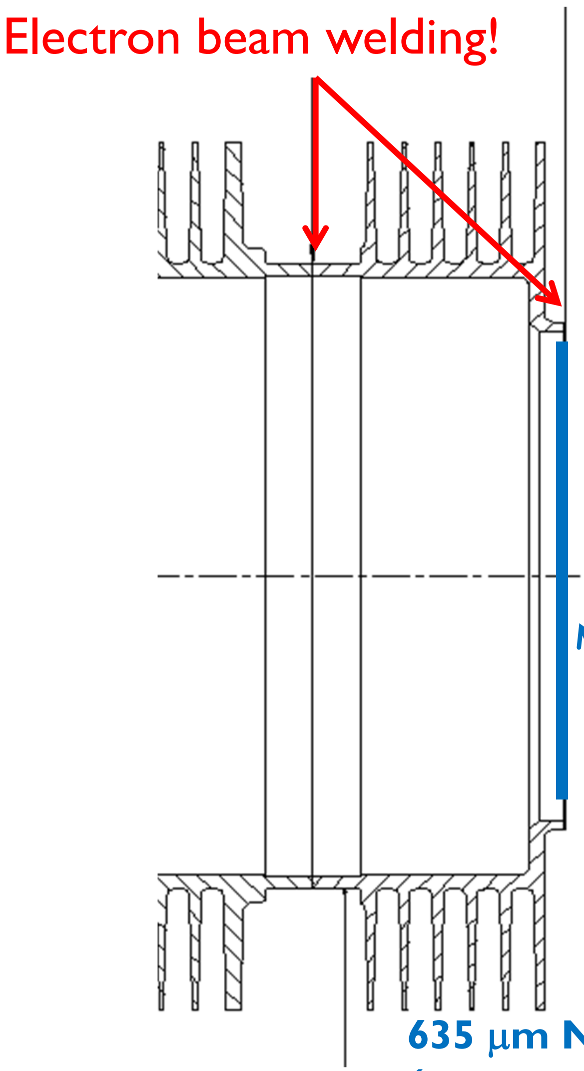



| | |
|---|---|
| Material used for the target | |
| Tube: | Al-Mg alloy |
| Windows: | Beryllium |
| Target support: | C-C |
| Target rod: | fine-grain graphite |

**0.5 bar at room temperature, 1.0 bar at operating conditions**



# Additional details on the target




- The tube has annular fins to **enhance the convective heat transfer**
  - He gas best to keep target wall at lower temperature BUT higher ΔT=76K
  - Al anodized to increase radiative heat transport to the tube
- Dedicated configuration conceived **to limit the heat load** on the target itself
- Target rods are on a carbon support structure with holes in order to **increase thermal exchange**

ar … m … **we** … e Al

**635 µm Ni-coa…**
**(preserve from…**
**(381 µm upstre…**

# CNGS target rod configuration (current configuration)

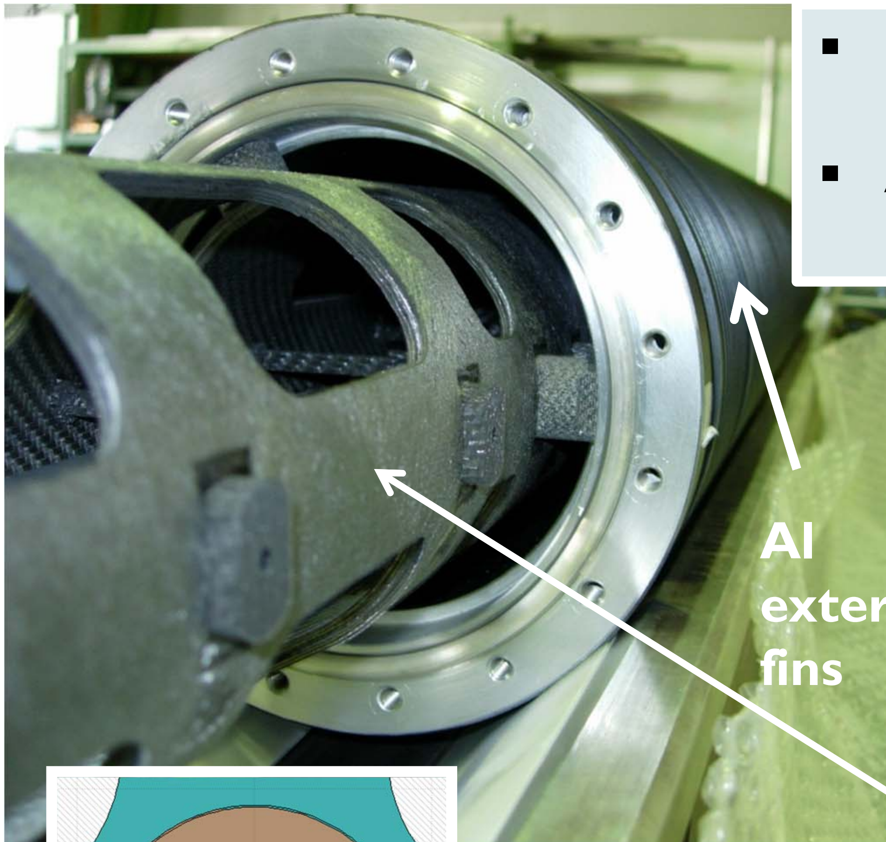
**5 units installed in a single target magazine**

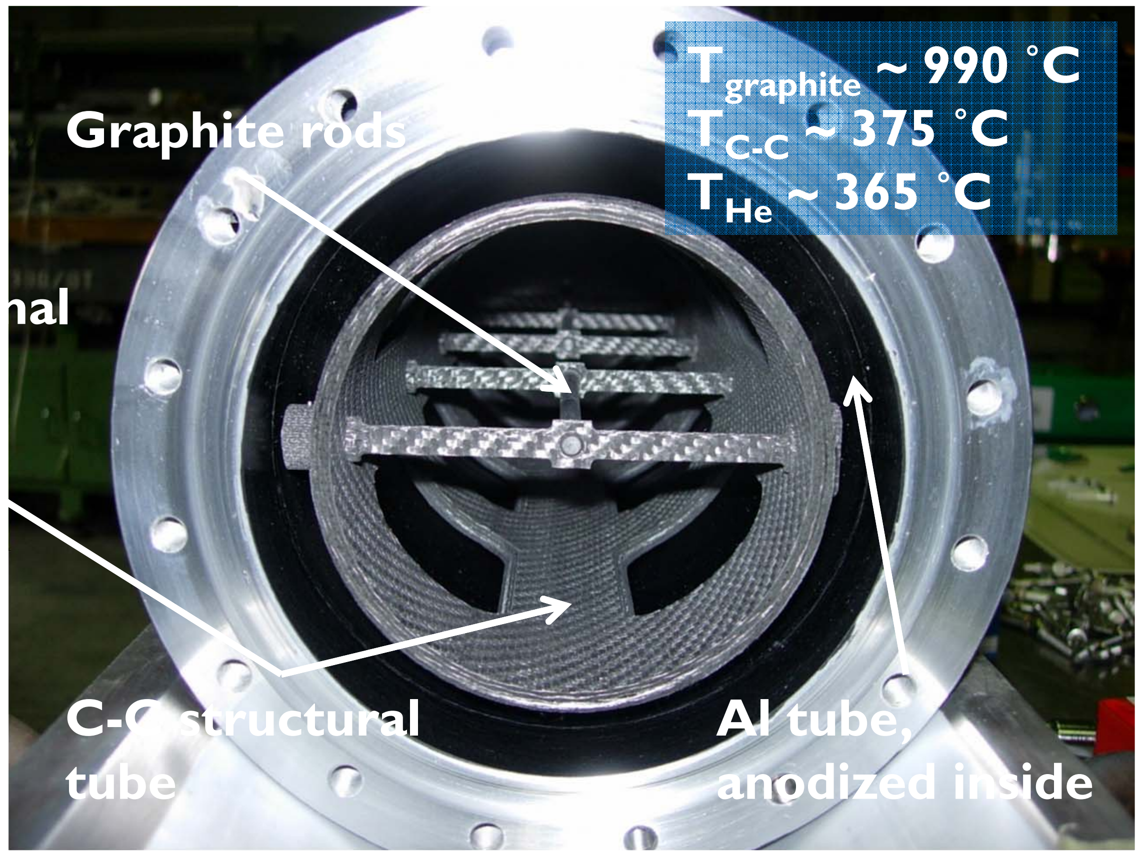
1. **Graphite** target with baseline geometry under **He** (Graphite 2020PT by Carbone Lorraine)
   - Best understood carbon (ρ=**1.76 g/cm³**) → standard target!
2. **Carbon** target with baseline geometry under **He** (Sintered Carbon SC24 by Sintec Keramik)
3. **C-C composite** target with baseline geometry under **He** (Aerolor A035 by Carbone Lorraine)
   - C-C suited for operation at high temperature (**thermal shock resistance** and **low coefficient of thermal expansion**) But radiation damage?
4. **C-C composite** target with baseline geometry under **vacuum** (Aerolor A035 by Carbone Lorraine)
   - Vacuum in order to address a possible concern of stress cycling on the Be window from thermal cycling of gas
5. **"Safe" target**: graphite target with all **5 mm** diameter rods under **He**
   - Introduced as a possibility to increase the beam size from 0.53 mm to 0.75 mm

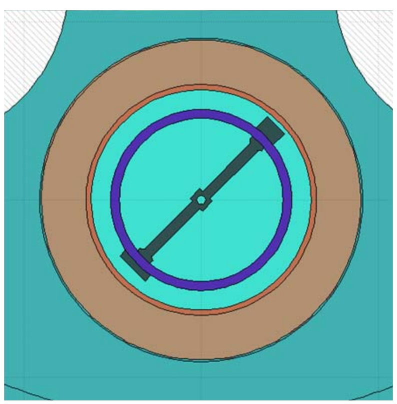
- All the materials from the different producers have been **tested and analyzed in lab** to cross-check the technical specifications

# The CNGS target units as built

- 5 units (1 active + 4 in-situ spare) are hosted in a target magazine
- An additional spare magazine is available in case of complete target failure

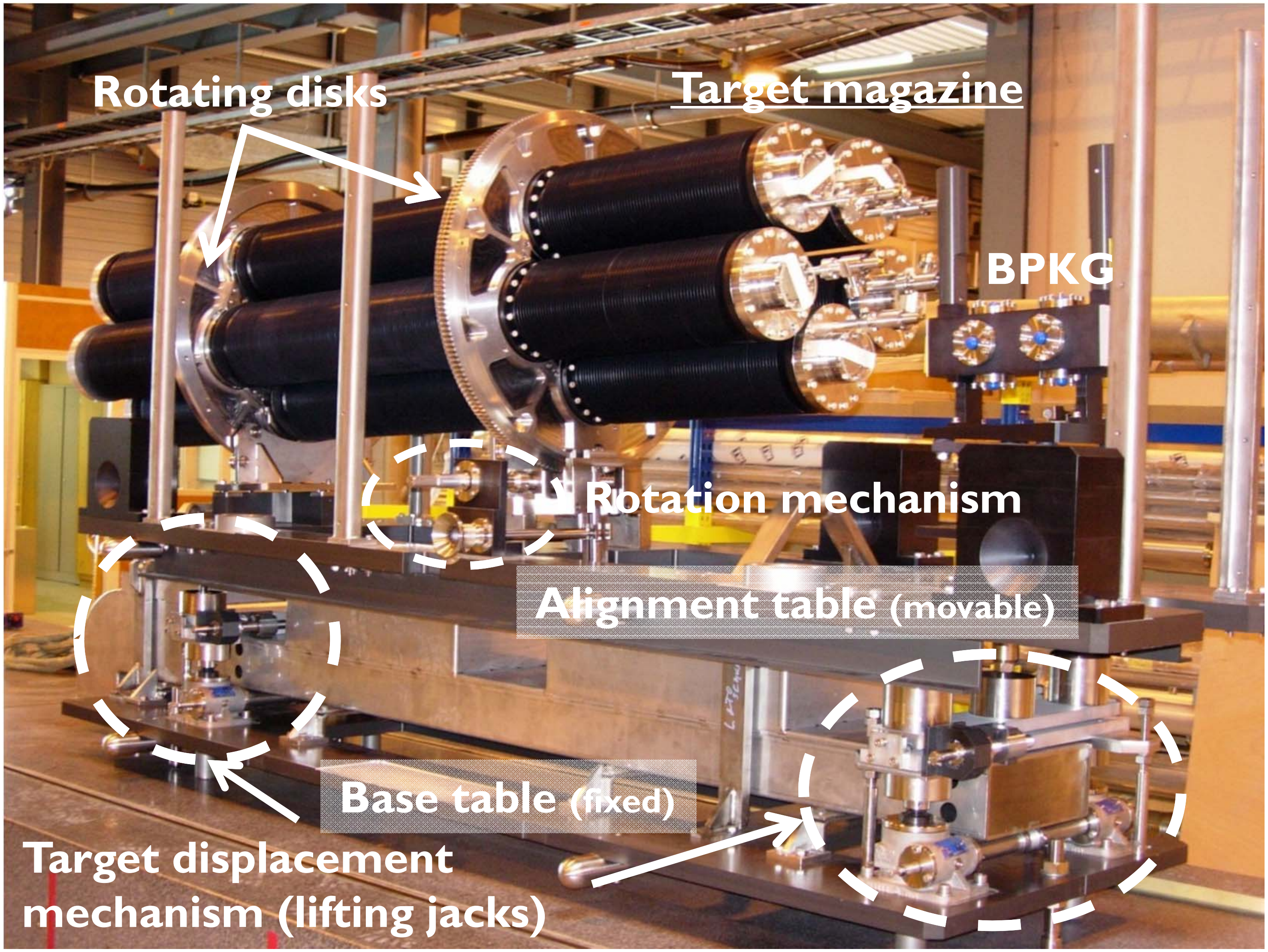


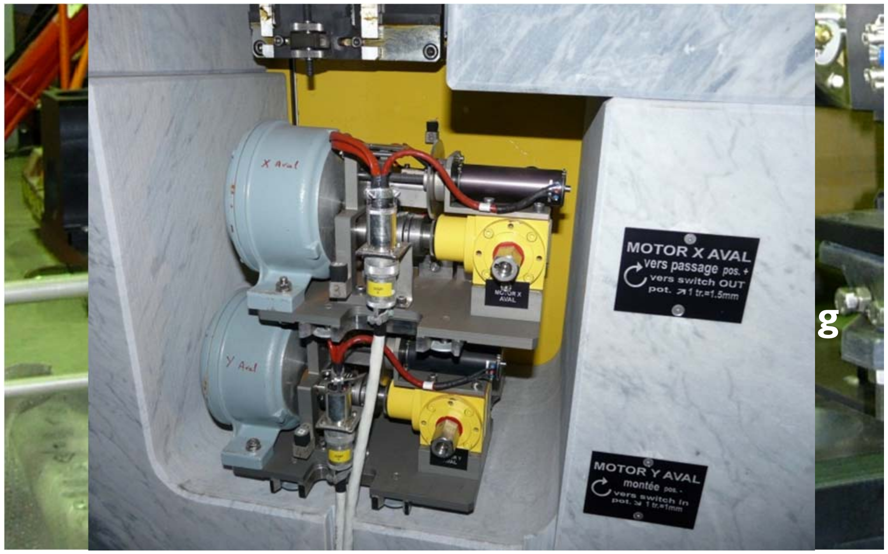



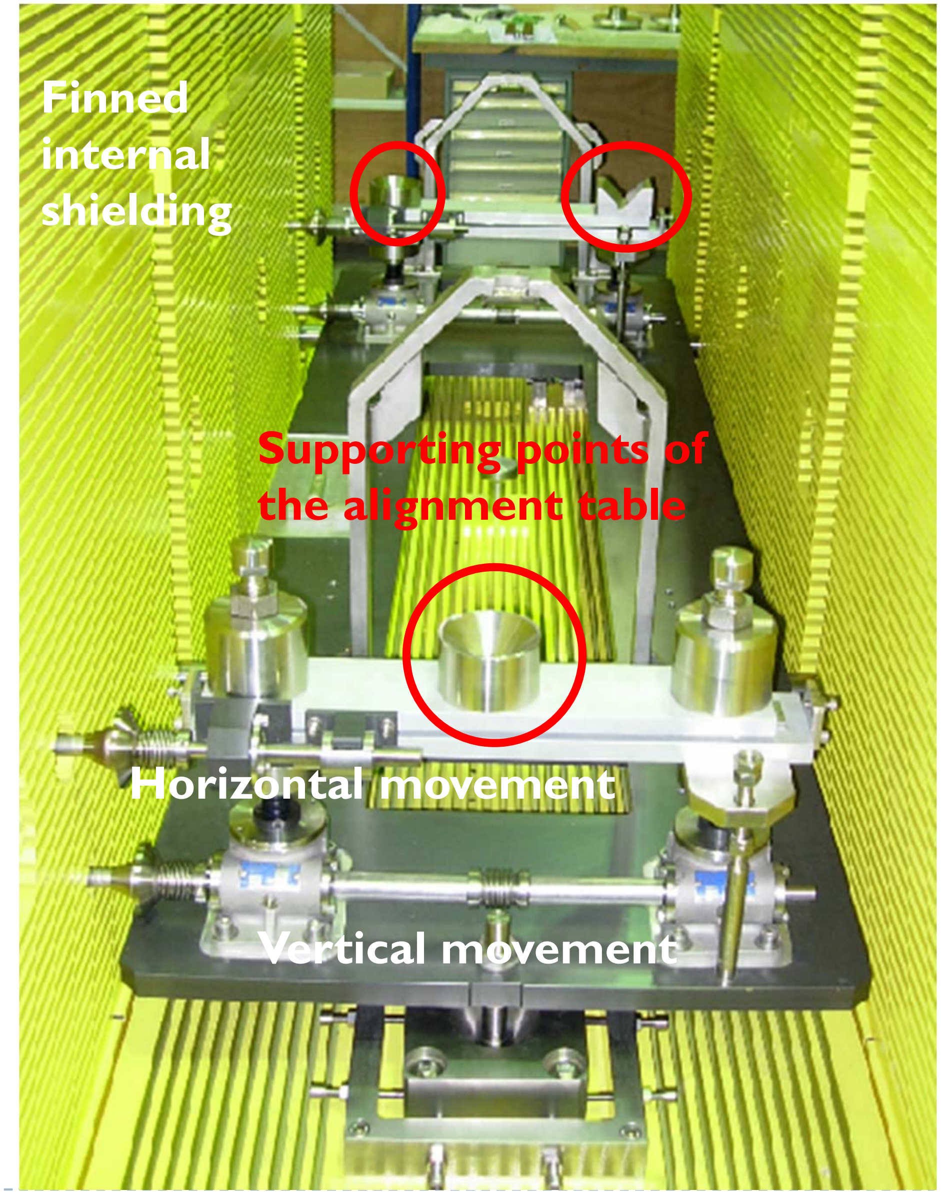
Implementation in FLUKA

# Target unit as built and installed in CNGS



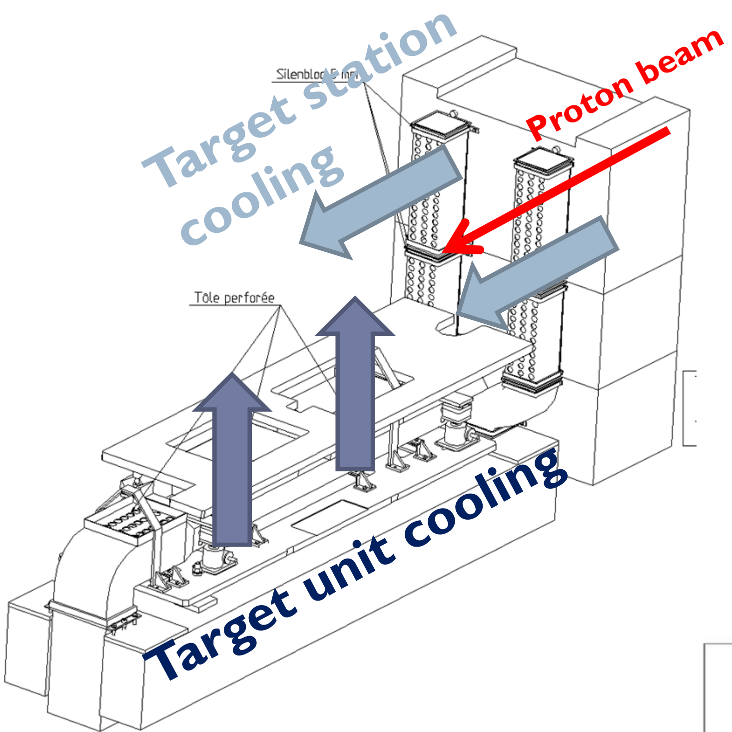
# The target base/alignment table




- Base/alignment table is placed by **guiding grooves** on three adjustable points
- **Motorization** driving the alignment table **is located outside of the shielding**
- The connection is realized through the shielding by shafts with **fast coupling systems**

# Target assembly cooling

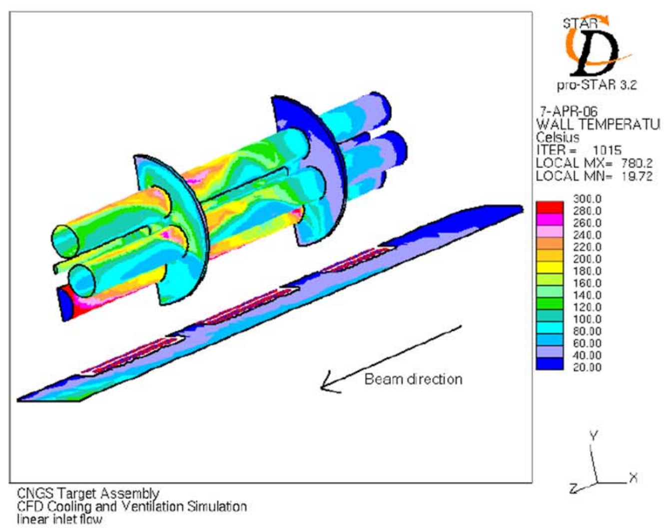


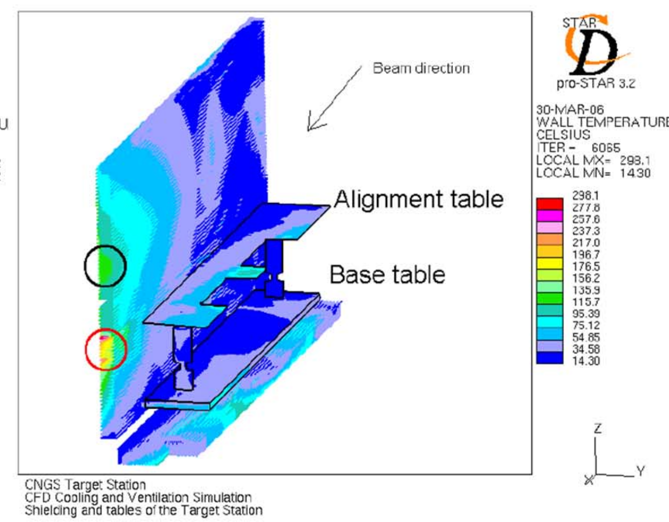

Two main air streams in the TS, not affected by each other (3600 $m^3/h$ cooling capacity):

- **Vertical airflow parallel to the fins** of the target assembly → **TARGET**
  - **~6 kW to evacuate (3.4 kW active unit + 1.5 kW spare unit)**
- **Horizontal airflow** parallel to the fins of the shielding → **SHIELDING**
  - **~15 kW (~13 kW side wall shielding)**

- $\mathbf{T_{av}}$ **= 85 °C**, $T_{max}$ = 93.5 °C (finned case!)
- $\mathbf{T_{avshield}}$ **~40 °C**, $T_{maxshield}$ ~300 °C

*M. Kuhn (2005)*

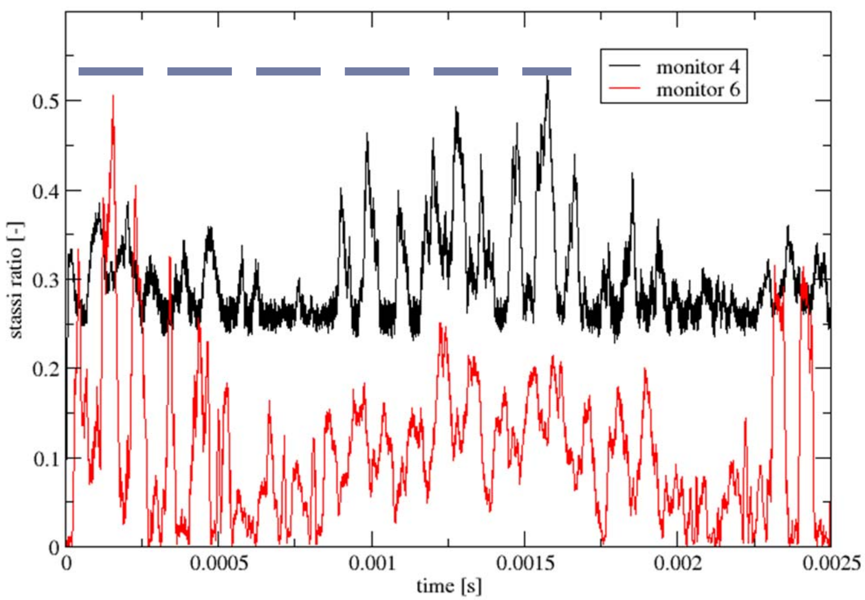


# Stresses on the CNGS target rods

A critical point for CNGS is the possibility to receive **off-axis beam**

- Worst loading conditions (1.5 mm OA, ultimate intensity, cold target, no damping)
- Stassi stress ratio (Stassi equivalent stress/tensile strength) employed for design consideration

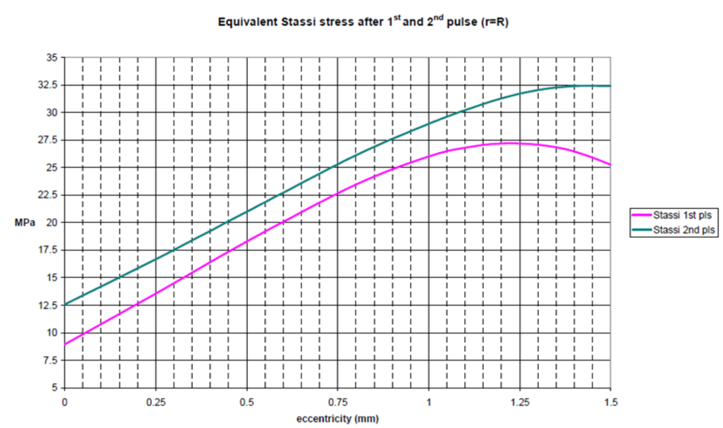



Temperature increase & boundary conditions → dynamic stresses on the rods → **rapid transversal vibration**

- Stassi ratio **always lower than 0.7** (safety factor of 1.5!) for single bunch
- ***Beam stability on target → well within these limits…***

Max. Stassi eq. stress found for *1.23 mm OA* = **27.1 MPa**

- ❑ Time for equilibrium is > than bunch spacing → effect of the 1st bunch still present when the 2nd comes
- ❑ **32.4 MPa** at *1.5 mm OA* → Stassi ratio **~0.89**



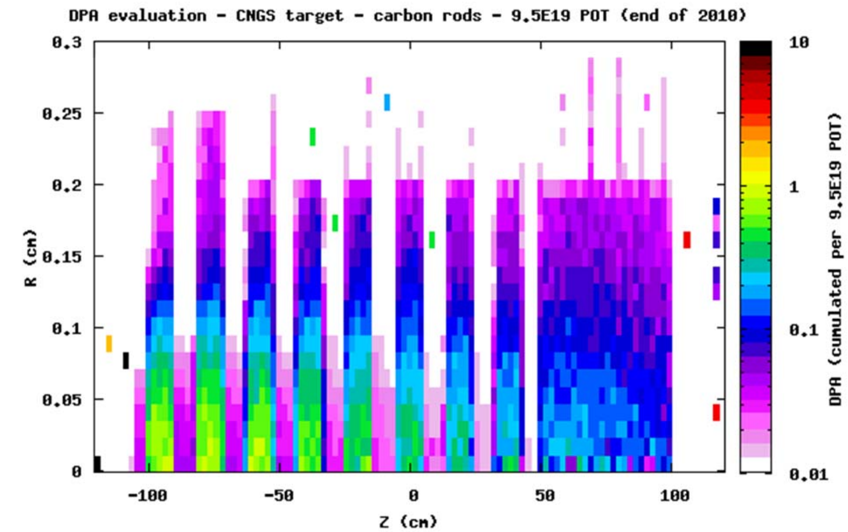

*L. Massidda, CRS4, 2005, A. Bertarelli, CERN, 2003*

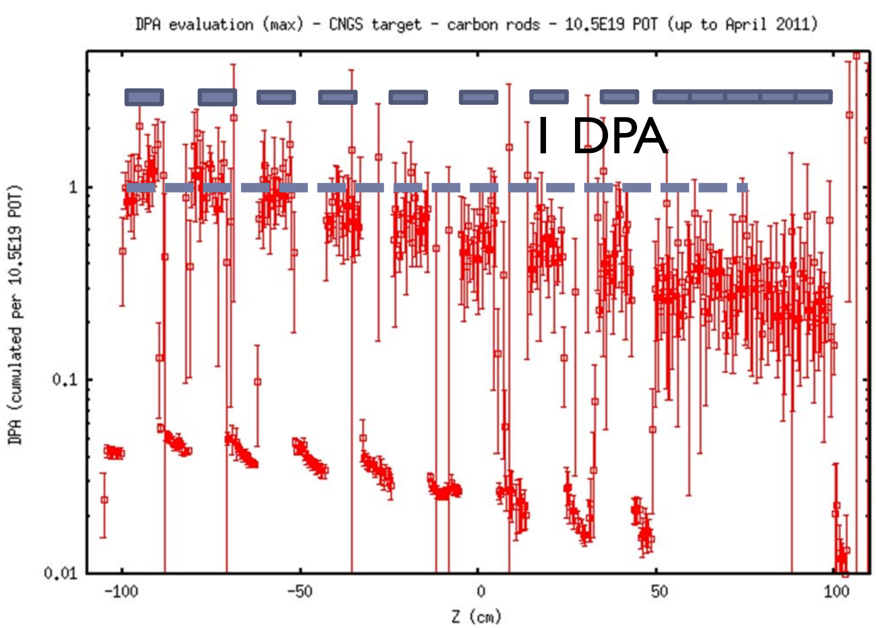
# DPA evaluation by FLUKA of the CNGS target rods

FLUKA adopted to evaluate the **DPA on the target graphite material**

- **~1.5 DPA** for the first 3 rods assuming $10.5*10^{19}$ POT (~0.2 mm radius)
- Expected **~3 DPA** at the end of expected CNGS run

➢ Shrinkage and reduction of thermal conductivity (higher stress) → minimized by operating at high T




- Operational T favors **annealing** and **reduction of imperfection** due to amorphous graphite
- **No apparent reduction in muon yield** observed from 2008 to now *(E. Gschwendtner, 2011)*
- Tests performed at BLIP (BNL) show **no damage at $5.9*10^{20}$ POT** in argon atmosphere of several type of graphite *(P. Hurh, HB2010)*

# Structural limits of the CNGS target

- **Mechanical limits**: **dynamic** (beam time structure) and **static** stresses (beam profile)
- **Thermal limits**: determined by cooling system
- **Radiation damage**: might lead to **defects** and **target failures**

- **Dynamic stresses** → spreading the beam in **more batches** and increasing the **spacing** between extractions → **up to $1*10^{14}$ p/cycle**
- At this stage, **target cooling would be the limiting factor**:
  - Graphite erosion by sublimation (can be an issue from ~**1.5 MW**)
  - Degradation of helicoflex seals

Nominal CNGS
**~510 kW**
⇒ **$4.8*10^{13}$ p/6s** ⇒ **$1.38*10^{20}$ pot/y** ⇒ **$7.6*10^{19}$ pot/y** ⇒ **$4.56*10^{19}$ pot/y**

*Secondary beam line elements (horn, HS, DP)* — 200d operation

*RP limit* — 200d operation, 55% efficiency

*CNGS working point* — 200d operation, 55% efficiency, 60% CNGS sharing

Ultimate CNGS
**~750 kW**
⇒ **$7.0*10^{13}$ p/6s**

*Design limit for target, kicker, instrumentation*

*M. Meddahi et al., CERN-AB-2007-013*

# Target rotation system failure – radiation induced effects on material

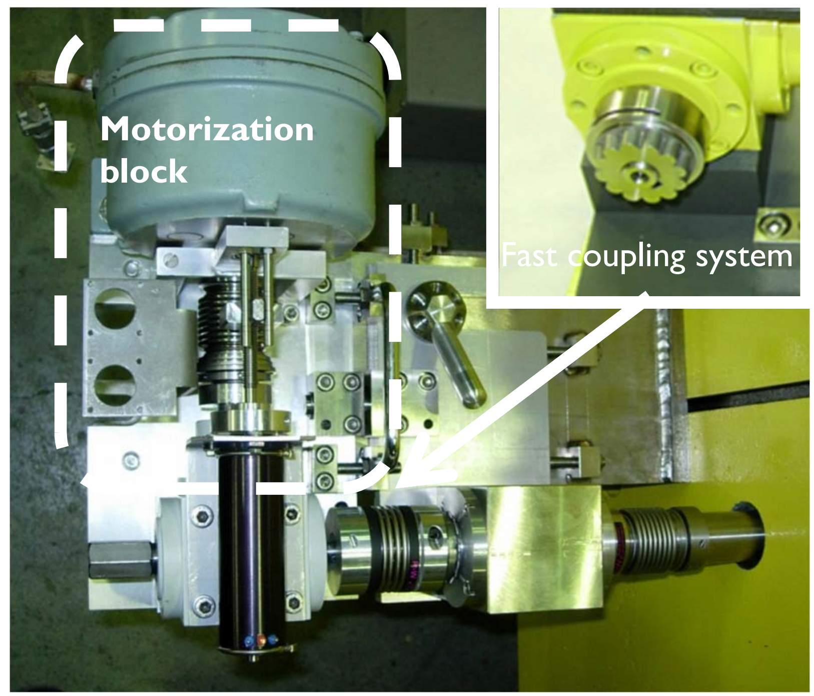
Usual **yearly maintenance** of the target unit includes(d):

- **Alignment motor maintenance**, DC motors with torque limiter outside the shielding block → 5 mm, precision of **100 μm**
- **Rotation** of the target magazines to 1) check the remote system movement capability and 2) to reduce formation of oxides in the bearings

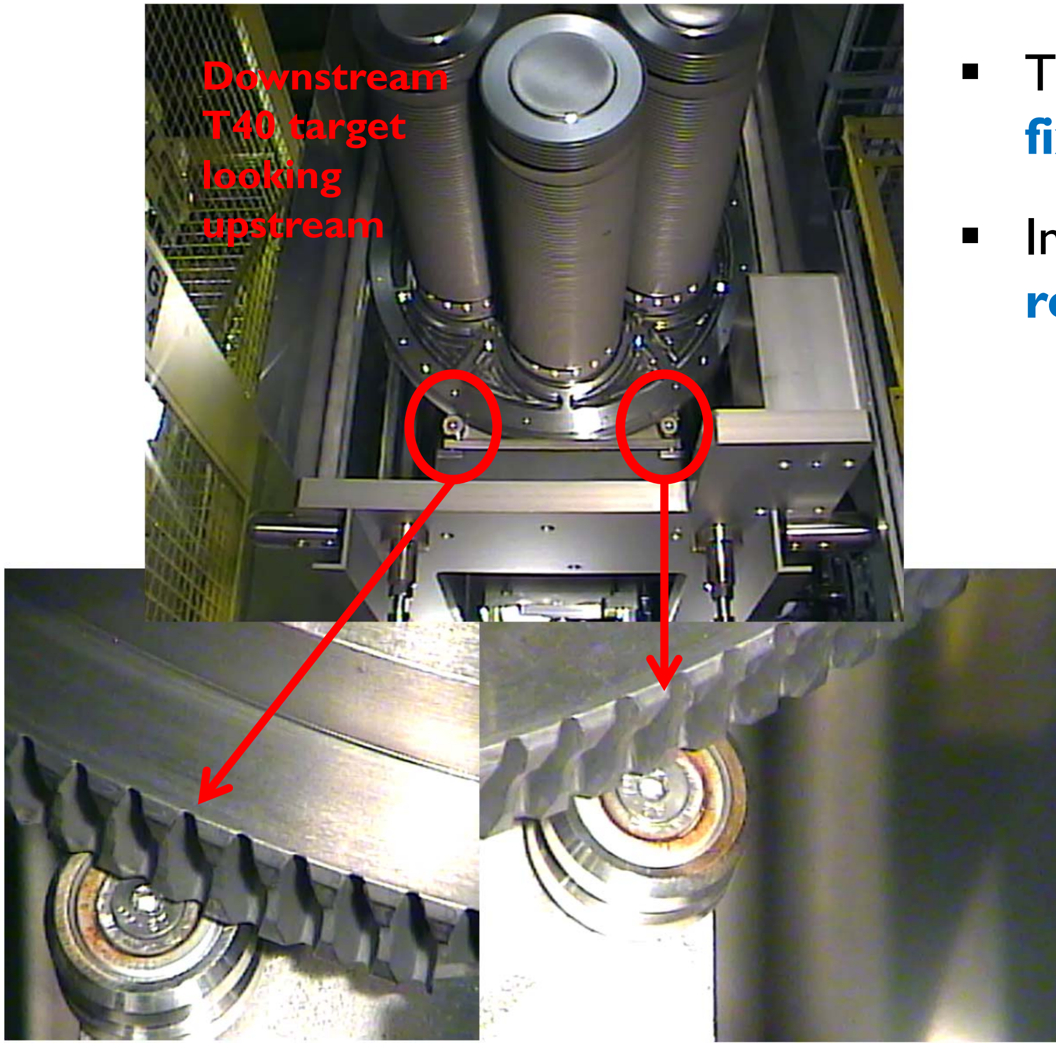
During inspection/maintenance in **March 2009** (**@1.94*$10^{19}$ POT**):

- Corrosion residues observed in the motorization elements (**expected**)
- **Increased torque in the magazine rotation motor (not expected!)**

**A thorough target inspection has been performed in April 2009**



# Target in-situ inspection – April 2009




- The target has been **removed from the fixed shielding**
- Investigation of the rotating magazine via **remote-controlled webcam-endoscopy**

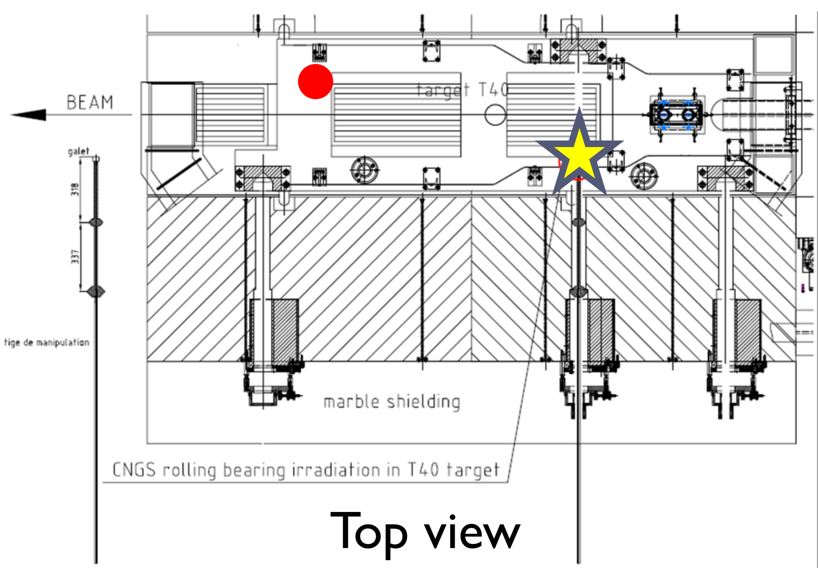
- All the ball-bearings for target rotations have sign of **rust**
- 3 moves (with difficulties) when the barrel moves
- 1 (downstream) **does not move at all**
- **In-situ measured torque of ~30 N*m vs. a design value of 8 N*m**

# Ball bearings irradiation in the CNGS target

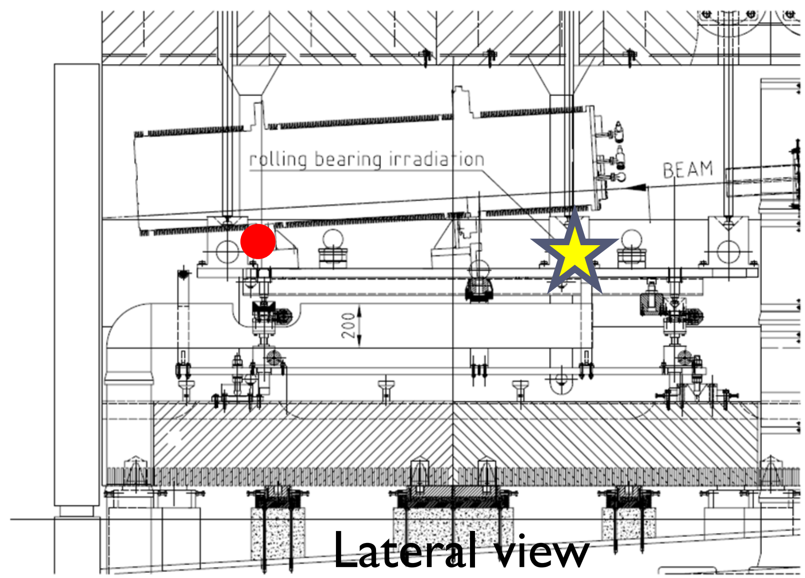
Material for the original bearings:
→ Martensitic SS **440C** (inner & outer races)
→ Martensitic SS **X46Cr13** (balls)
→ Lubricant (YVAC3) and anti-dust cage used

New bearings ordered in 2009 from the original manufacturer **without lubricant** and **anti-dust cage**

→ Installed in CNGS in **July 2009** for **irradiation** on a specially designed bar

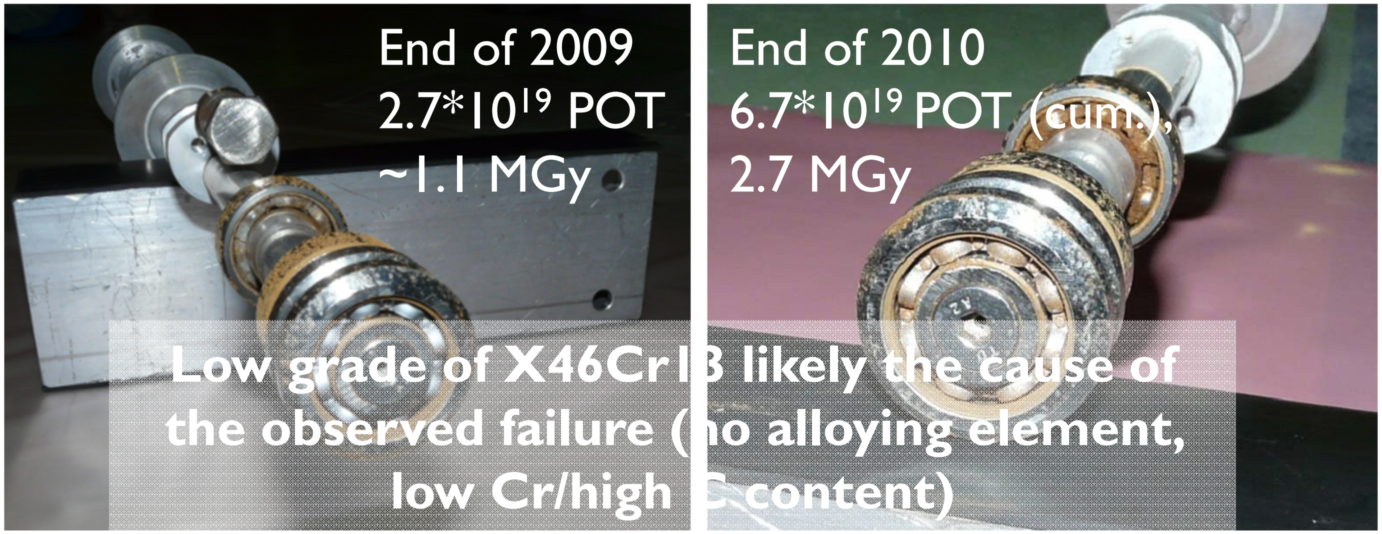


Top view



Lateral view

# 2010/2011 observations




**Observations:**

- Significant **rust/pitting corrosion** present in both cases ???
- Very difficult to turn the bearings, **>>10 N*m estimated**

**Next steps:**

- Spare target with different ball bearings:
  - Complete **ceramic type** – $Si_3Ni_4$ or $ZrO_2$
  - "Hybrid", with ring in Cronidur 30/Alacrite 554 and spheres in $Si_3Ni_4$.
- **Testing of these bearings in CNGS** (>June 2011)

If a **target failure** occurs:

- Move manually (dose …)
- Move with a motor

→ Risk of braking the coupling element

→ Exchange with spare target magazine

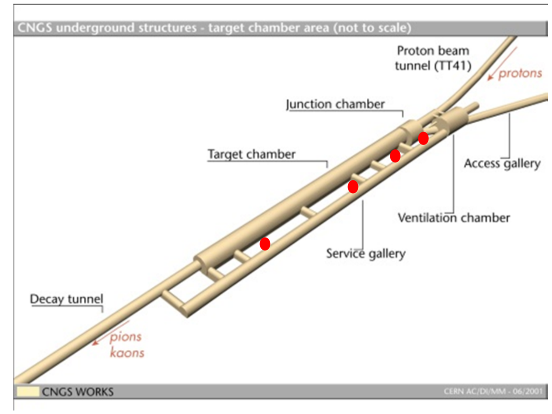
# Conclusions

- **CNGS is in operation since 2006**
  - It has received up to now $10.5*10^{19}$ POT, out of the approved $22.5*10^{19}$ POT, performing very well (no target exchange needed)
- The target design has drawn experience form past CERN fixed targets, with **increased challenges due to the high proton beam power** (510 kW → 1.5 MW possible)
- Operational issues encountered in operations are similar to those observed at other high power neutrino facilities
- An **upgrade of the spare target will be performed** to prepare for a possible target failure

**Thanks a lot for your attention!**

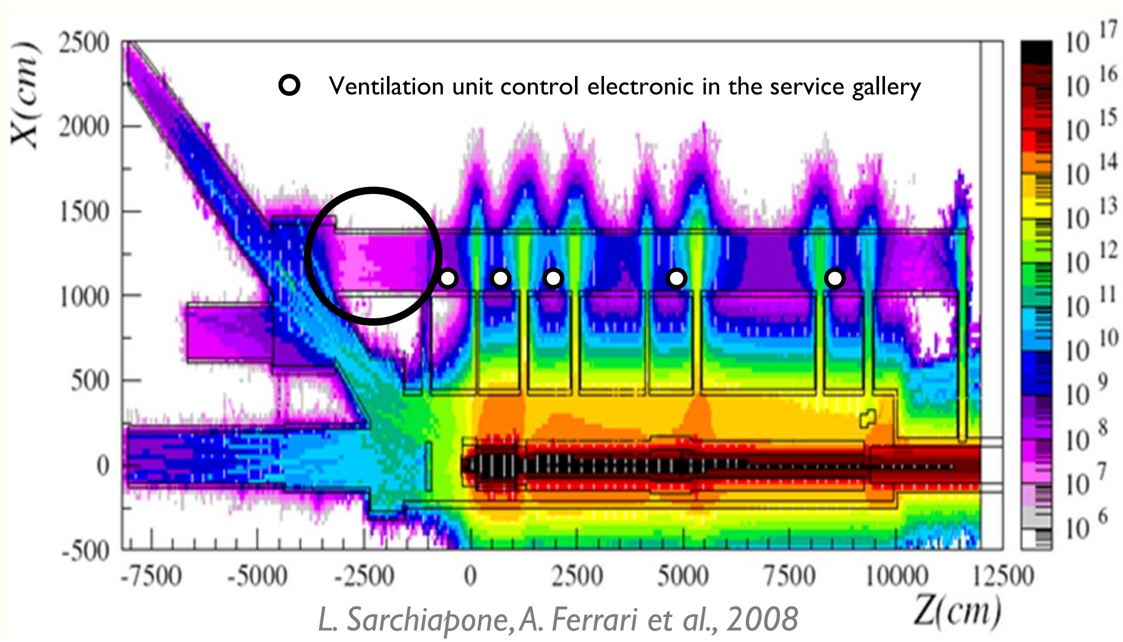
# Radiation on electronics issue (1/2)

CNGS installation is deep underground (~60 m below surface level) → no surface building above CNGS target area
→ A large fraction of electronic is located in the tunnel area




During CNGS run in **2007** (after **$7.9*10^{17}$ pot**)

- Failure of ventilation system installed in the CNGS tunnel area due to radiation effects in the control electronics (COTS) (**SEU due to high energy hadron fluence**)




L. Sarchiapone, A. Ferrari et al., 2008

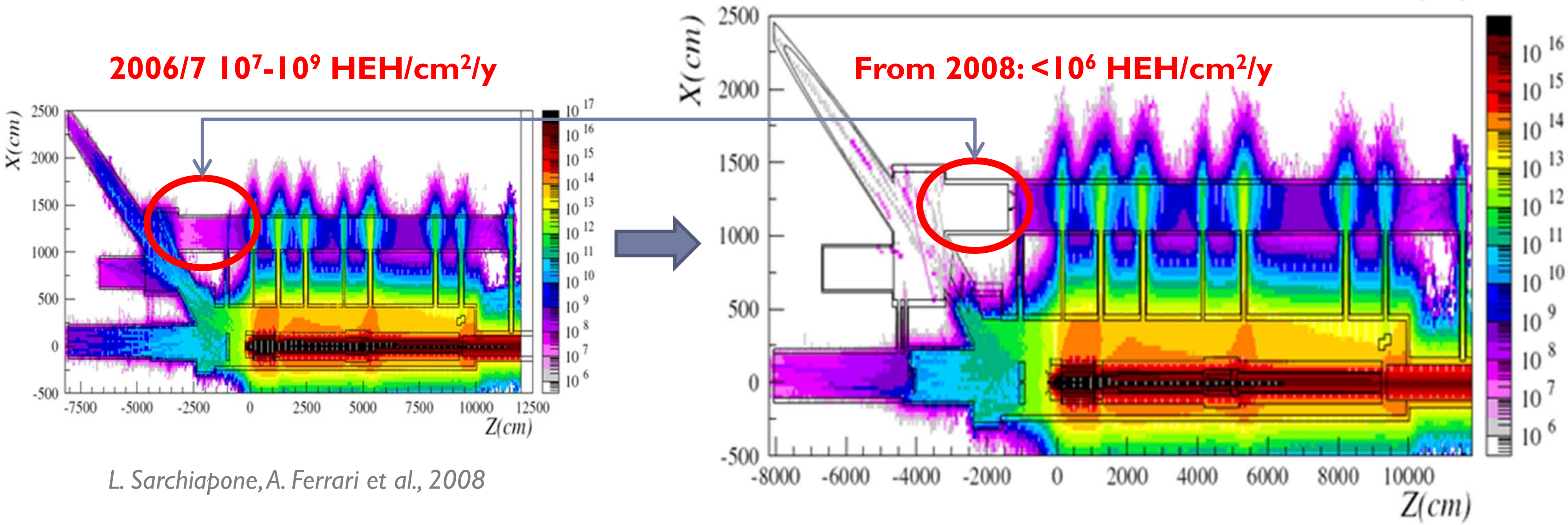
*High-E (>20 MeV) hadron fluence for a nominal year ($10^7$-$10^9$ HEH/cm$^2$/y)*

**Operation stopped when a fluence of only $1\text{-}5*10^7$ cm$^{-2}$ was reached**

# Radiation on electronics issue (2/2)

<u>Modifications during **2007/2008 shutdown**</u>

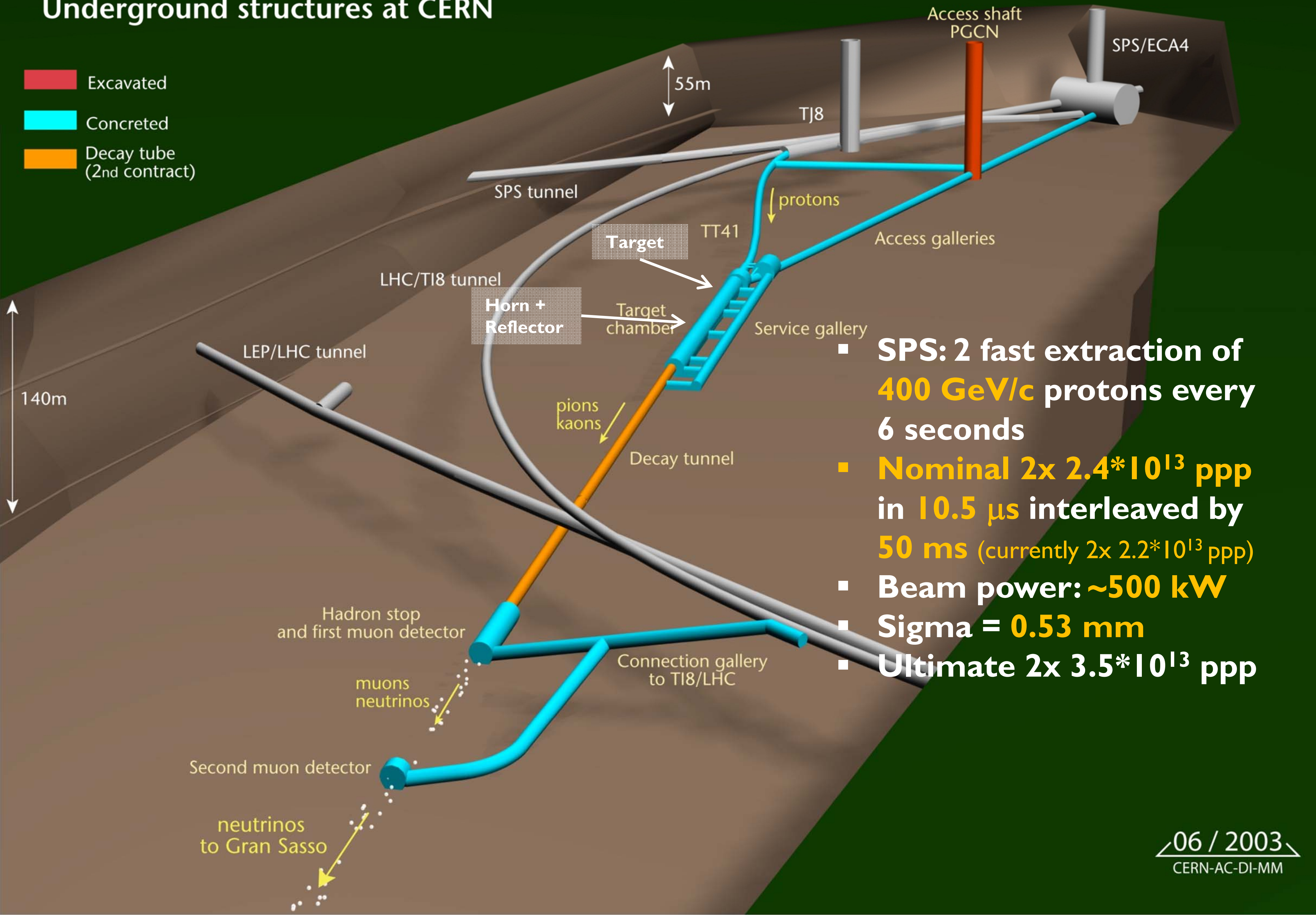
- Move as much electronics as possible **out of the CNGS tunnel area**
- Create **radiation safe area** for electronics which needs to stay in the CNGS areas → massive shielding (movable plugs + chicane) added!




*L. Sarchiapone, A. Ferrari et al., 2008*

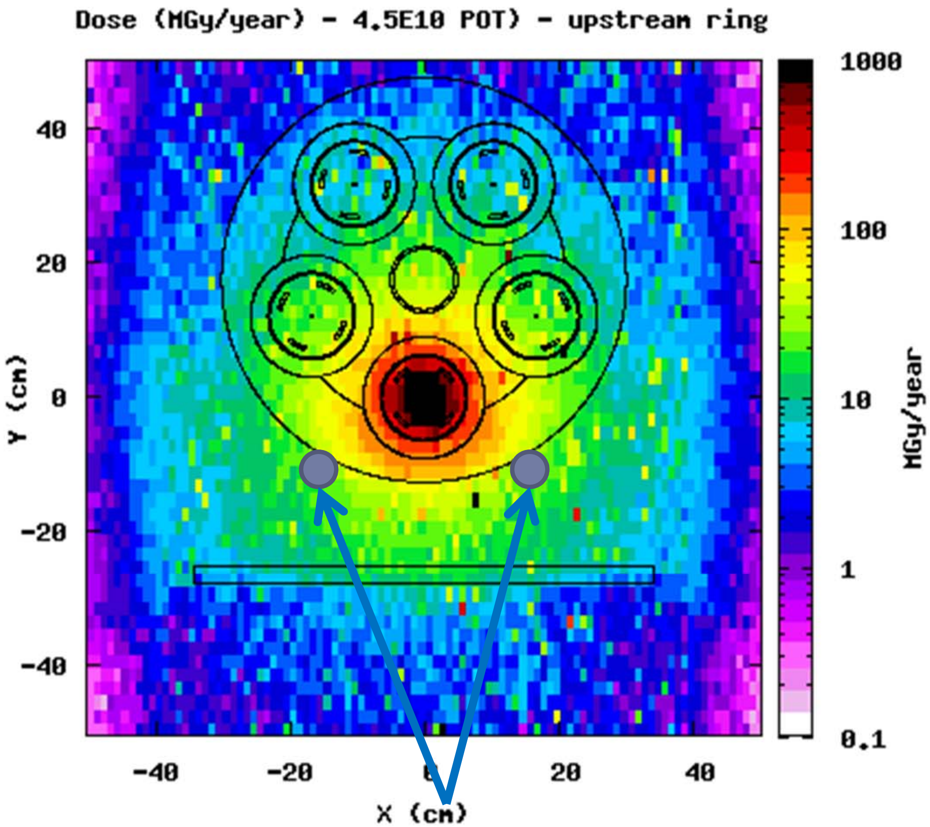
Accumulated dose not a problem for operation → **$HEH/n_{th}$ effects on COTS electronics are a problem to be addresses since the beginning in the design of high power hadron machines!**

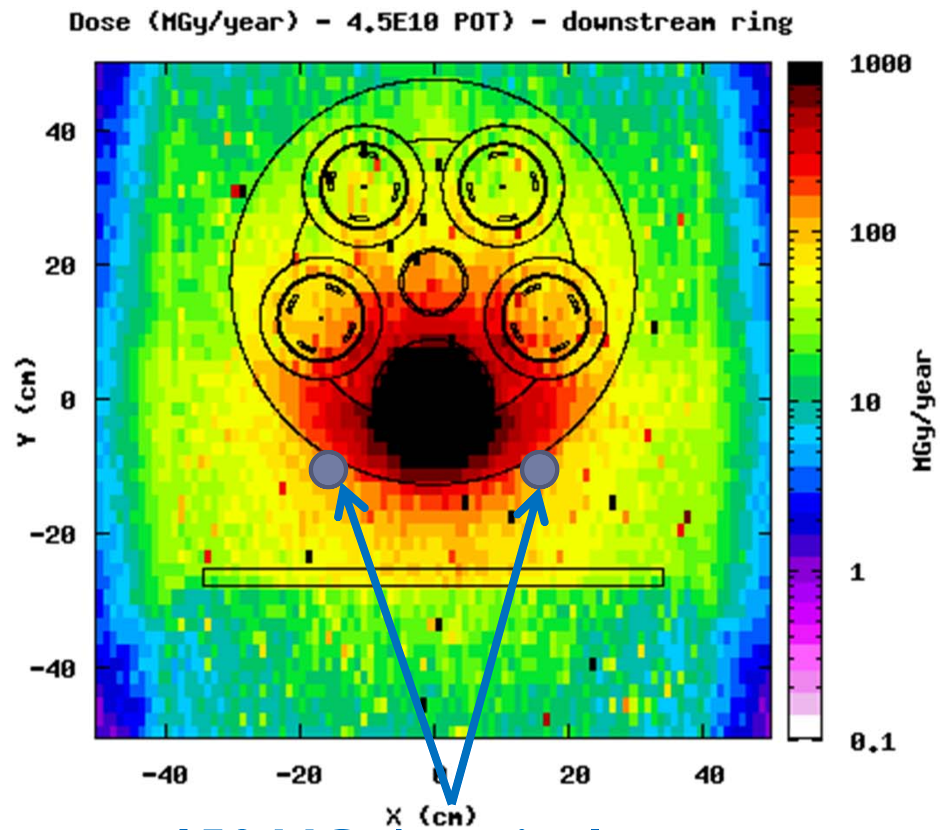
# CERN NEUTRINOS TO GRAN SASSO
## Underground structures at CERN




- SPS: 2 fast extraction of 400 GeV/c protons every 6 seconds
- Nominal 2x $2.4*10^{13}$ ppp in 10.5 μs interleaved by 50 ms (currently 2x $2.2*10^{13}$ ppp)
- Beam power: ~500 kW
- Sigma = 0.53 mm
- Ultimate 2x $3.5*10^{13}$ ppp

# FLUKA - accumulated yearly dose at target




**~20 MGy/nominal year**
(upstream bearing)

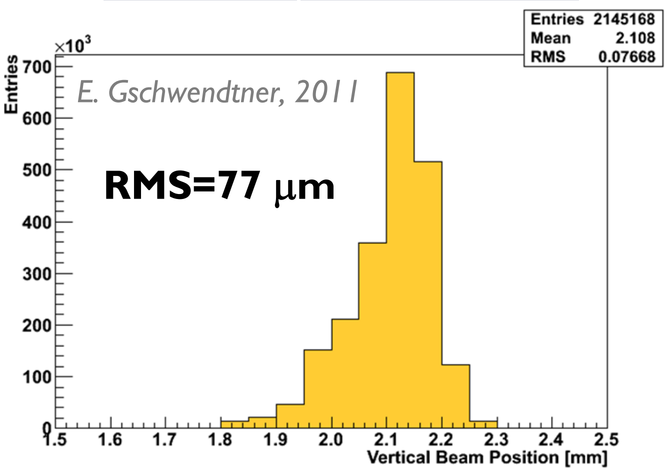
**~150 MGy/nominal year**
(downstream bearing)

- Failure of the bearings become evident at **~60 MGy** cumulated dose ($1.94*10^{19}$ pot)
- Test bearings are in a zone where the radiation is **~2 MGy/nominal year**

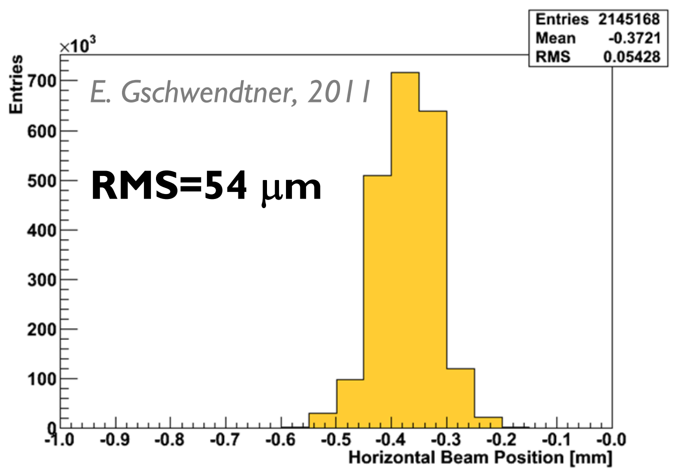
# CNGS POT

| Year | POT/yr |
|---|---|
| 2006 | $0.08*10^{19}$ |
| 2007 | $0.08*10^{19}$ |
| 2008 | $1.78*10^{19}$ |
| 2009 | $3.52*10^{19}$ |
| 2010 | $4.04*10^{19}$ |
| 2011… | $\sim 1*10^{19}$ |
| **Total** | **$10.5*10^{19}$** |

- Nominal CNGS working point = $4.5*10^{19}$ POT/y
- Received **$10.5*10^{19}$** up to now
- **CNGS approved for $22.5*10^{19}$ POT**
- Before the CERN 1st LS (2013/14) CNGS would have accumulated **$\sim 18.9*10^{19}$ POT**
- Operation after this date will be addressed in 2012




Vertical beam position [mm]




Horizontal beam position [mm]

**Beam on target position stability** over the entire run (H/V)
→ in agreement with the **requirements of the design study** (stresses on the target)

# Physics requirement of the CNGS target

**Physics requirement** from the CNGS target:

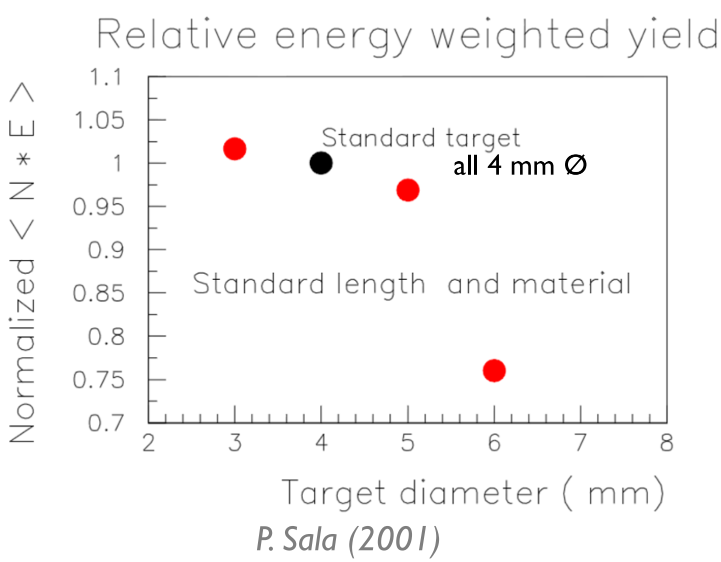
1. Provide the **highest possible proton interactions**
2. Decrease at the same time **probabilities of secondaries reinteraction**:

→ For HE ν beams the target needs to be **segmented**, in order to allow small-angle high momentum secondaries to escape the target with less path length

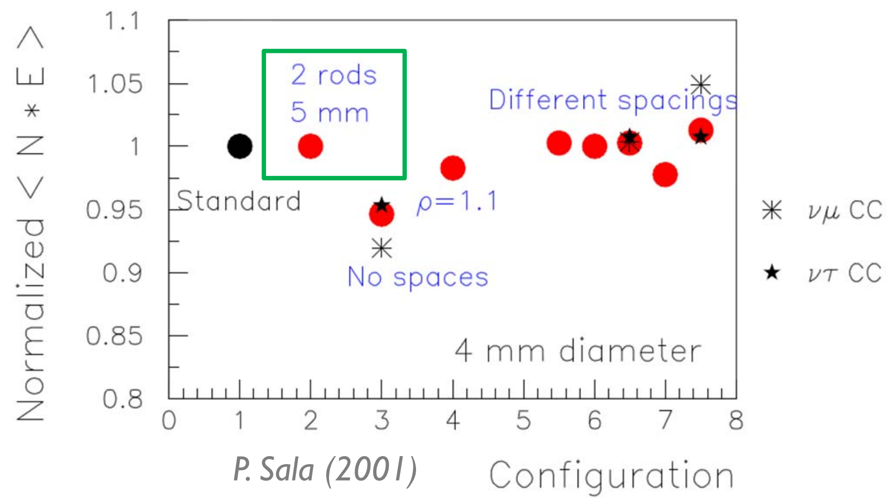
## Physics optimization of the CNGS target

Overall length 2m, C length 1.261m "standard target in these figures"

### Effect of **target size** (on π yield)




### Effect of **target configuration** (on π yield)



# General design constrains – CNGS target

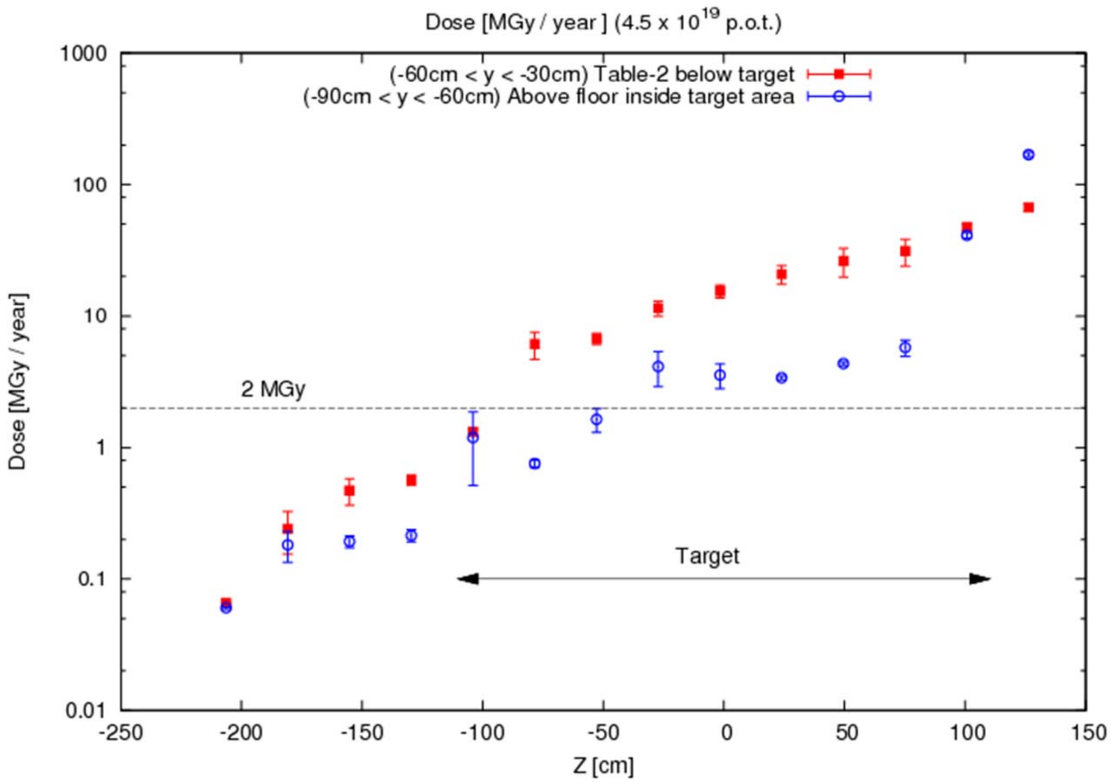
I. Target rods **segmented** and **thin** to maximize pion production and reduce secondaries reinteraction
II. Target need to be **robust to resist beam-induced stresses**
III. Due to particle energy deposition the target must be **cooled**

*With the following technological constraints:*

- The target **should not be cooled by water**, in order to avoid mechanical shocks and increases activation/radioprotection issues
- Material choices should **minimize the absorbed beam power** and **maximize radiation resistance**
- Target should be **replaceable**, with in-situ spares
- The target station should allow remote handling by a crane
- The target station should allow remote calibration of the alignment table

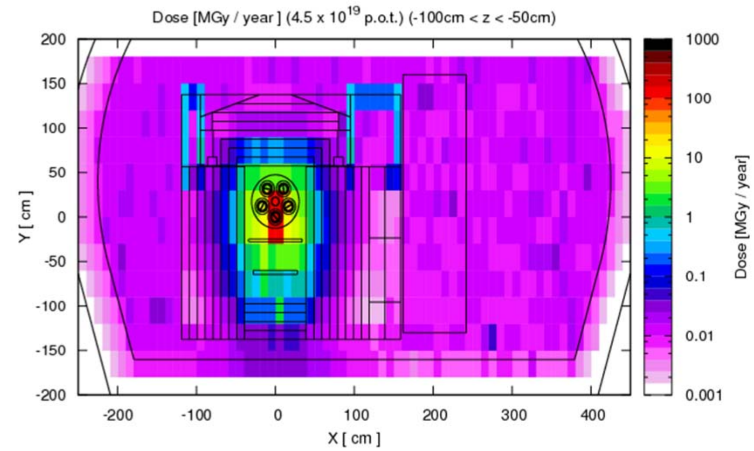
*L. Bruno*

# Yearly accumulated dose – CNGS target

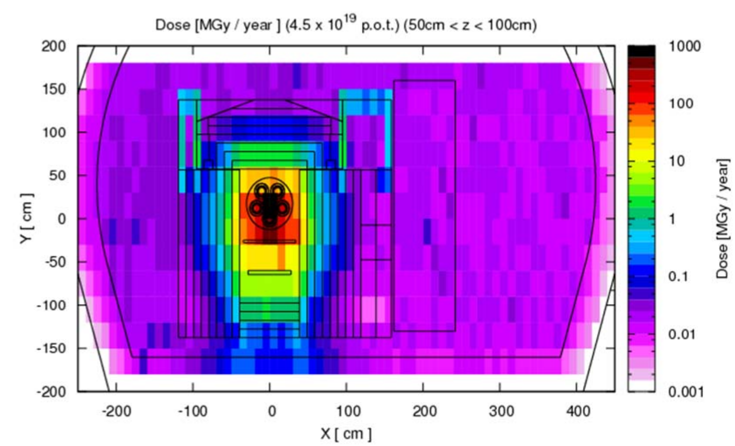



Dose below target along the beam direction

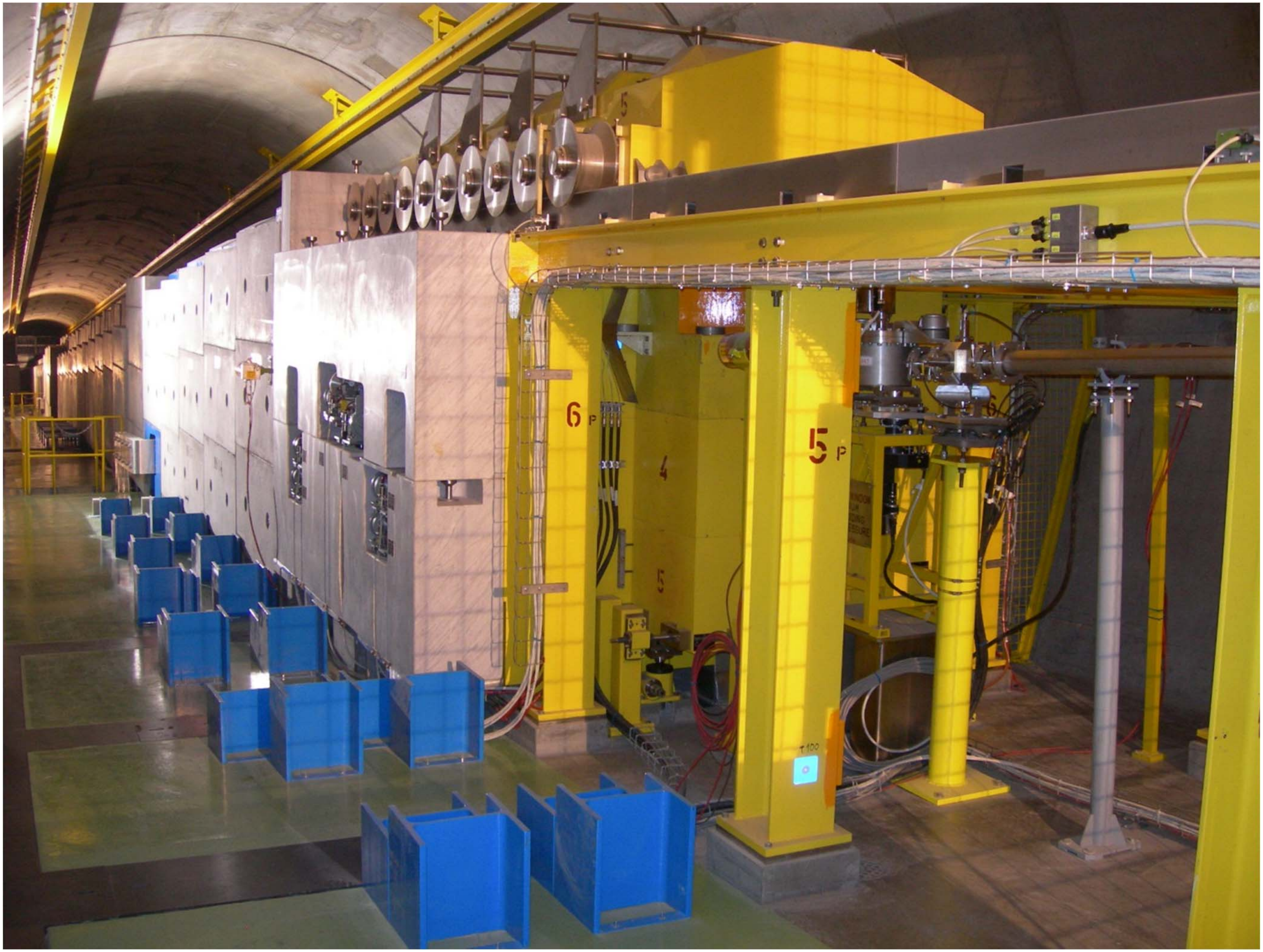
Transversal cut, beginning of target



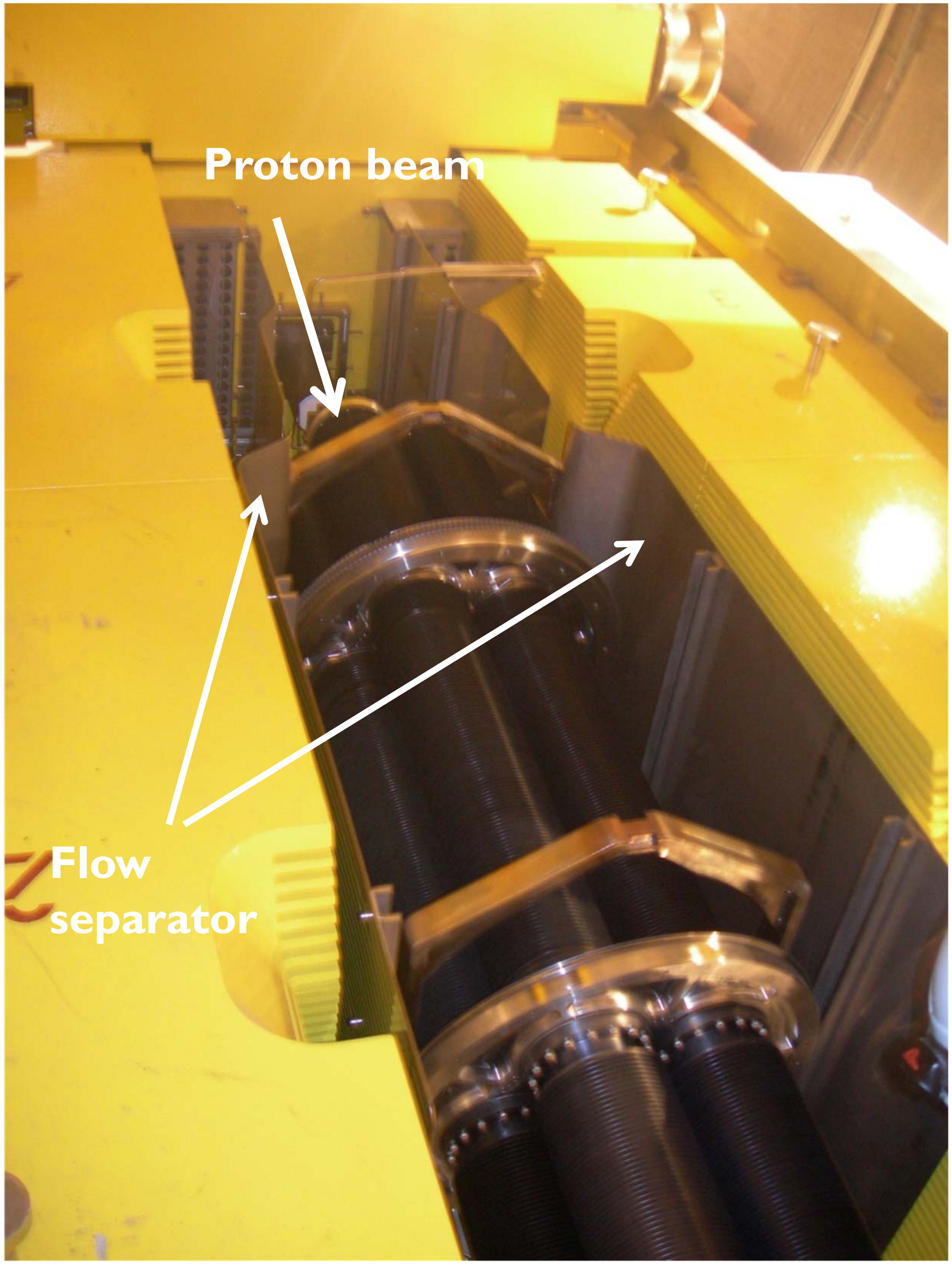

Transversal cut, end of target

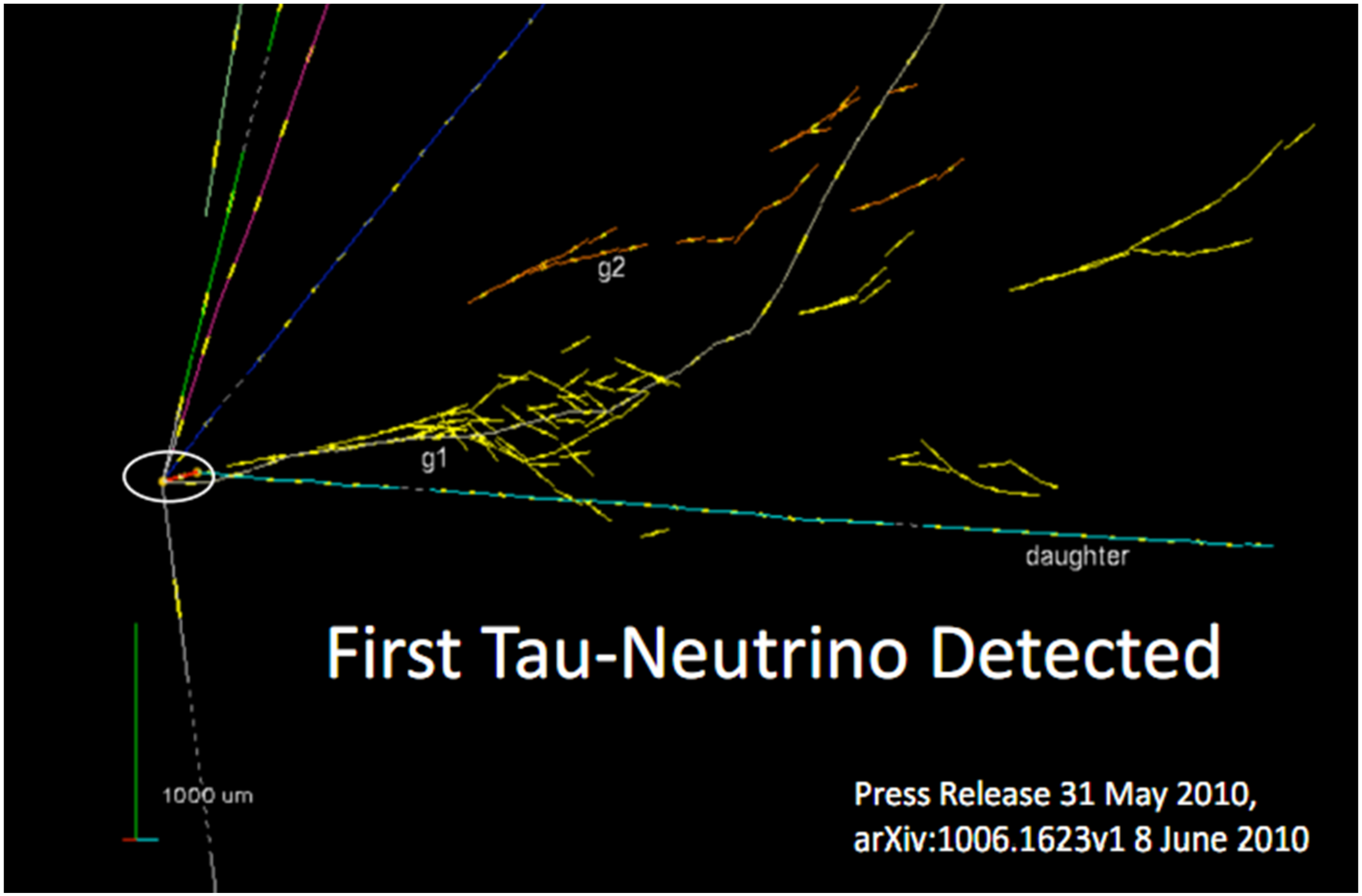


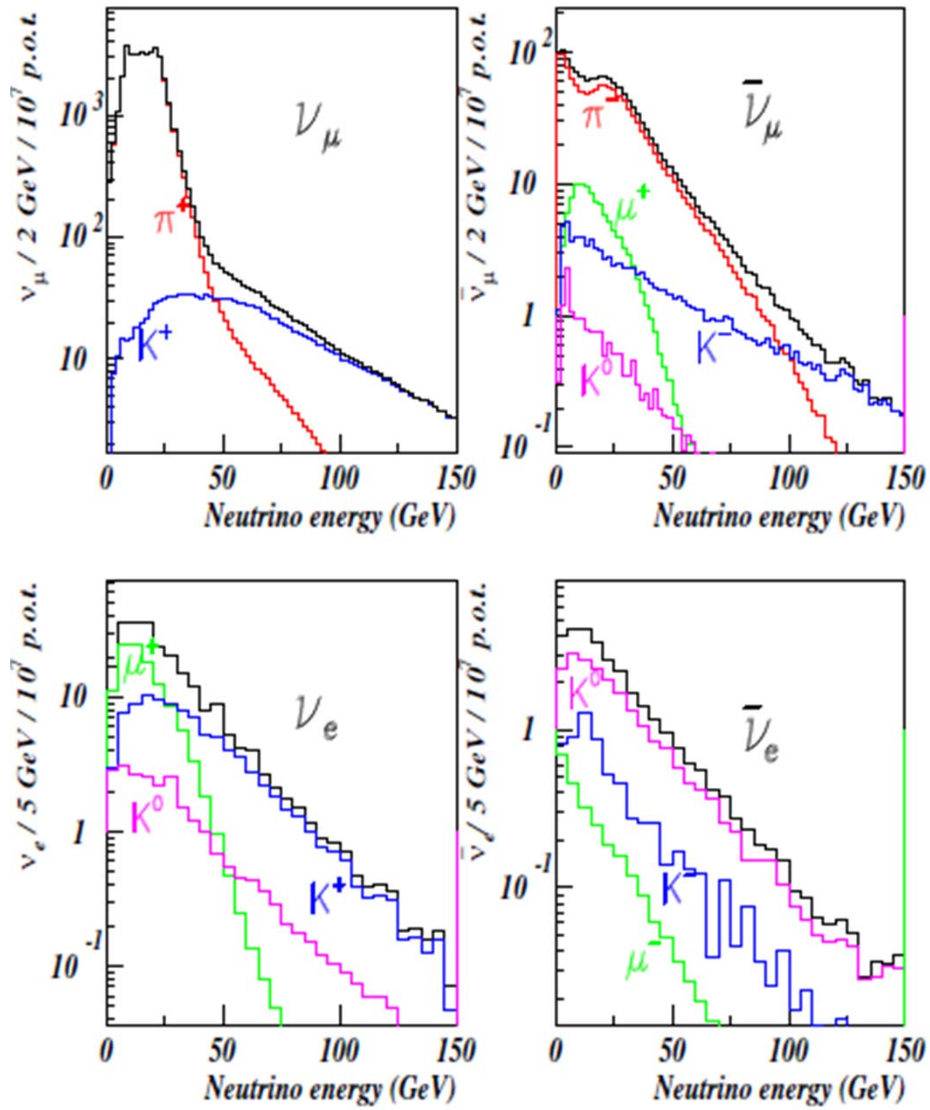

*K. Roeed, 2011*


6 P
5 P
4
5


hBN
collimator
Air inlet


Proton beam
Flow separator


g2
g1
daughter
First Tau-Neutrino Detected
1000 um
Press Release 31 May 2010,
arXiv:1006.1623v1 8 June 2010



$\nu_\mu$ / 2 GeV / $10^7$ p.o.t.
$\nu_\mu$
$\pi^+$
$K^+$
$\bar{\nu}_\mu$ / 2 GeV / $10^7$ p.o.t.
$\bar{\nu}_\mu$
$\pi^-$
$\mu^+$
$K^-$
$K^0$
$\nu_e$ / 5 GeV / $10^7$ p.o.t.
$\nu_e$
$\mu^+$
$K^0$
$K^+$
$\bar{\nu}_e$ / 5 GeV / $10^7$ p.o.t.
$\bar{\nu}_e$
$K^0$
$K^-$
$\mu^-$
Neutrino energy (GeV)