MAGNETIC HORNS

for CERN neutrino beams

from the sixties to 2003

J.M. Maugain EP/TA3

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1. INTRODUCTION

CNGS neutrino beam project is entirely in AB's hands
(NPA, TCL, EF, ECP, EP, →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.

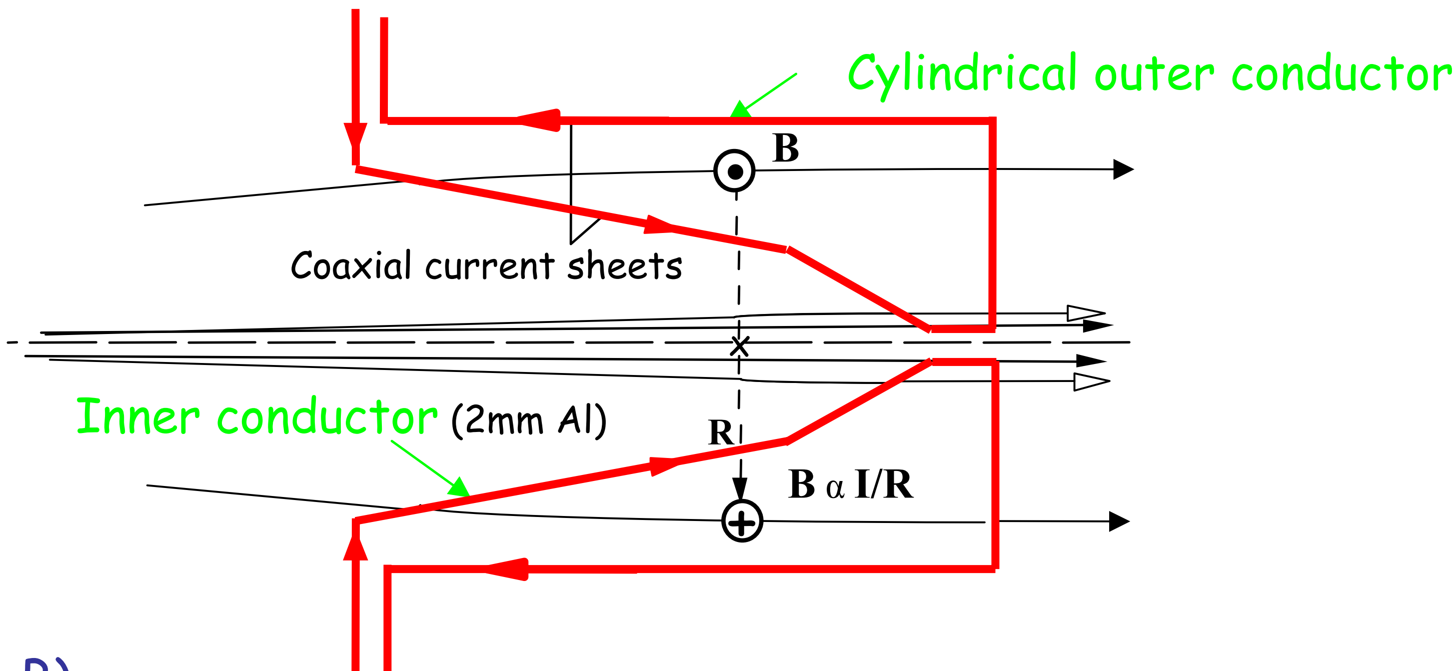
Invented in 1961 by S. Van der Meer for collection of charged particles emerging from a target. Used mainly for focusing

- Pion / kaon beams for neutrino generation
- Antiproton beams for p p^- storage rings


S. Van der Meer in 1961
MAGNETIC HORN

HORN FOCUSING PROPERTIES

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

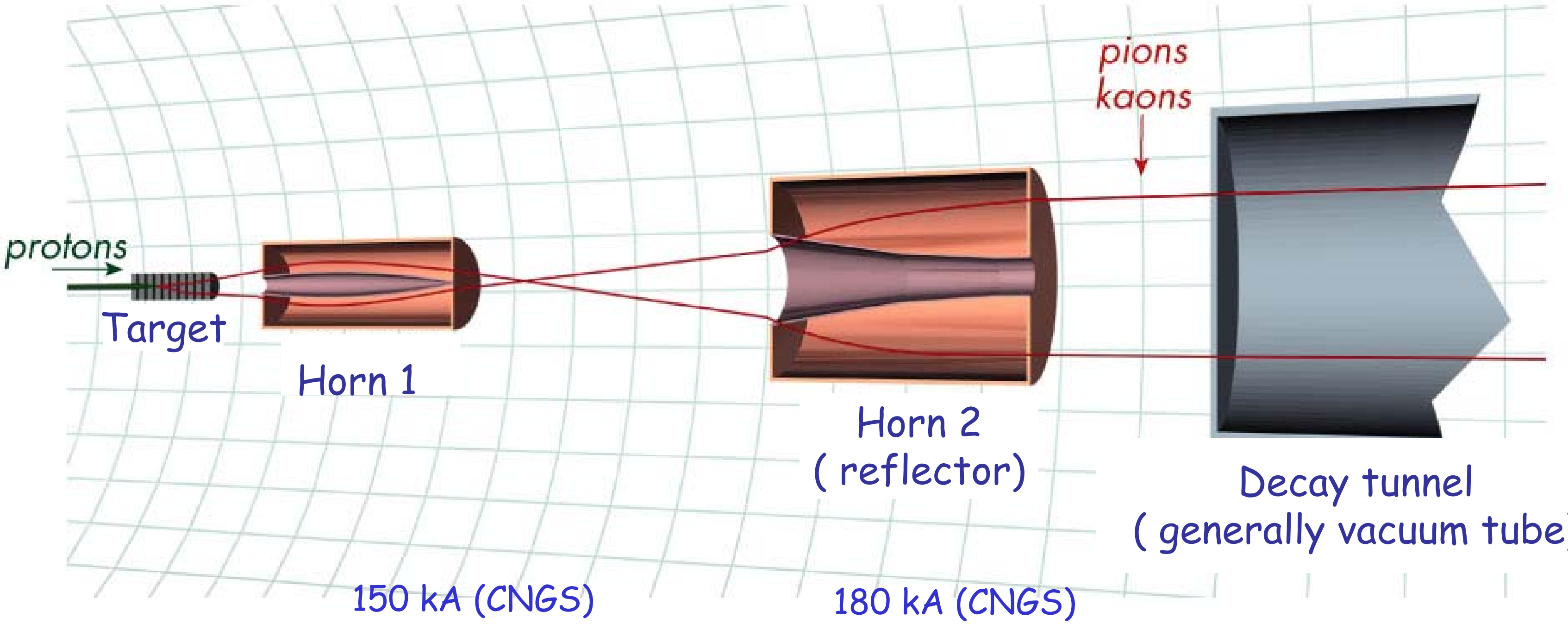


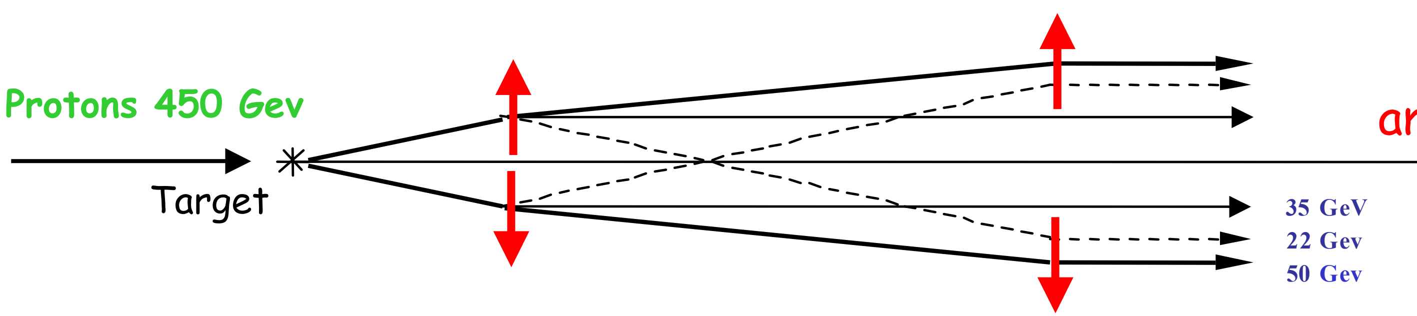
$F = q\,(v \wedge B)$

$B = \mu_0\, I / 2\,\pi\, R$

CNGS → I=150 kA, R =15.4 mm B = 1.95 Tesla

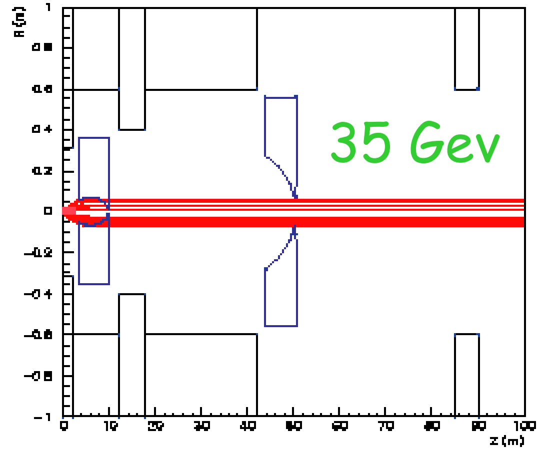
Usually 2 horns are needed to produce a parallel wide band beam where a much larger number of particles emerging at various energies and angles are collected.





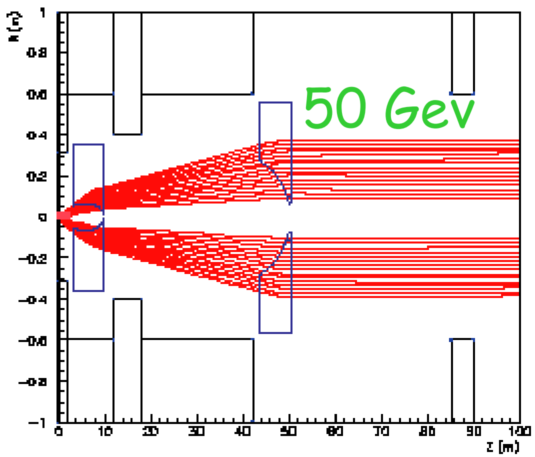
■ flux amplification factor in detector (> 10)

HORN/REFLECTOR – positive particle focusing of CNGS horn



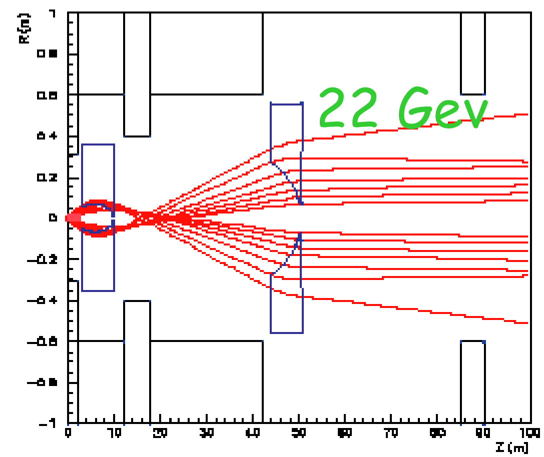
Reflector Focusing:
p = 50GeV
p_t = 180-780MeV
(horn under-focused)

Reflector Focusing:
p = 22GeV
p_t = 100-400MeV
(horn over-focused)

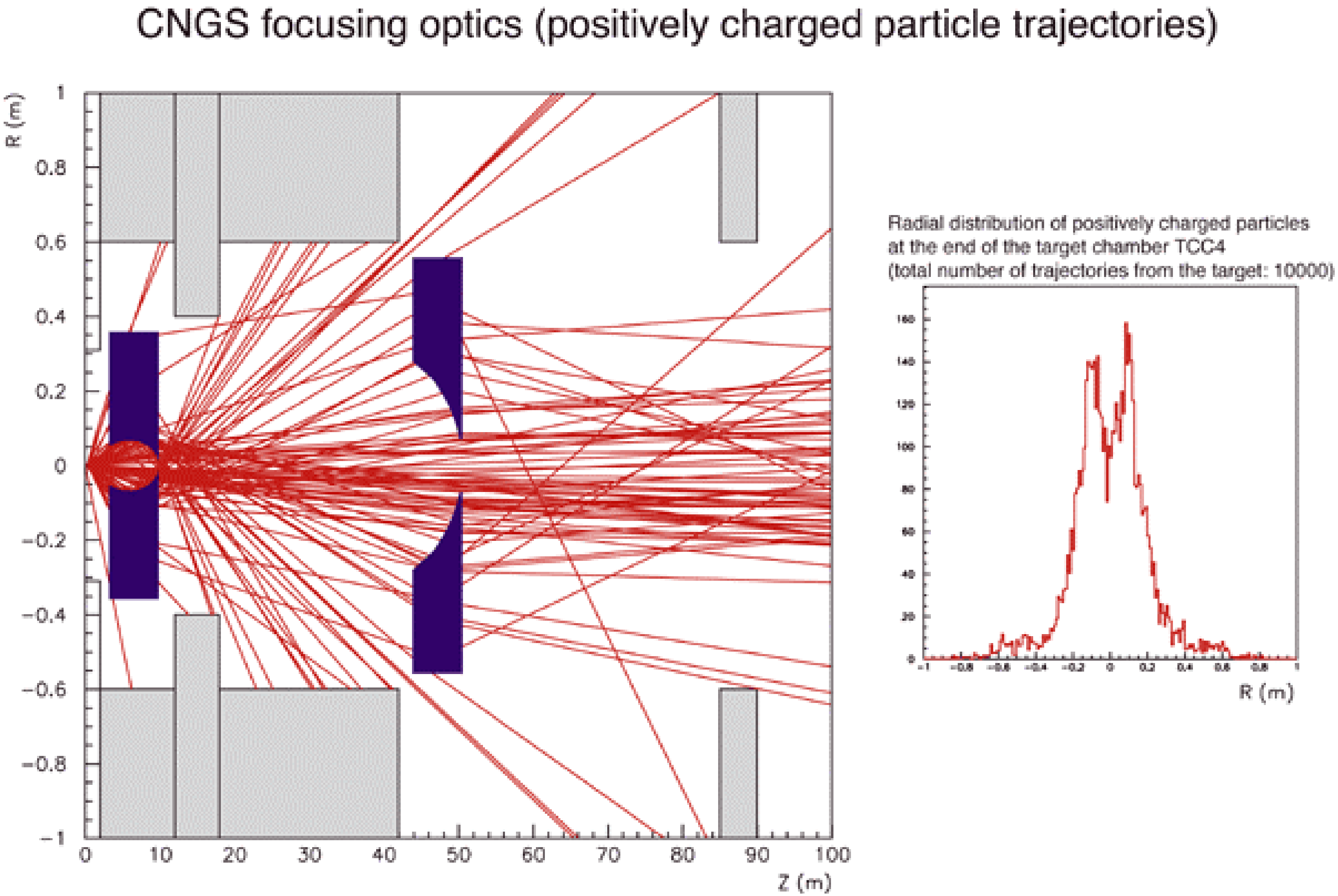


Horn Focusing:
p = 35GeV
p_t = 80-680MeV

Horn-target distance = 2.7m
Reflector-target dist.= 43m



F- Pietropaolo – INFN-Padova



Picture – CNGS web server

Horn function in neutrino beam production summarized

protons hit target (450 Gev in WANF & CNGS)

π^+ / K^+ produced in solid angle corresponding to acceptance

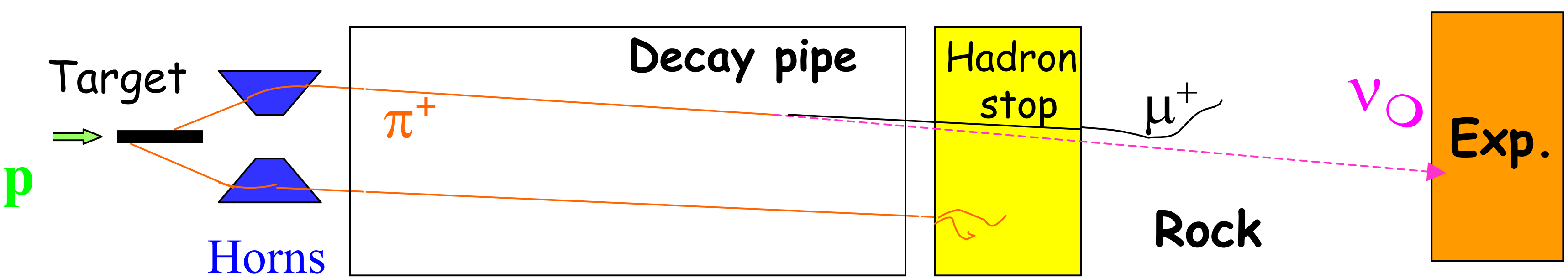
magnetic horns to focus π^+ / K^+

π^+ and K^+ decay to $\mu^+ + \nu_\mu$ in long evacuated pipe

left-over hadrons shower in hadron absorber

rock shield ranges out μ^+

ν_μ 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

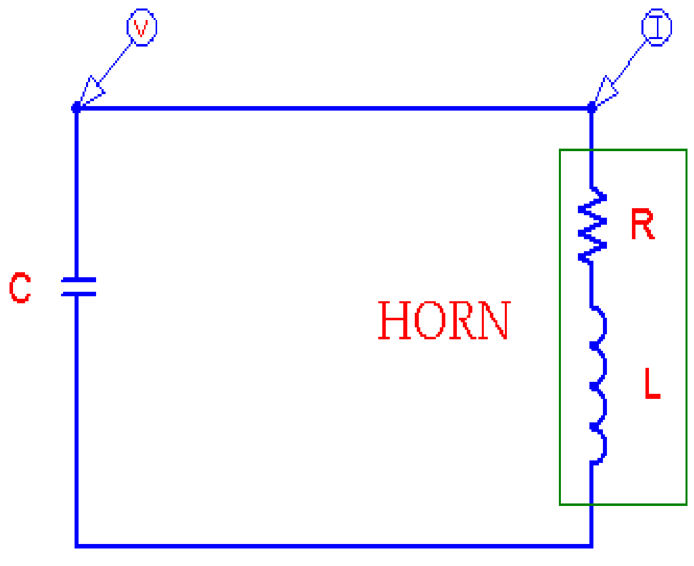
Nu_mu CC interactions (<100GeV) at LNGS (%)

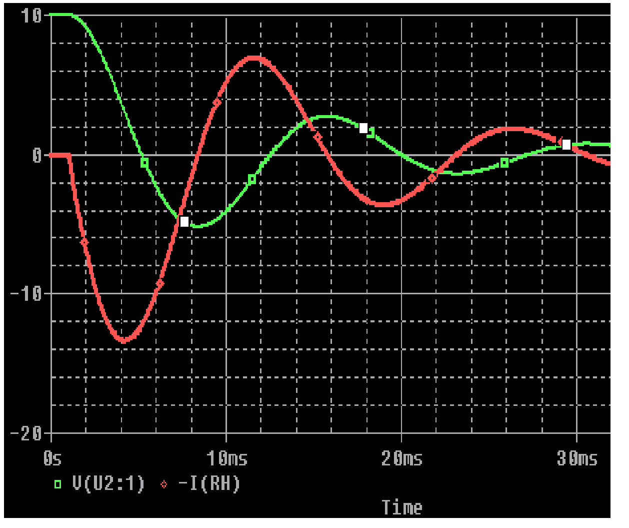
Horn_Refl. zero-current	**:**	**10%**
Reflector zero-current	**:**	**~ 50%**
Standard configuration	**:**	**100%**
Horn-Refl. half thickness	:	111%
Horn-Refl. zero thickness	**:**	**123%**
Perfect focusing	:	~ 200%

2.2 How is a horn powered?

Horn is a short circuit i.e. small inductance 0.1 to 3 μH and small resistance 100 to 1000 μΩ

Current is produced by discharge of a capacitor bank into horn in resonant mode (resonant L C R circuit)

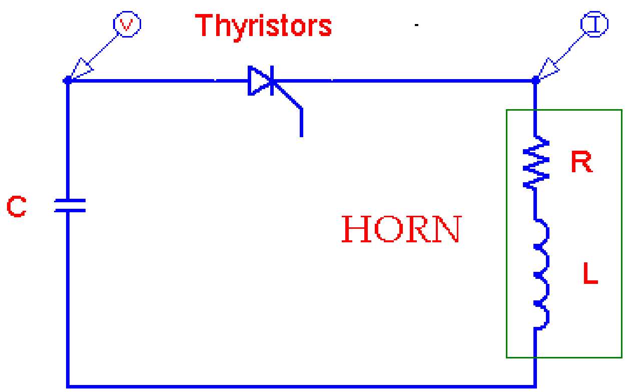


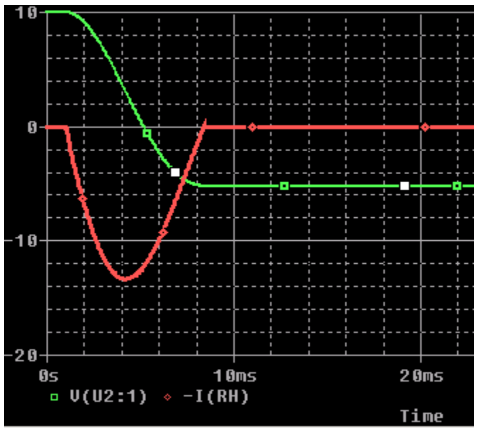


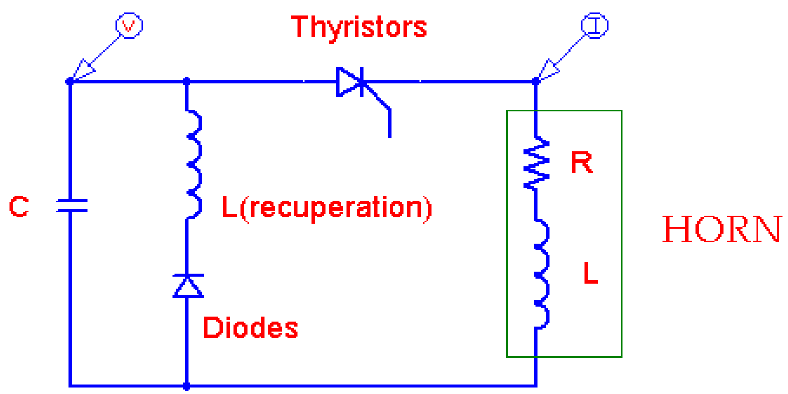
High currents → pulsed mode

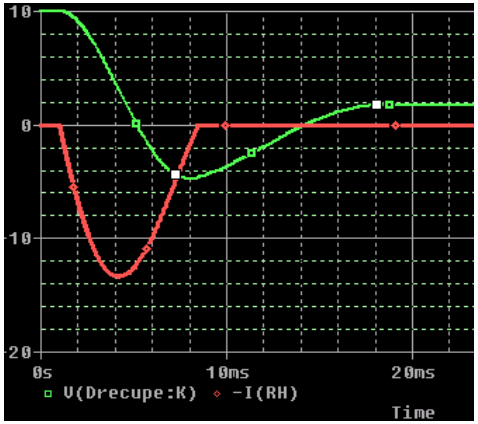
(reduced heating and power consumption)

Pulse length can vary from the 10μs range up to the 10ms range. $T/2 \cong \pi\,(L\,C)^{1/2}$

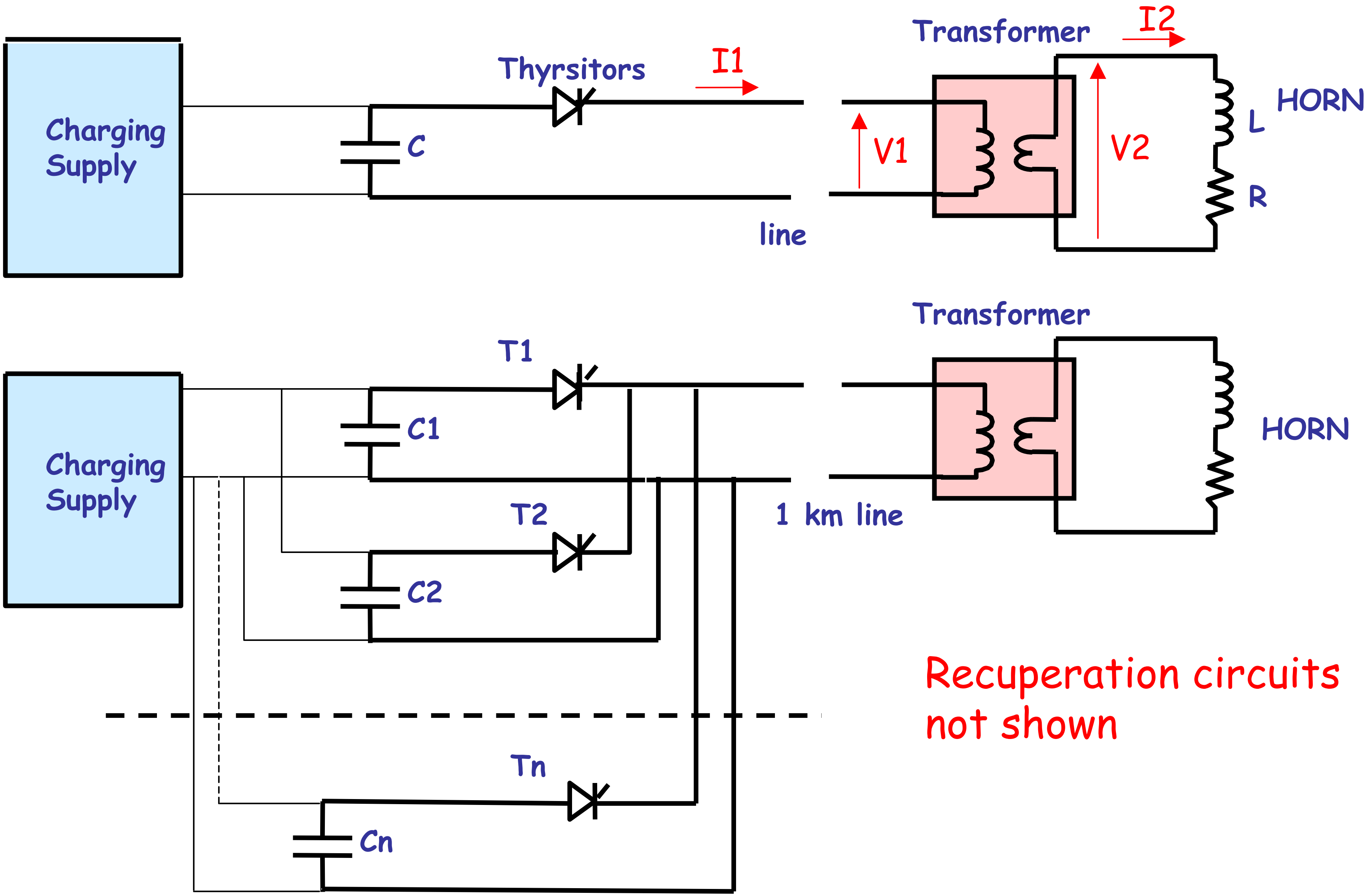








Typical horn capacitor discharge circuits



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)

$$V2 = V1/m$$

Simplifies also the thyristor switch

(since $I1 = I2/m$)

Disadvantage :

- pulse length is longer by factor m

  $T/2 \cong m \, \pi \, (L \, C)^{1/2}$
- 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

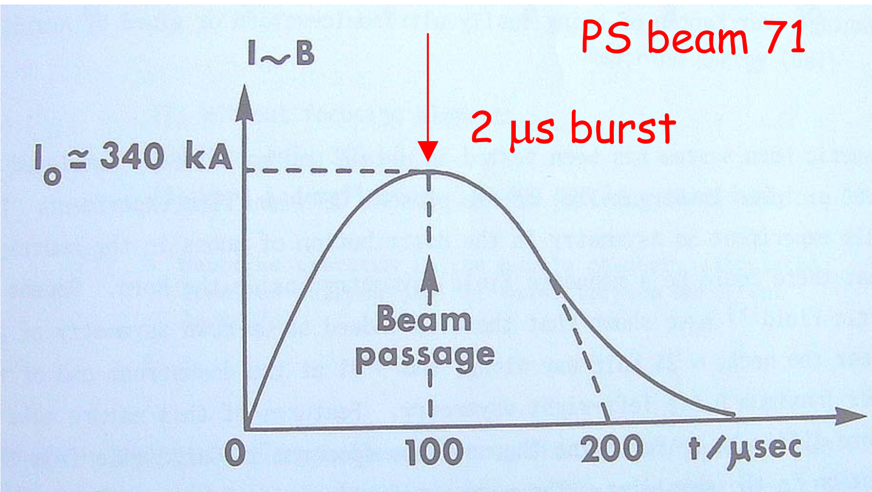
Ex. LV horns : -low voltage capacitors without transformer
ex. : NUMI at Fermi lab

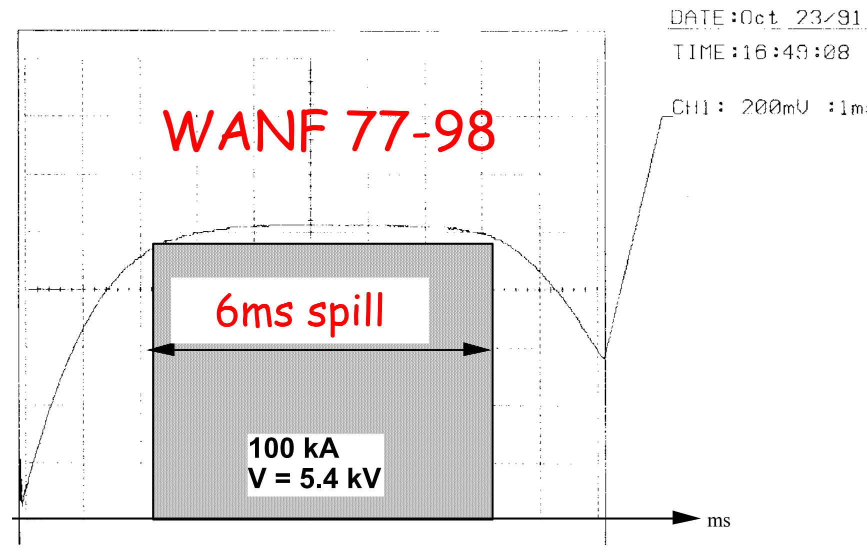
-high voltage capacitors with transformer
ex. : WANF, CNGS, KEK

If heating is critical, short pulse lengths are compulsary.
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





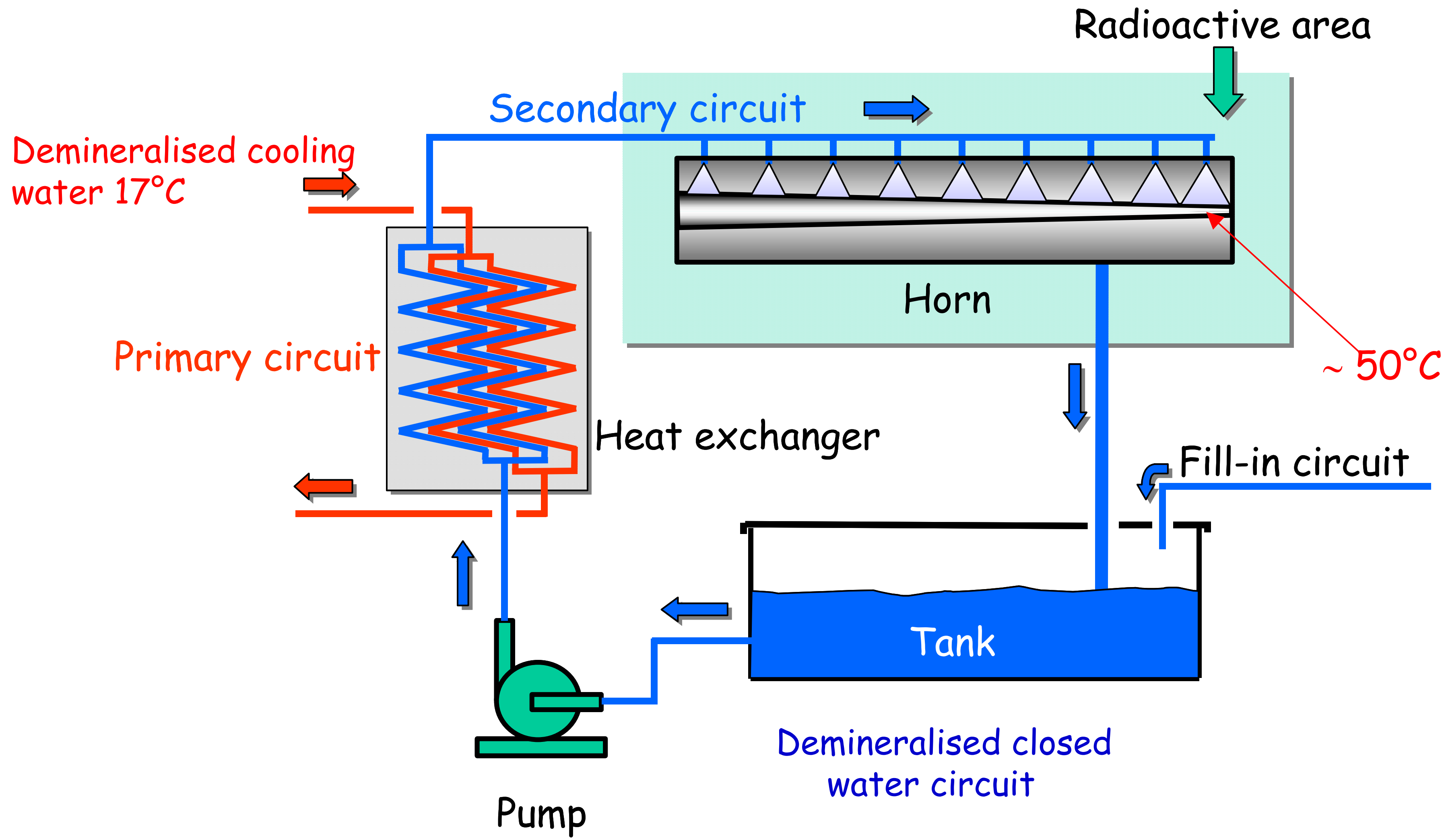
Measured horn current

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

CNGS HORN

2.5. Cooling

Secondary circuit is vapor tight



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, δ= 1.6 mm for 2500Hz i.e. 200 μs pulse)

Mechanics

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

- Magnetic forces are cyclic $p = (\mu_0 I^2 / 8 \pi^2 R^2)(1 - \tau/6)$
  $\tau = t/R$ with t=wall thikness

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

→ Repetition rate must not hit a natural frequency of horn system

Calculations are made using ANSYS

→ static FE analysis to estimate thermal stresses

→ modal analysis to estimate natural frequencies

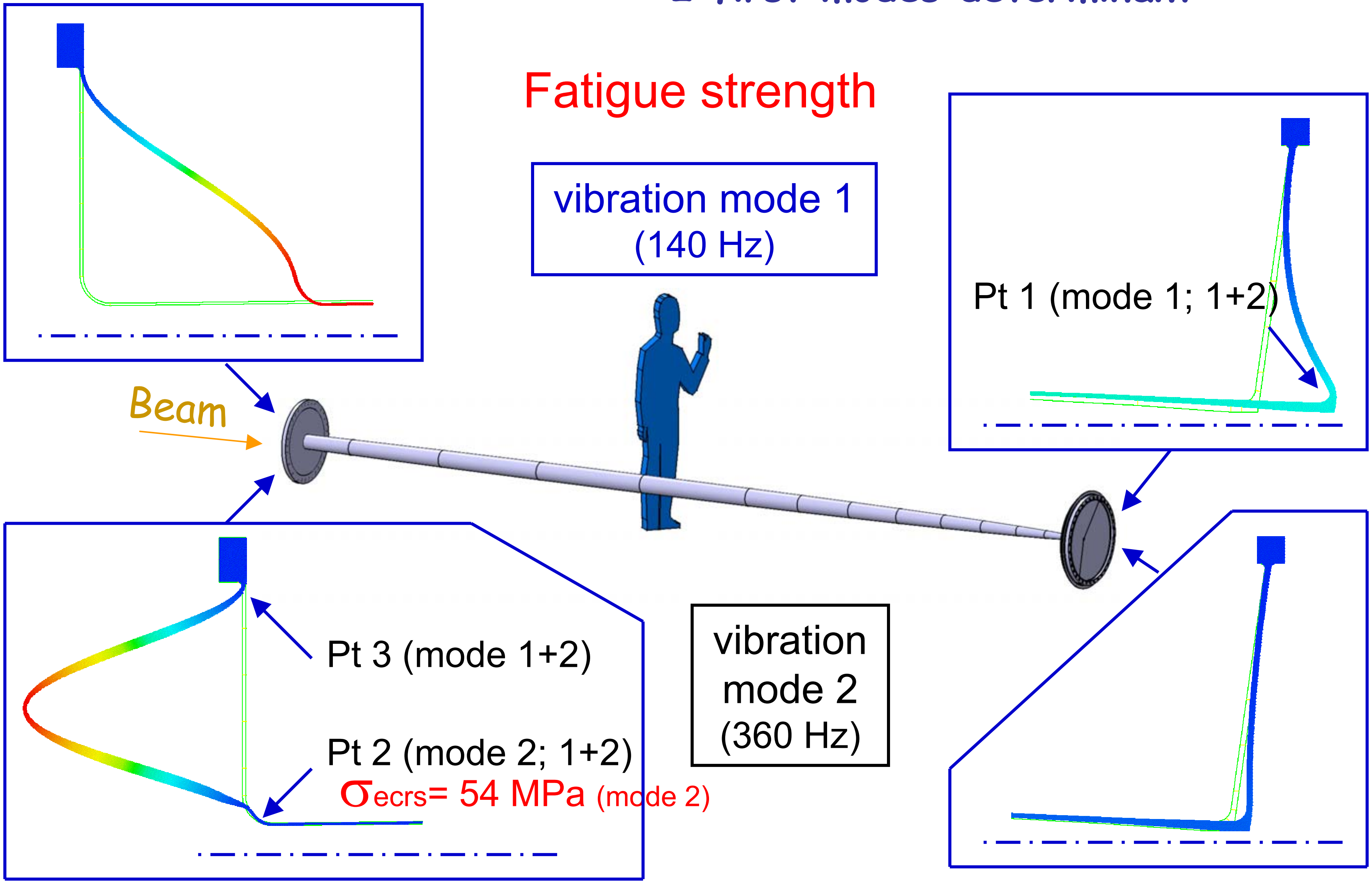
→ ANSYS FE dynamic stress calculations

→ fatigue analysis (evaluation of maximum equivalent completely reversed stress σ_{ecrs})

→ measurements on BA7 test circuit of natural frequencies and displacements due to vibrations

LAL-Orsay- S. Wallon
CERN-EST-ME – Marek Kozien et al.

CNGS HORN INNER CONDUCTOR – 2 first modes determinant



CNGS HORN

Fatigue strength

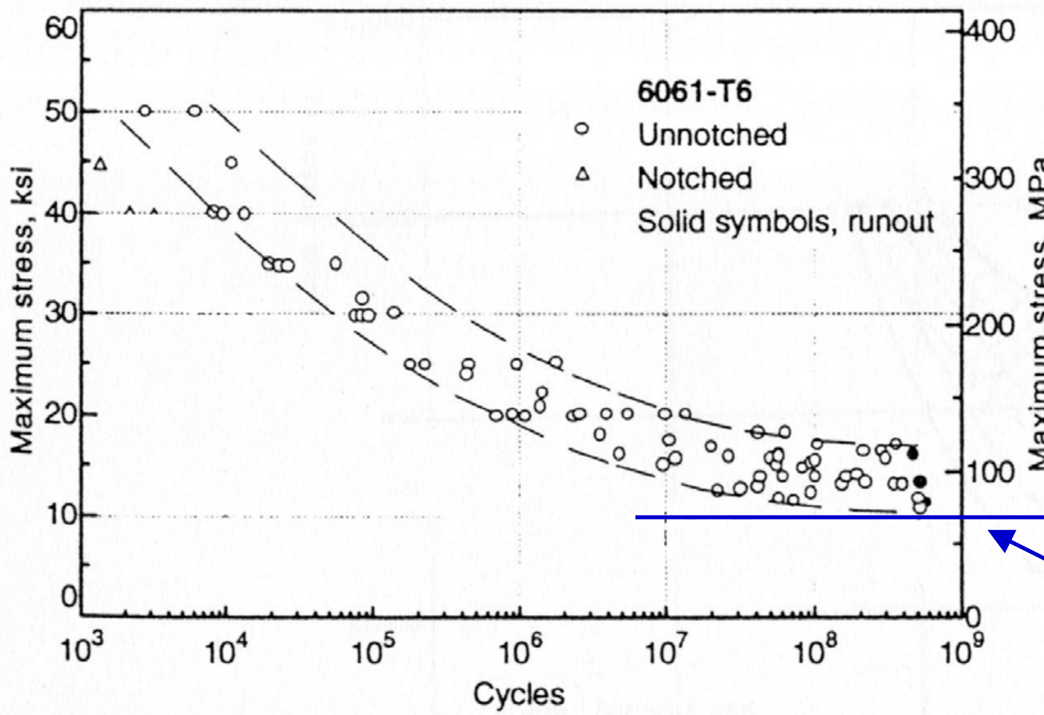


Fig. 70 6061-T6 notched (radius at notch root <0.001 in.) and unnotched rotating beam fatigue at room temperature. Solid symbols indicate runout (no failure). Longitudinal and transverse specimens from extruded bar (5/8 x3.5 in.), rolled-and-drawn rod (0.75 in.), and rolled plate (1.25 in. thick). R.R. 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

we are below this limit

Mechanical studies and measurements

↓

HORN 150 kA

REFLECTOR 180 kA

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

→ cyclic heat effect dilatation

→cooling sprayed water along inner conductor

Cyclic magnetic forces → cyclic mechanical strain

→ induced vibrations

→ all effects produce mechanical fatigue

Pulsed electric system → special capacitors

High current discharges → 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

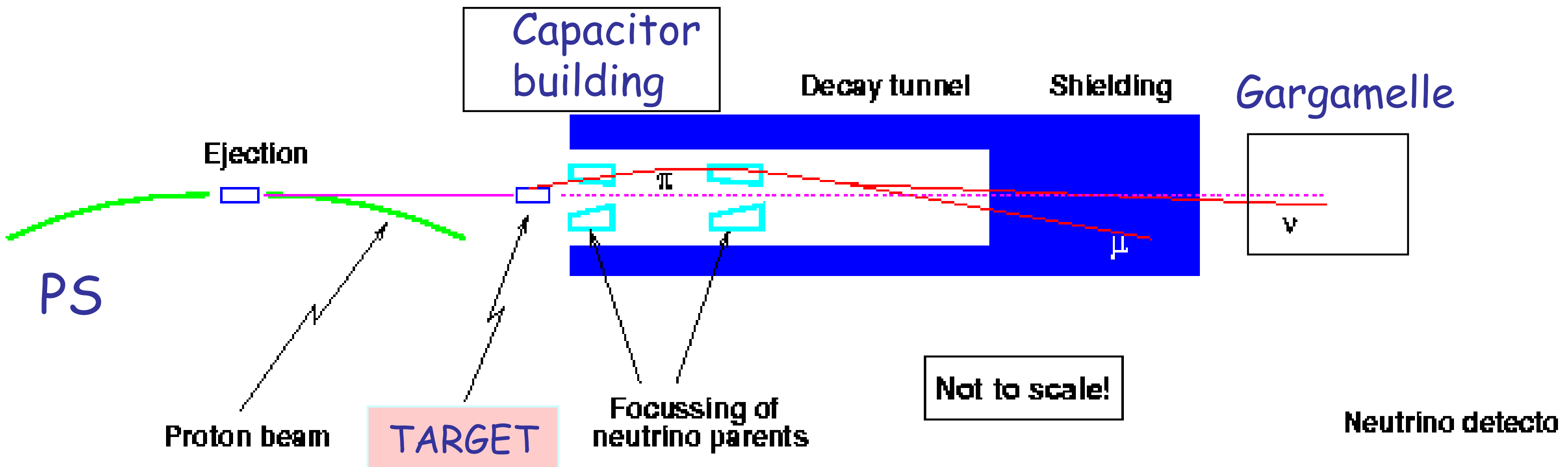
A Fast Coupling System is under development at LAL/Orsay which may relieve of the necessity to use a robot for CNGS horn replacement.
Automatic procedures without human intervention should prevail.

3. 40 YEARS of HORN PROJECTS at CERN

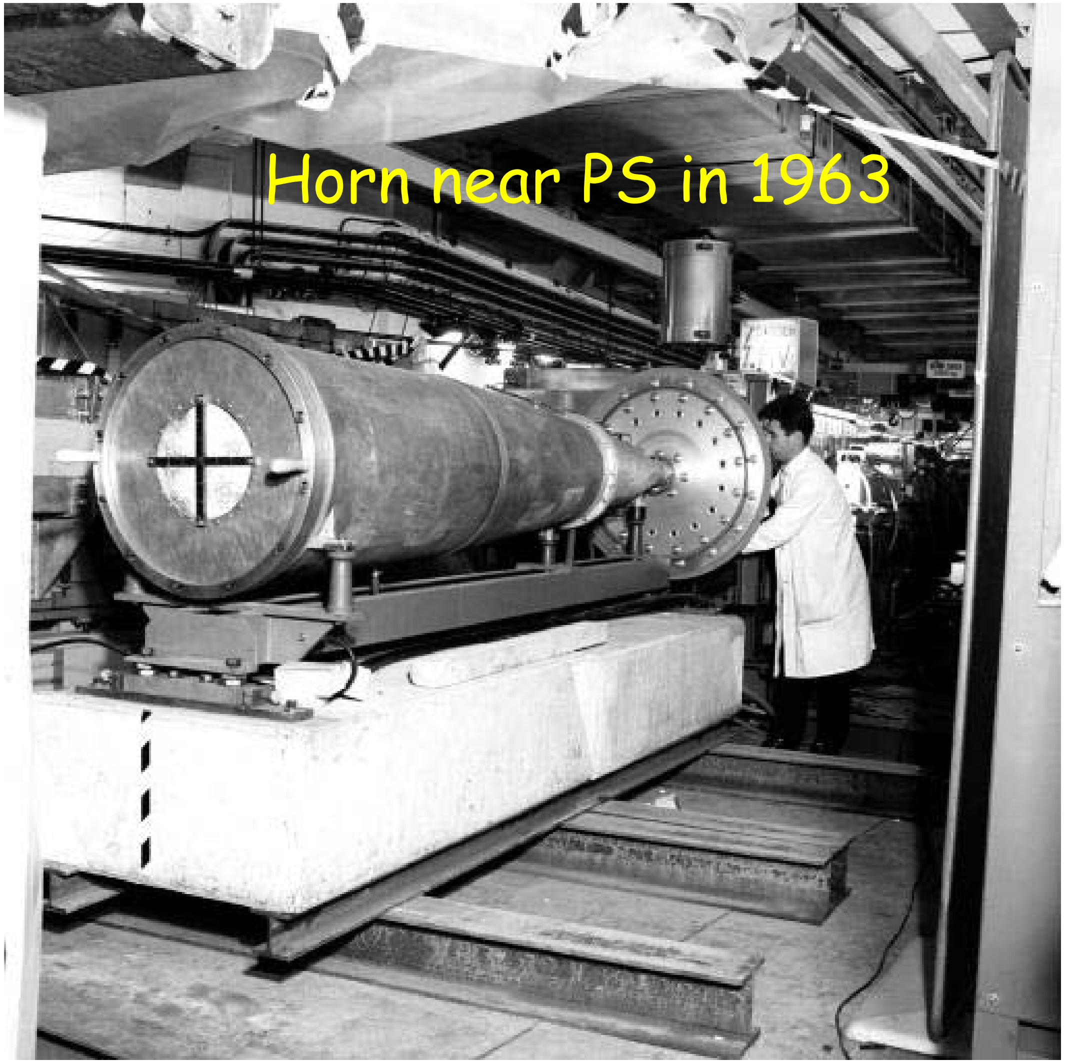
3.1 PS   neutrino beams from 61 -> 75

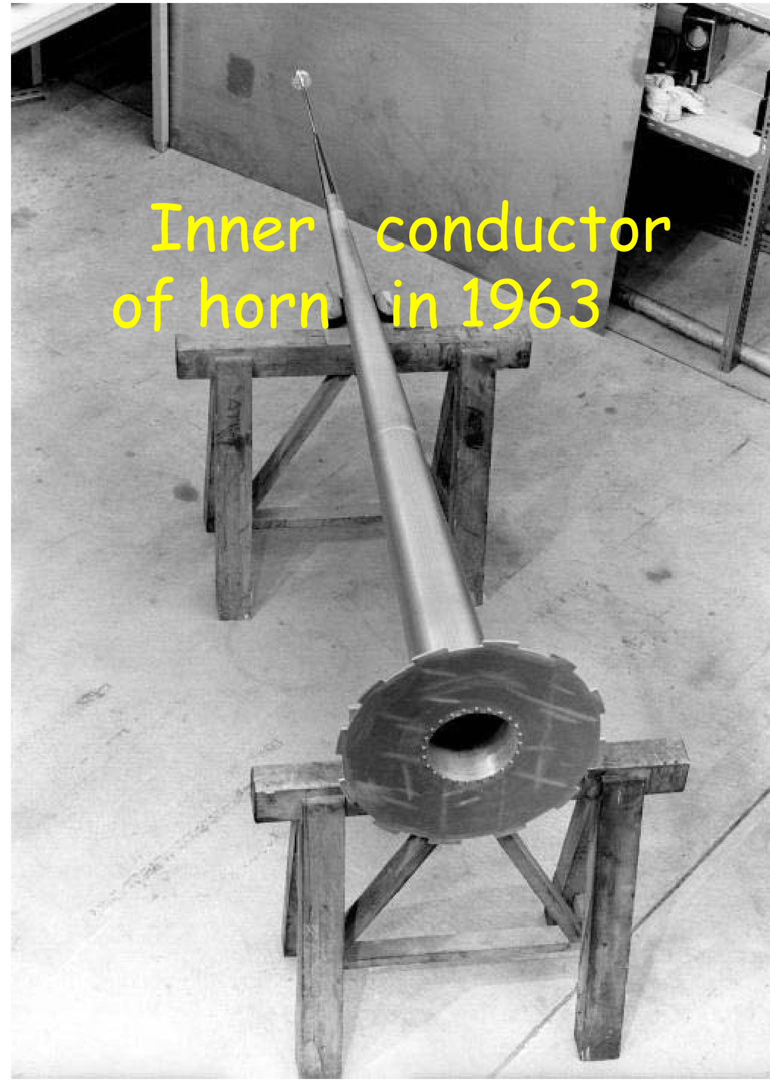
2s cycle with fast extraction from the PS of ” 2 μs proton burst

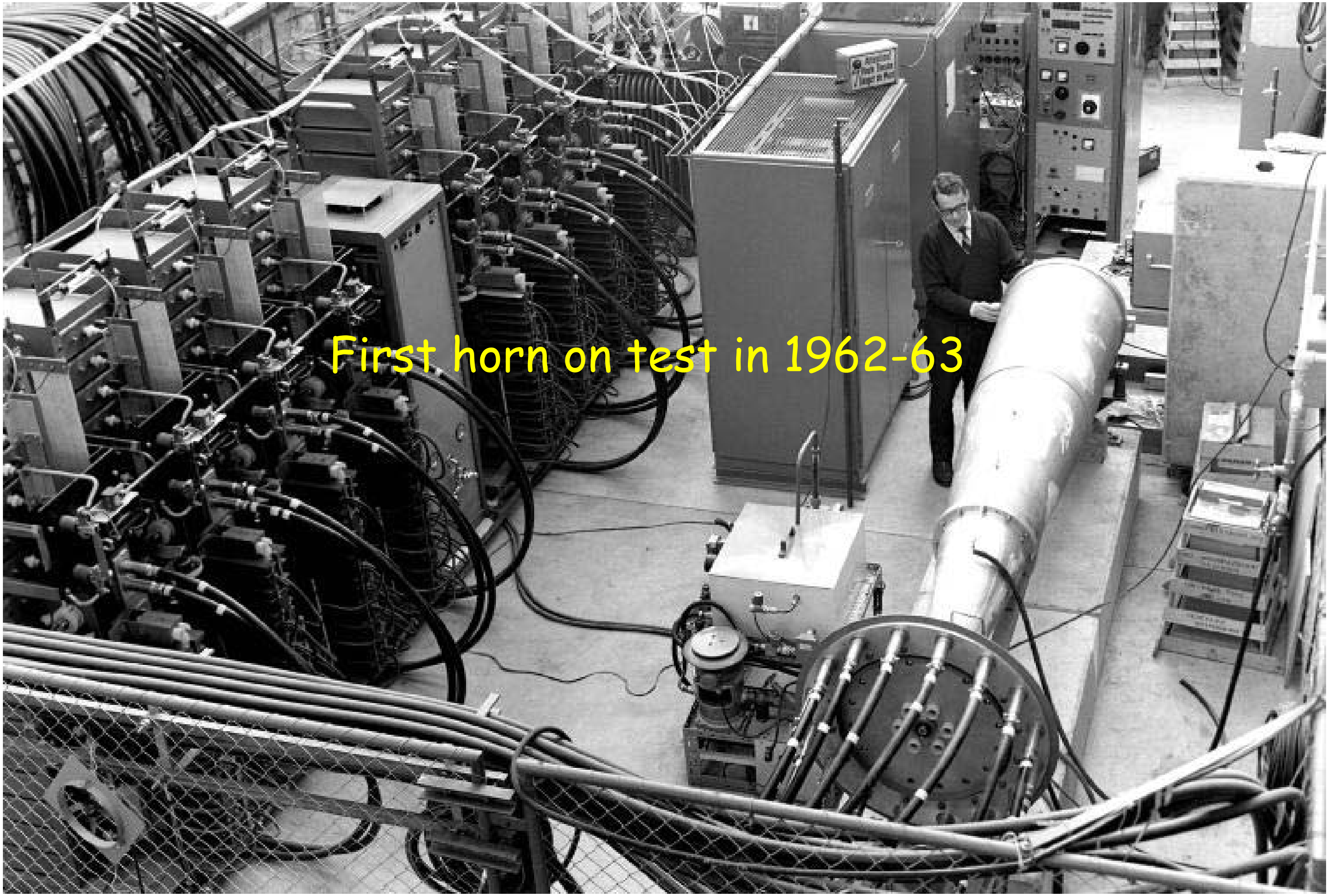
at 25 GeV   (up to 10E12 protons on target)



One of the first horns (63-64 PS neutrino experiment)



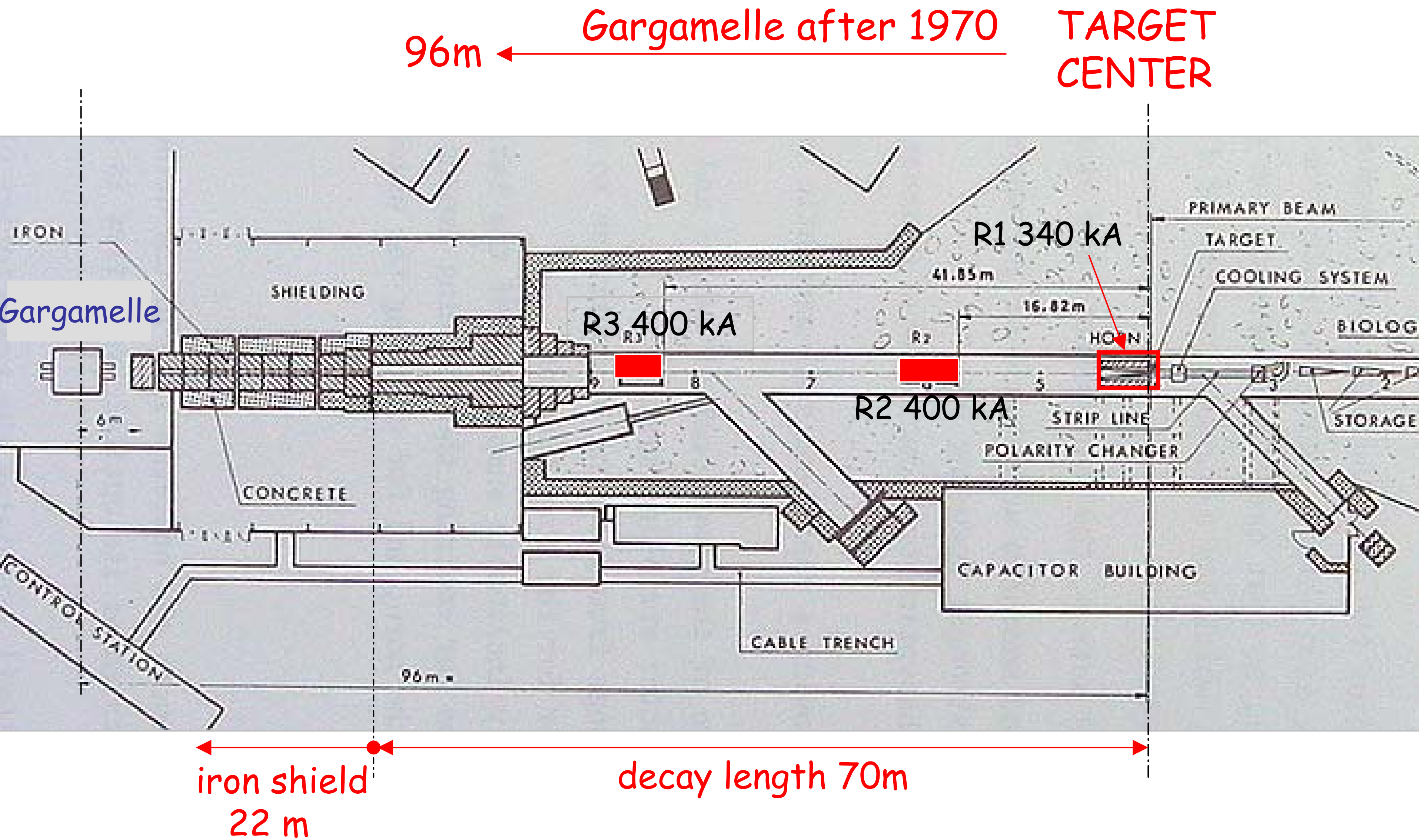


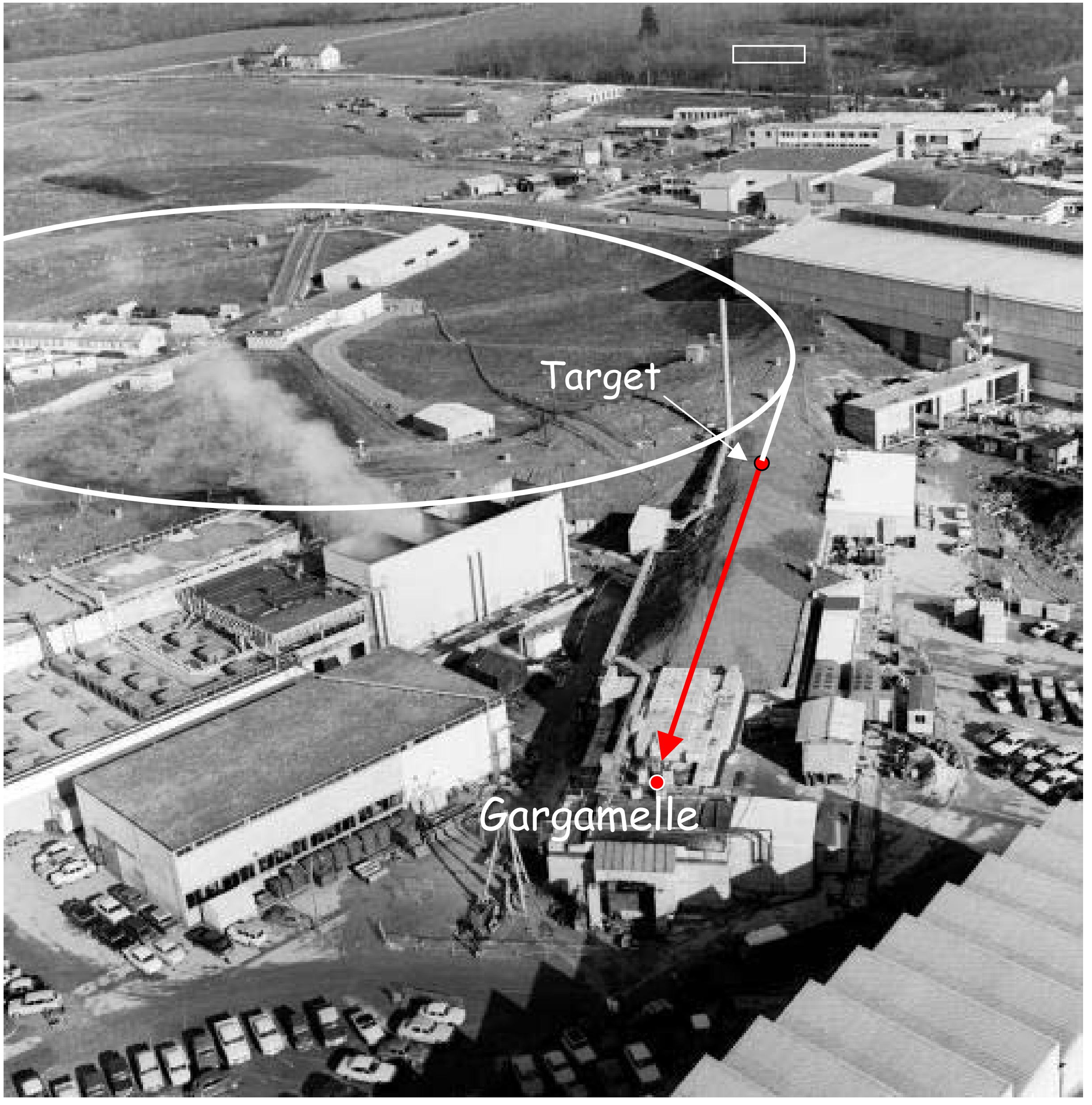

First horn on test in 1962-63

PS Sout East Area neutrino beam constructed in 65-66

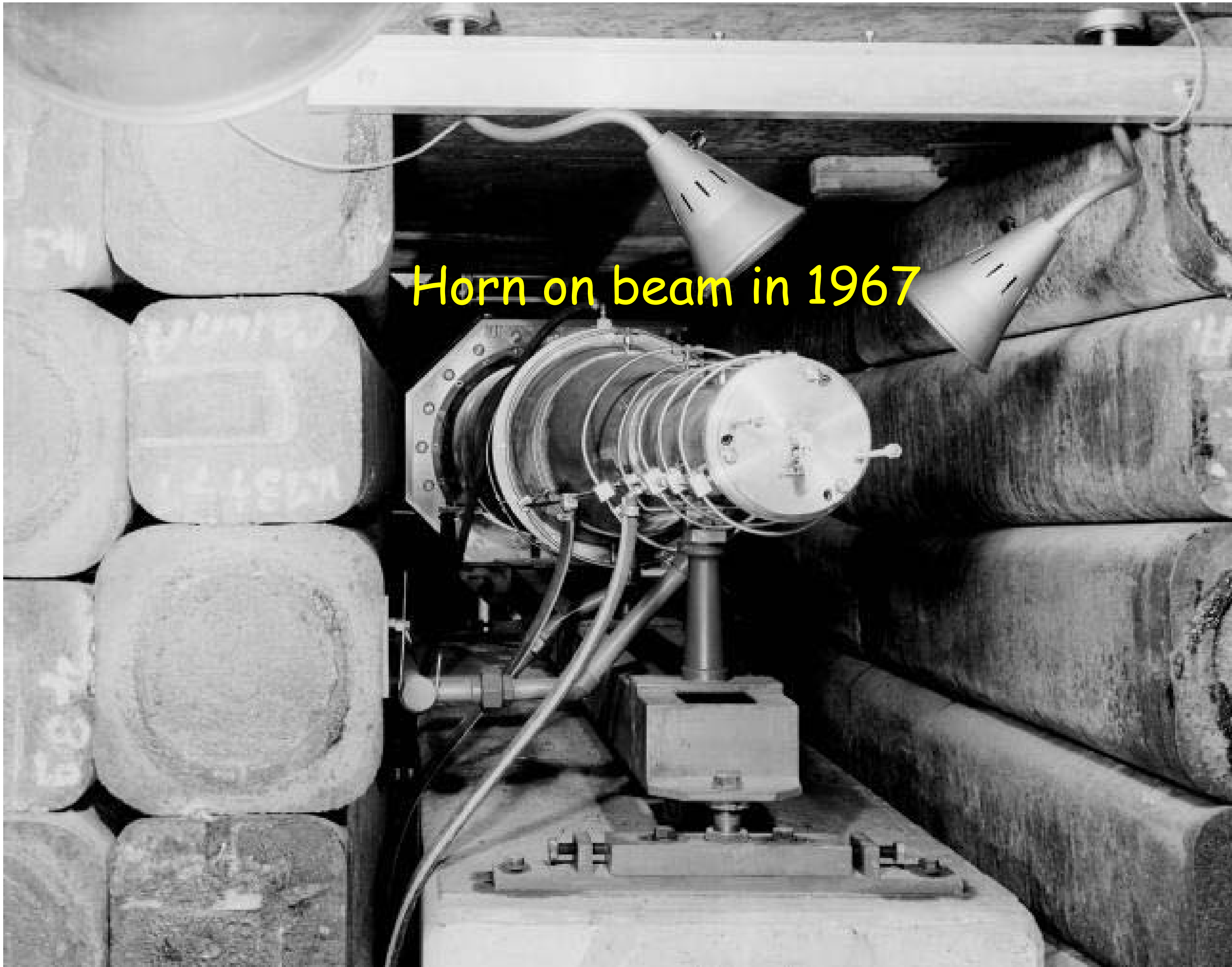
1 - 3 Gev neutrinos

up to 26 Gev protons

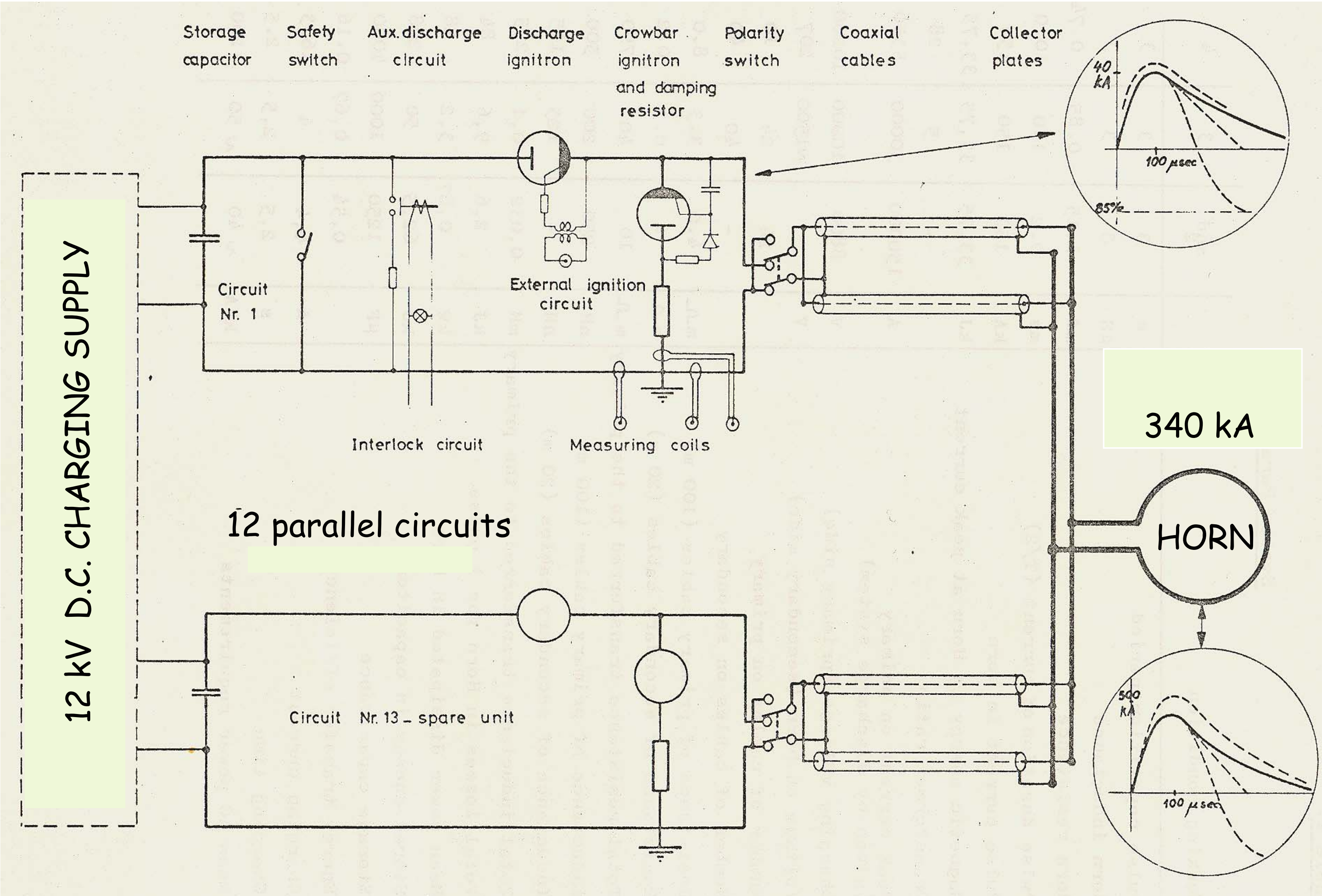




South East
Area of PS

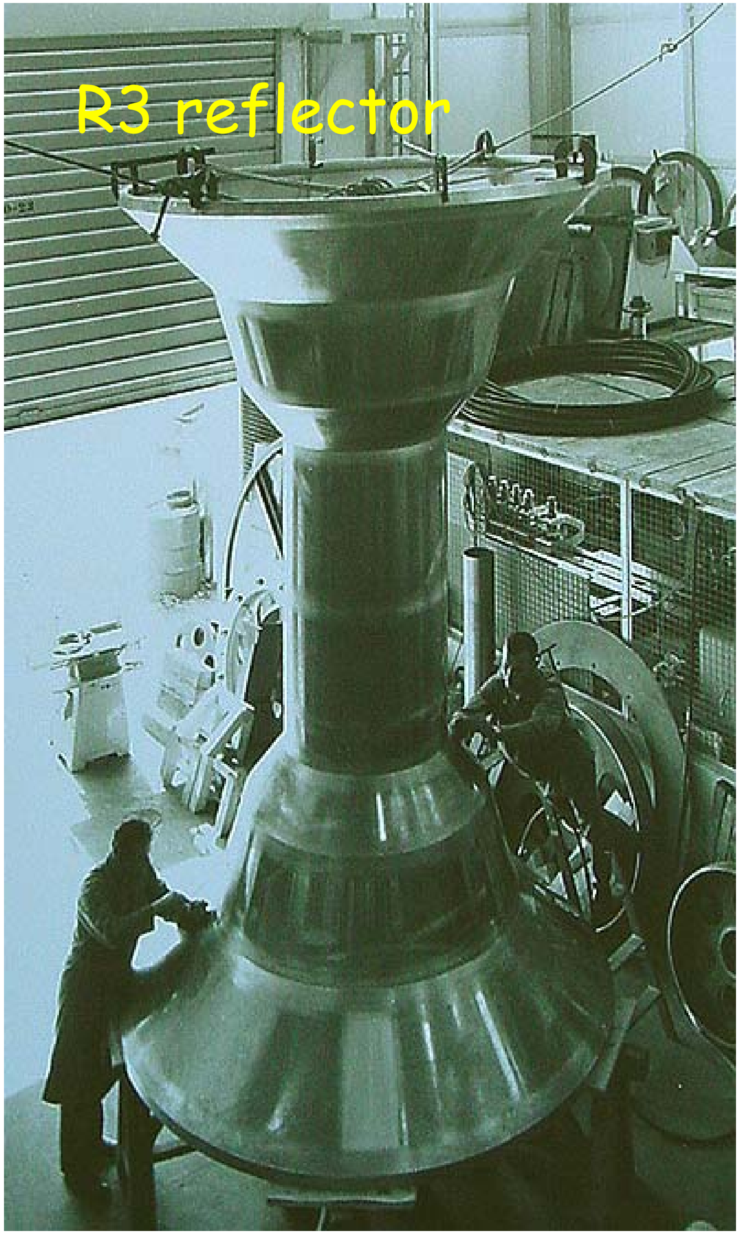


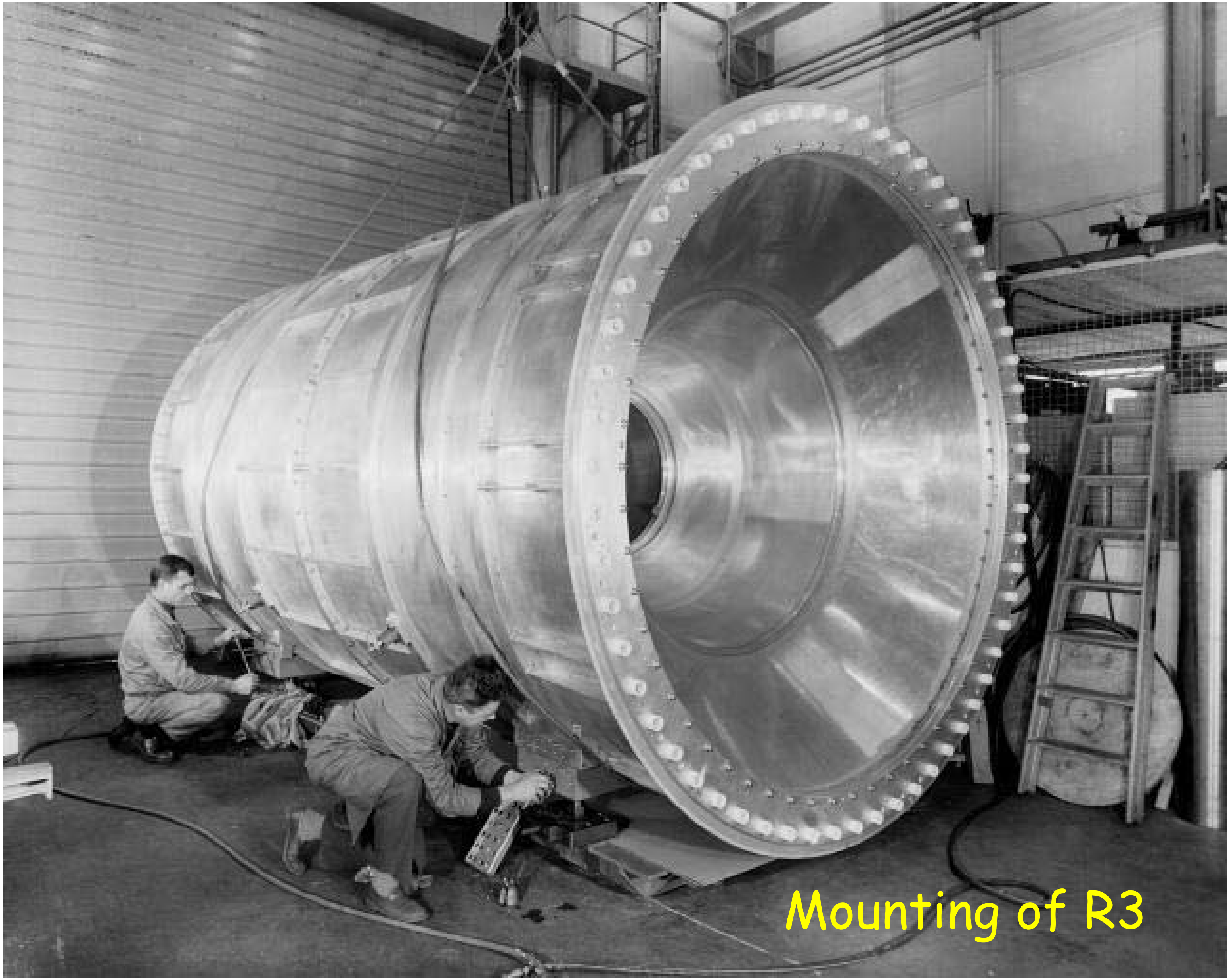
Horn on beam in 1967



CAPACITOR DISCHARGE CIRCUIT with CROWBAR 10.10.68


R2 reflector


R3 reflector


Mounting of R3

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)

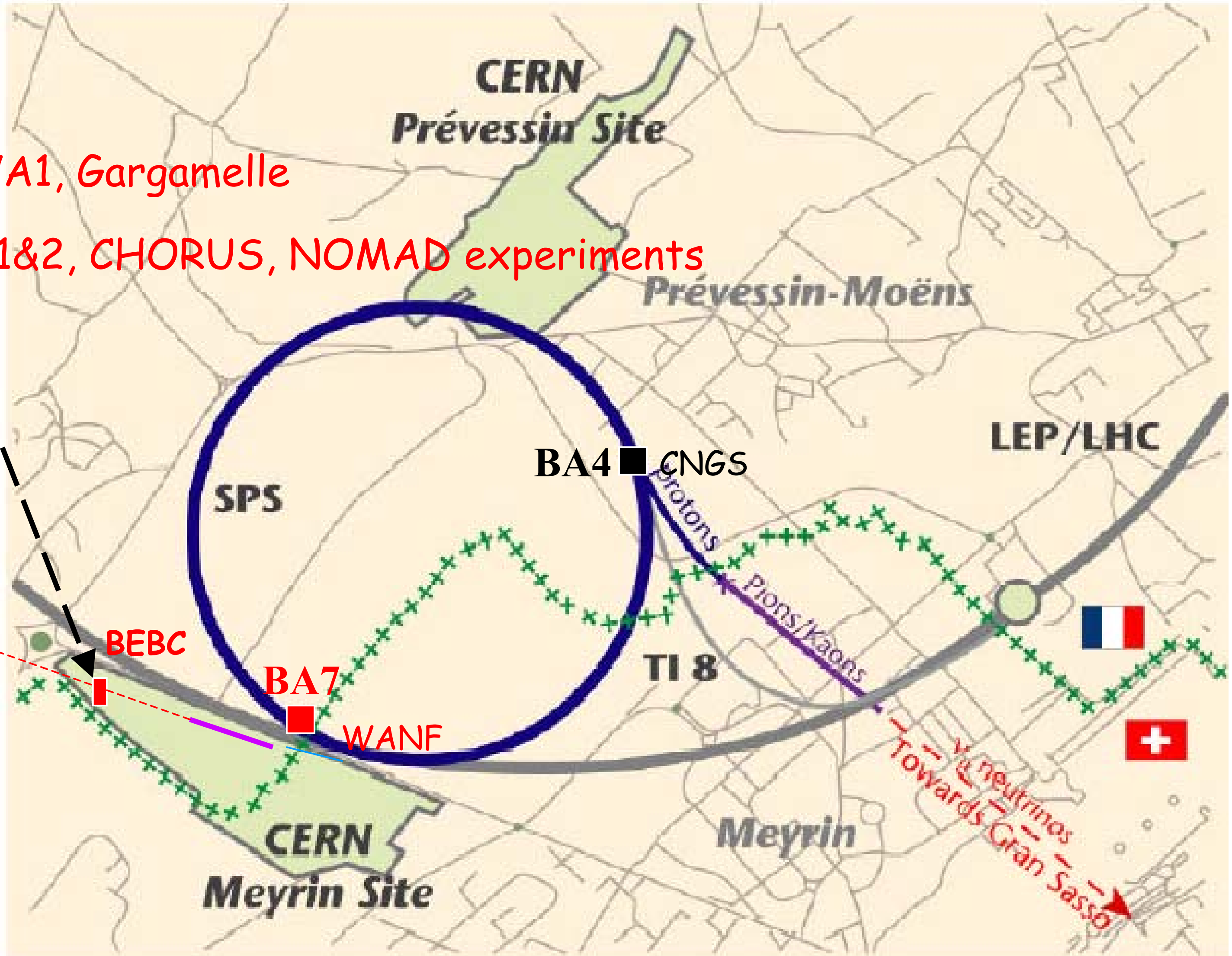
This was the first (indirect) evidence of the existence of the W and Z particles which were explicitely discovered 10 years later also at CERN by the UA1 and UA2 experiments
(Carlo Rubbia and Simon van der Meer obtained Nobel prizes for this discovery).

End of runs in South West Area ”1975

3.2 SPS neutrino beams from 77 to 98

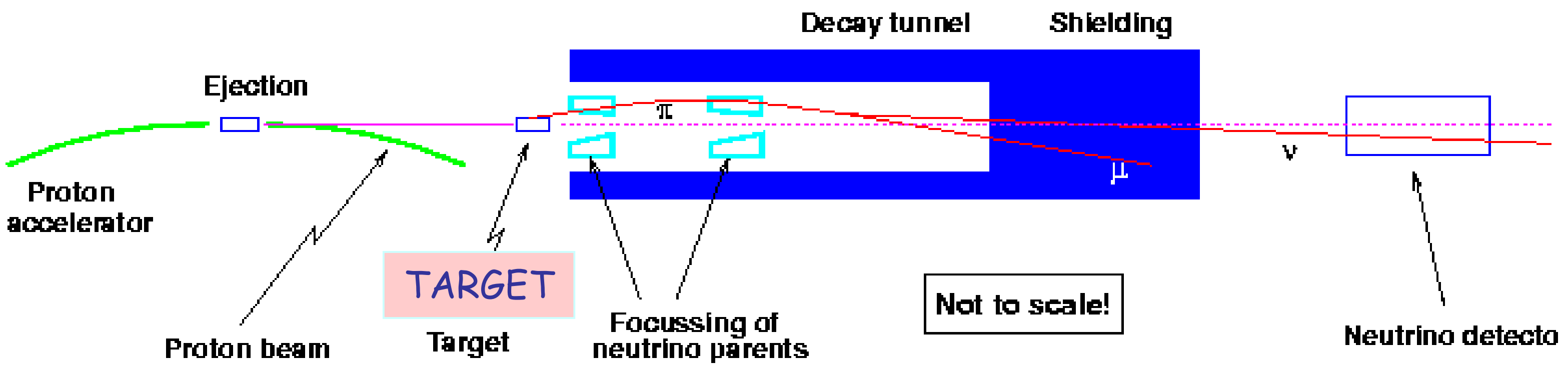
BEBC, WA1, Gargamelle

CHARM 1&2, CHORUS, NOMAD experiments

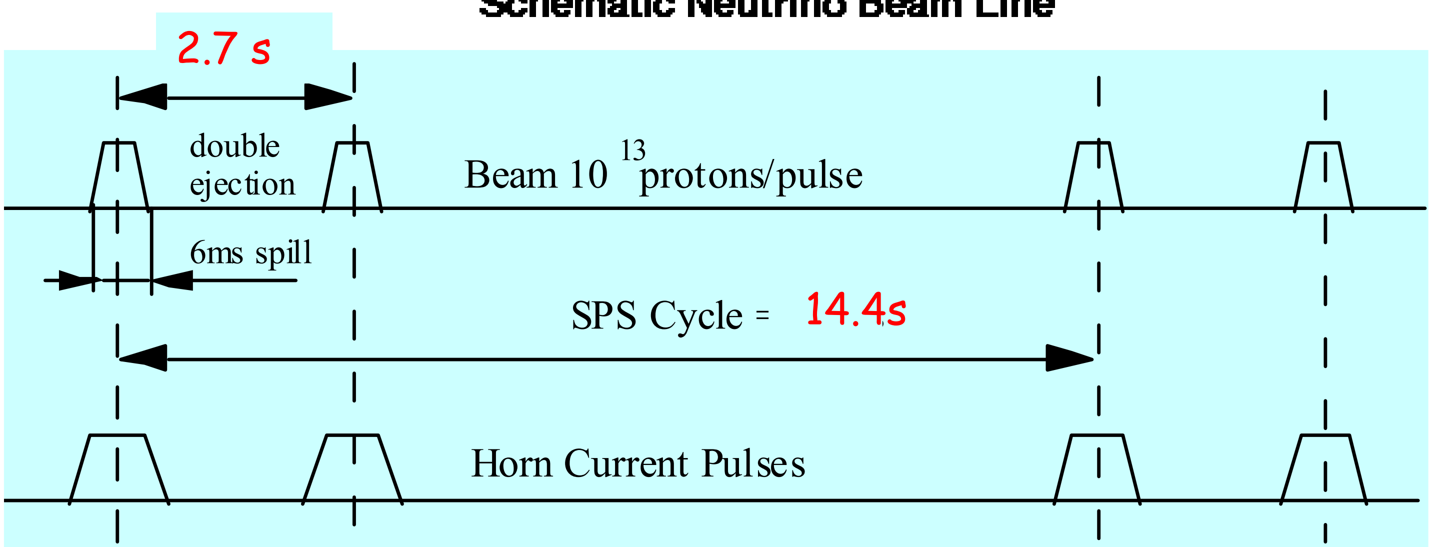


fast/slow extraction from the SPS : two 6 ms long spills at 450 GeV

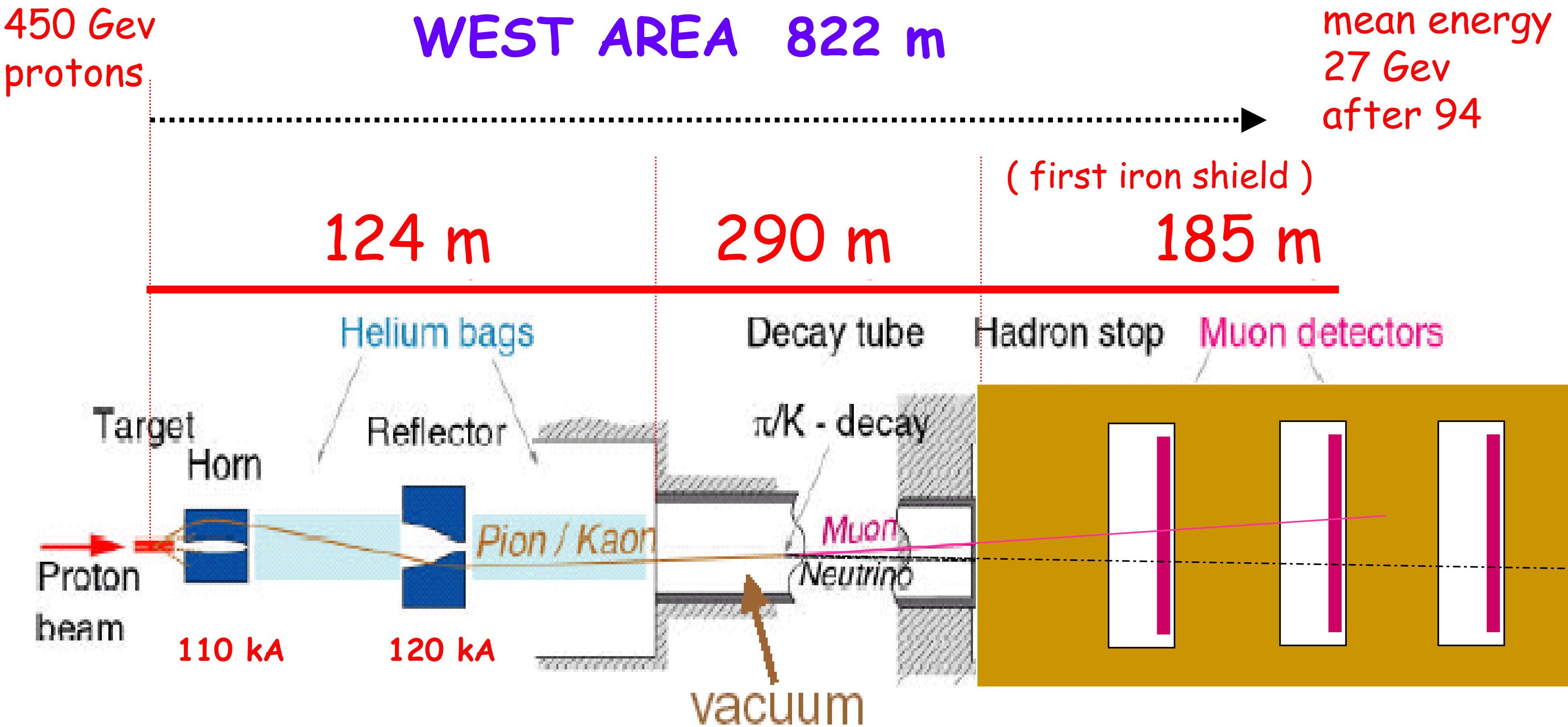
(1 - 1.5)X10E13 protons on the target



Schematic Neutrino Beam Line

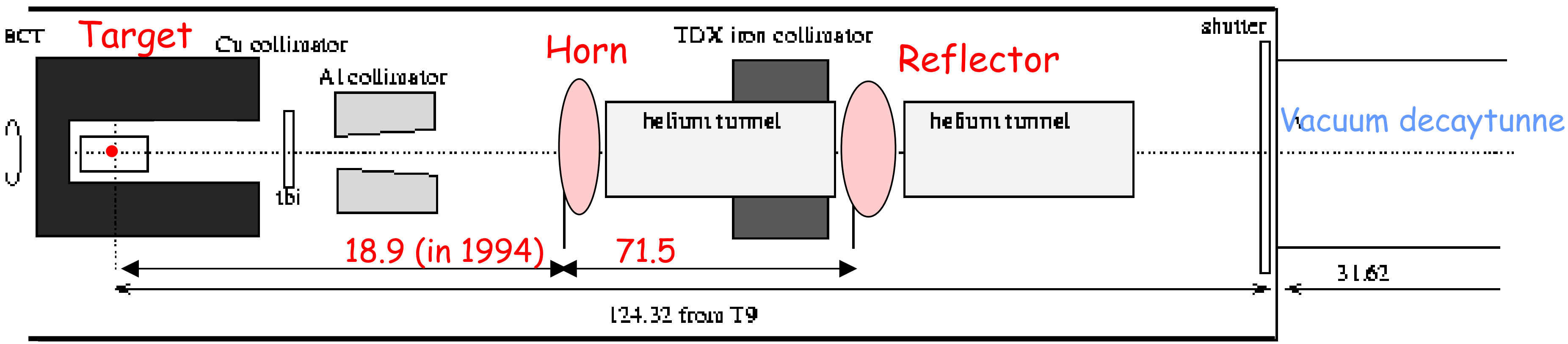


DETECTORS
WEST AREA 822 m

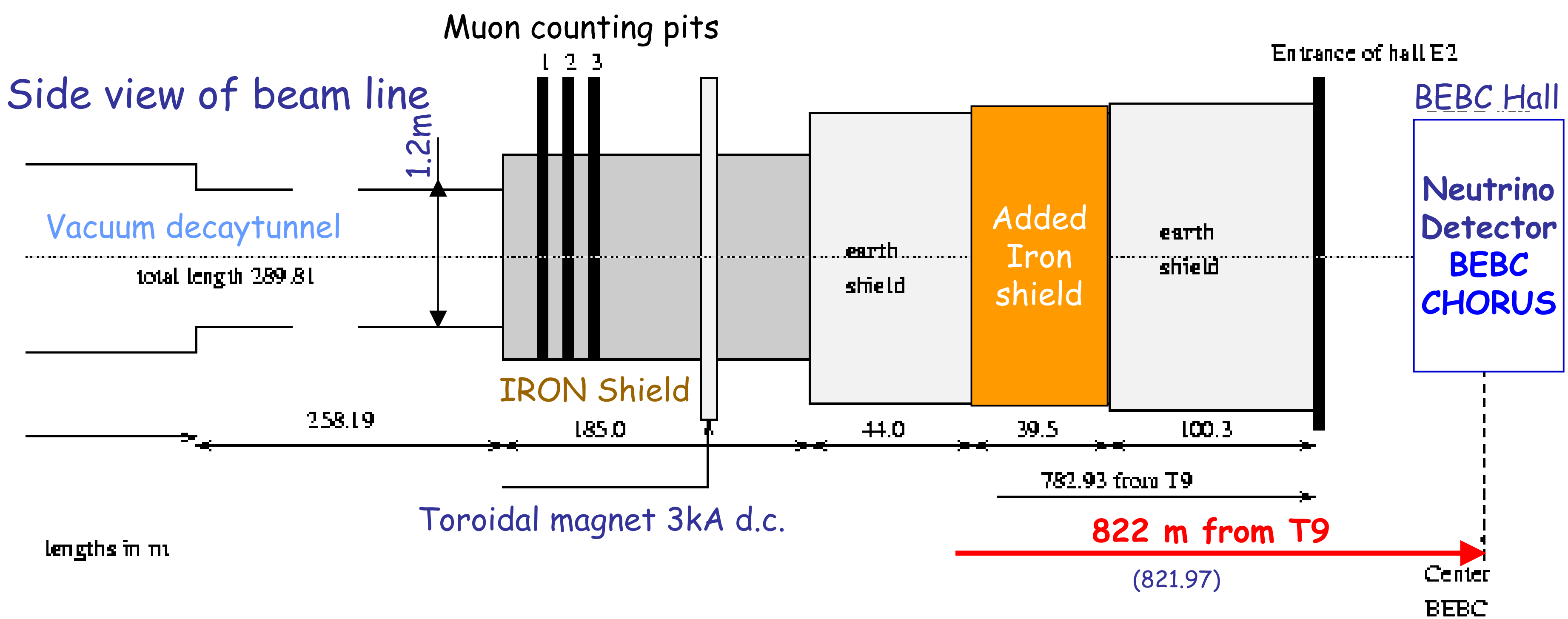


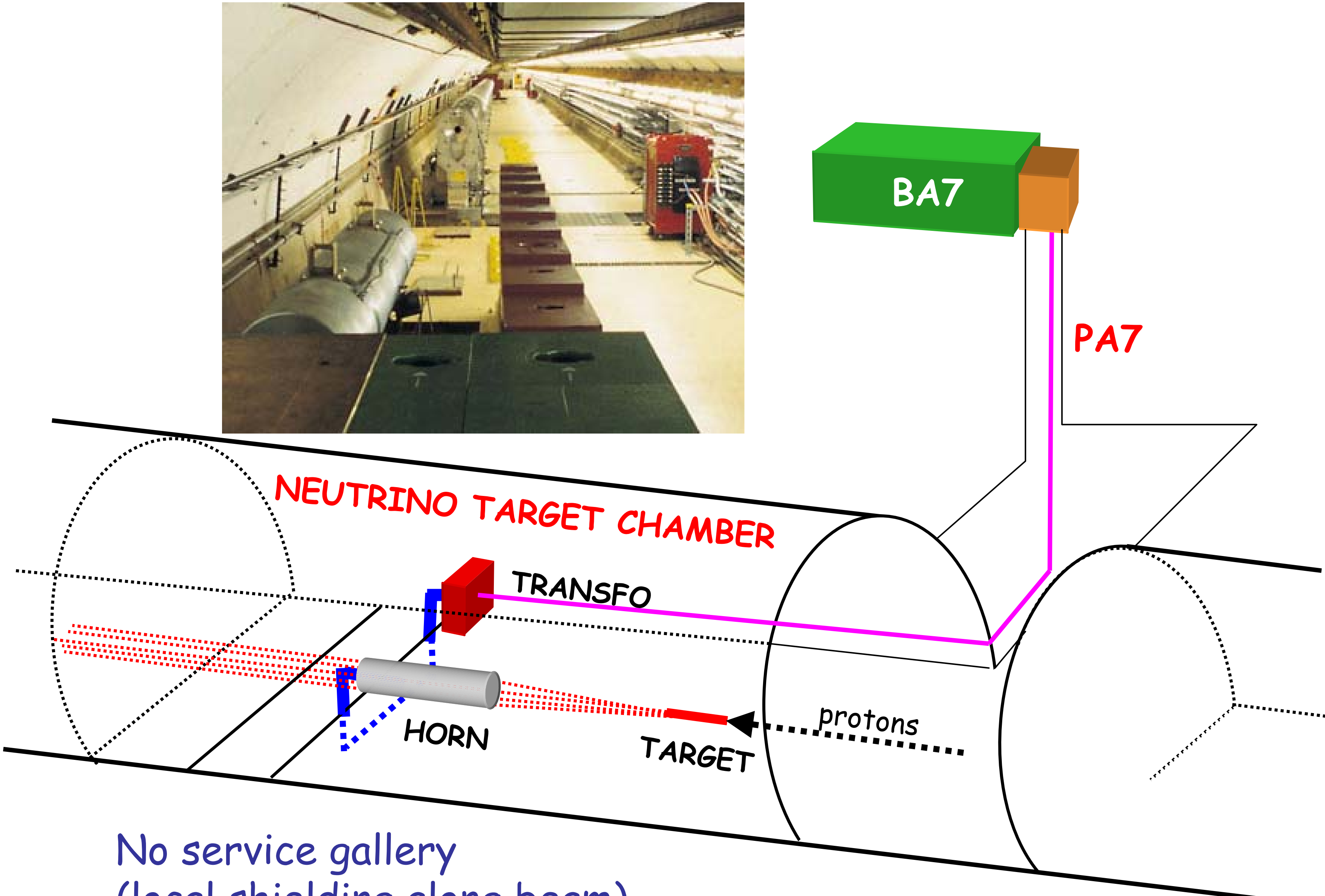
West Area Neutrino Facility (WANF)

Top view of neutrino cave



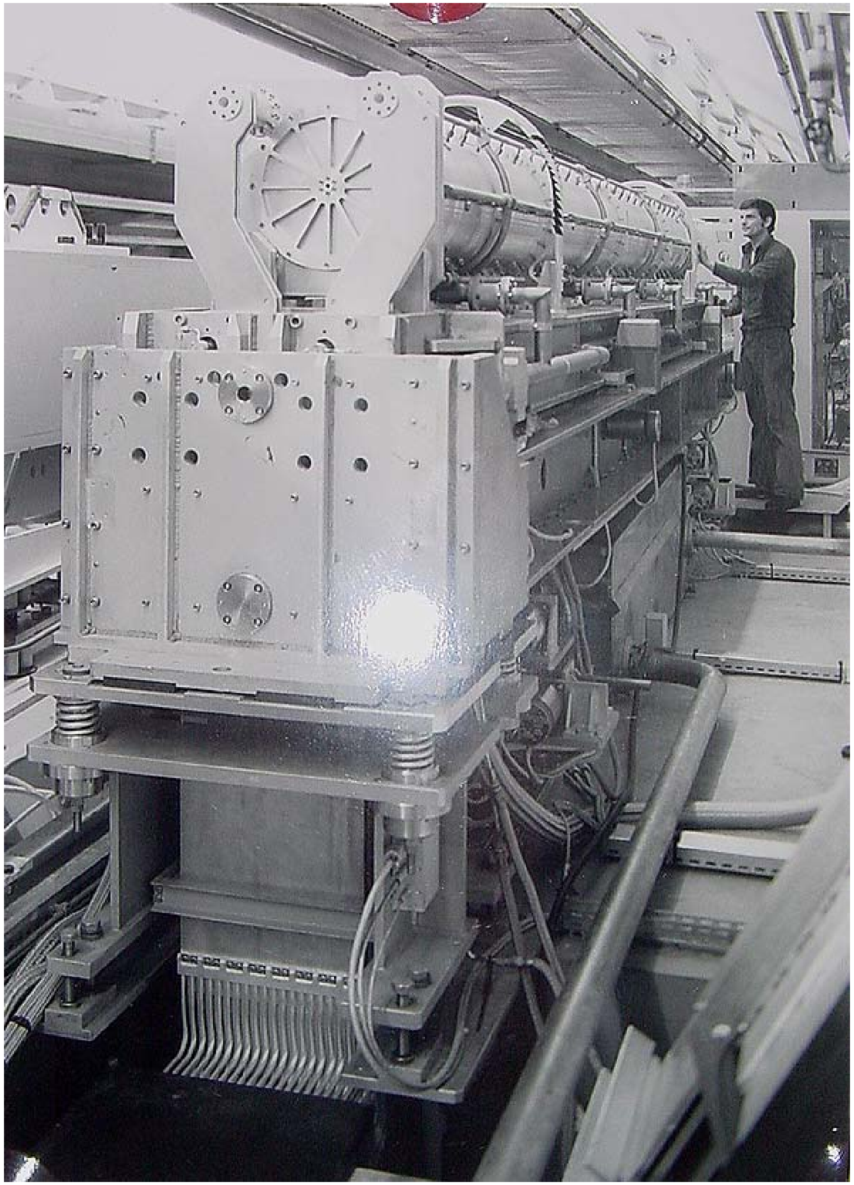
Side view of beam line



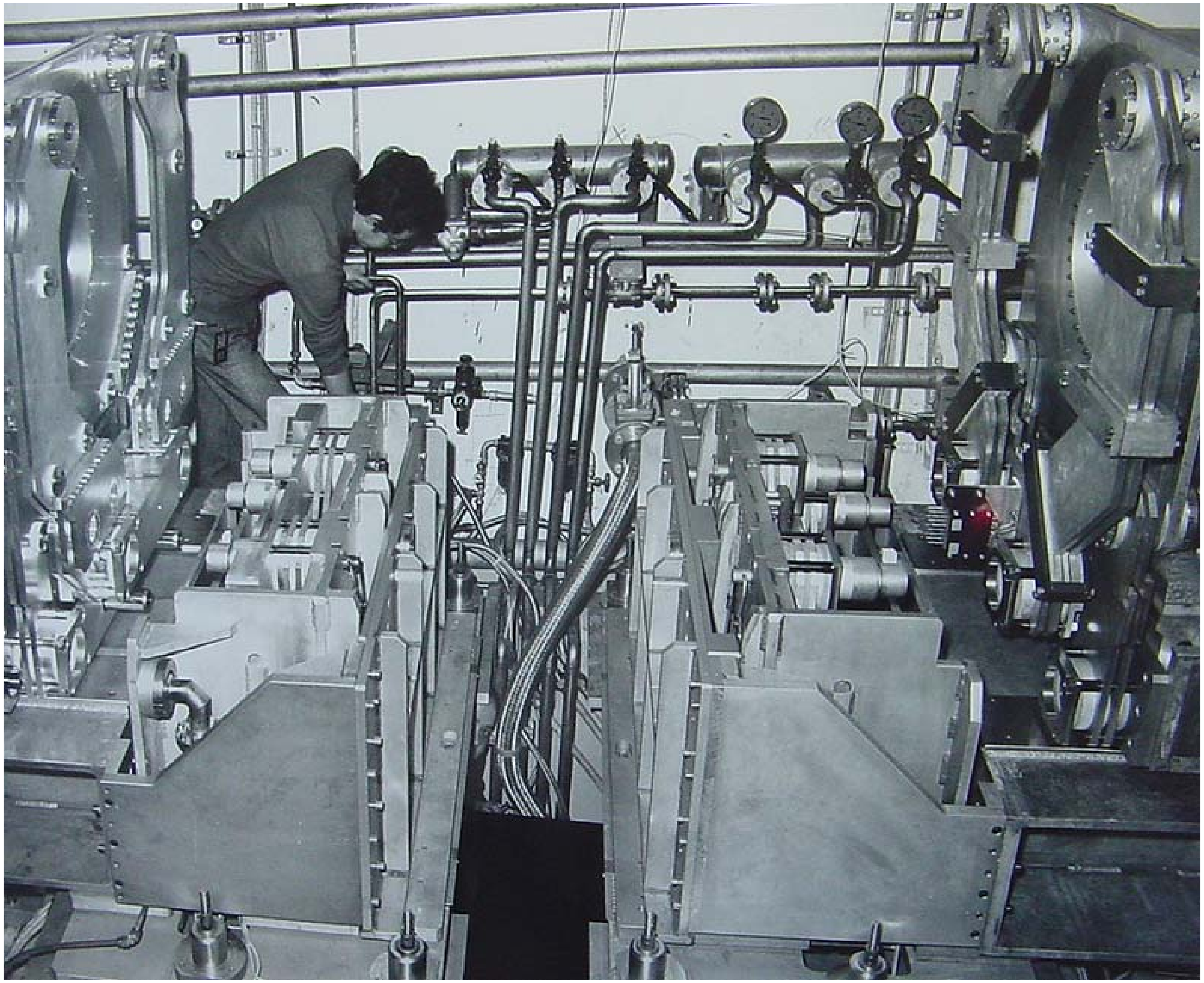


No service gallery
(local shielding along beam)

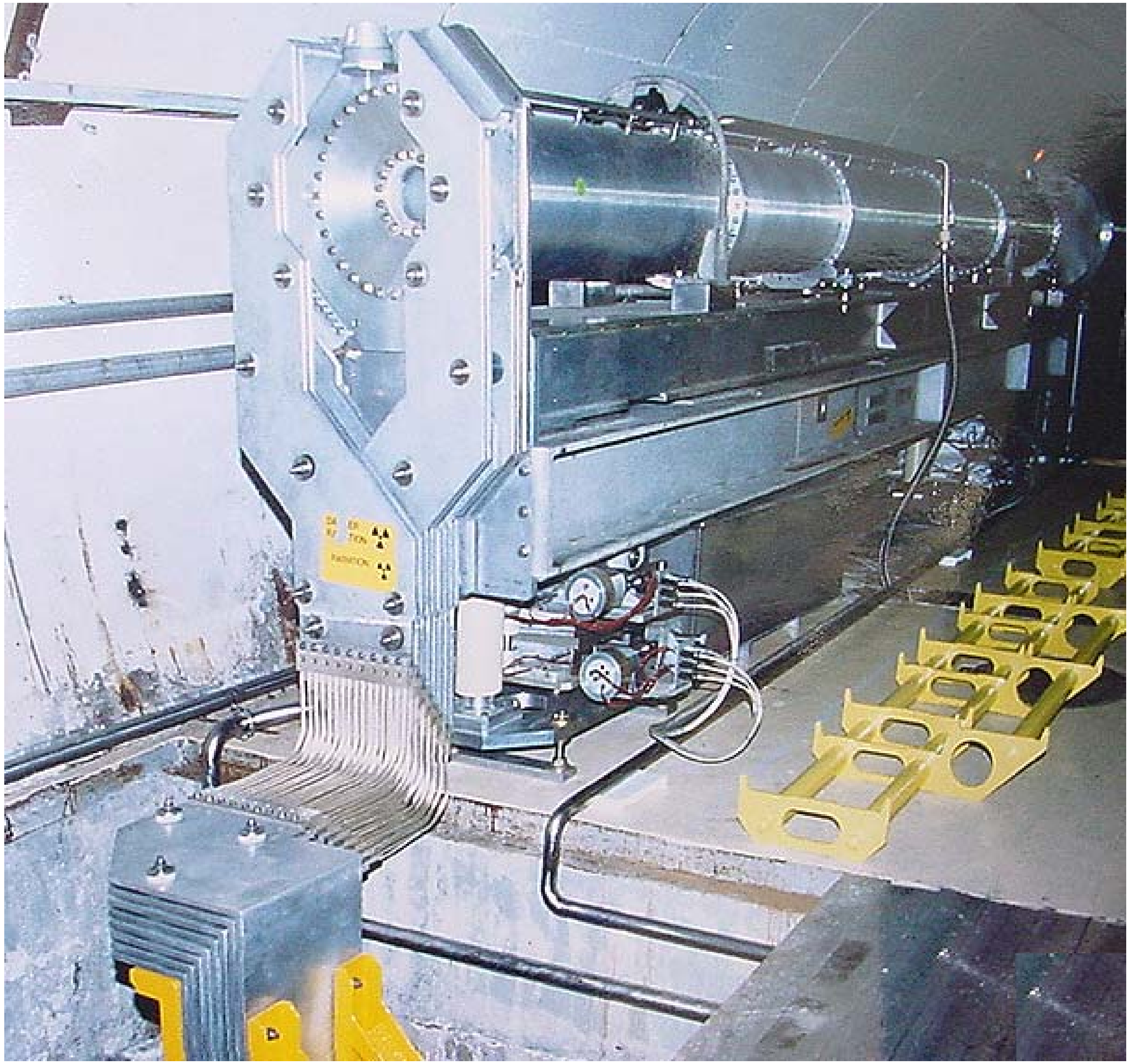
First horn in 76



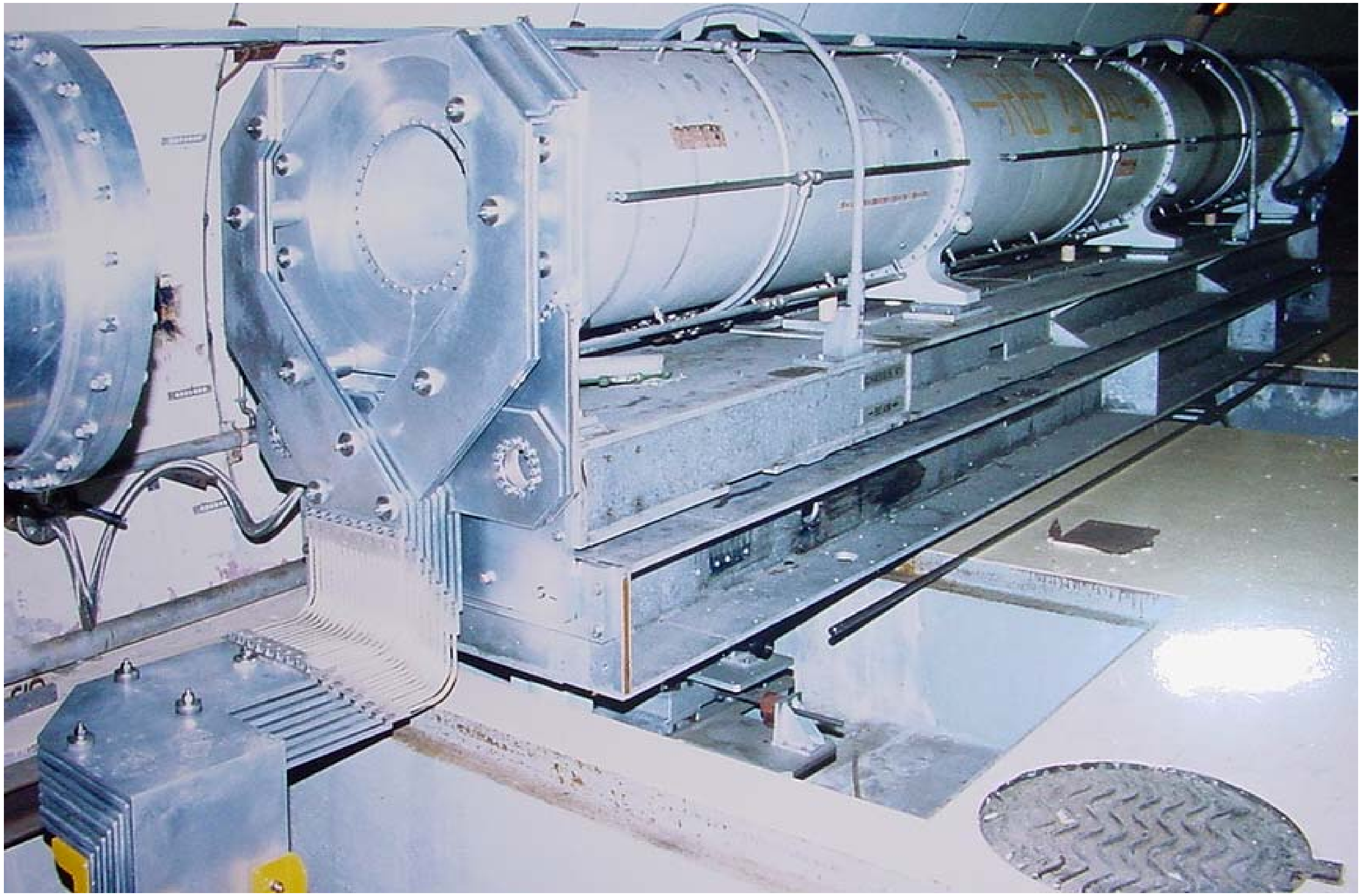
Reflector positioning base



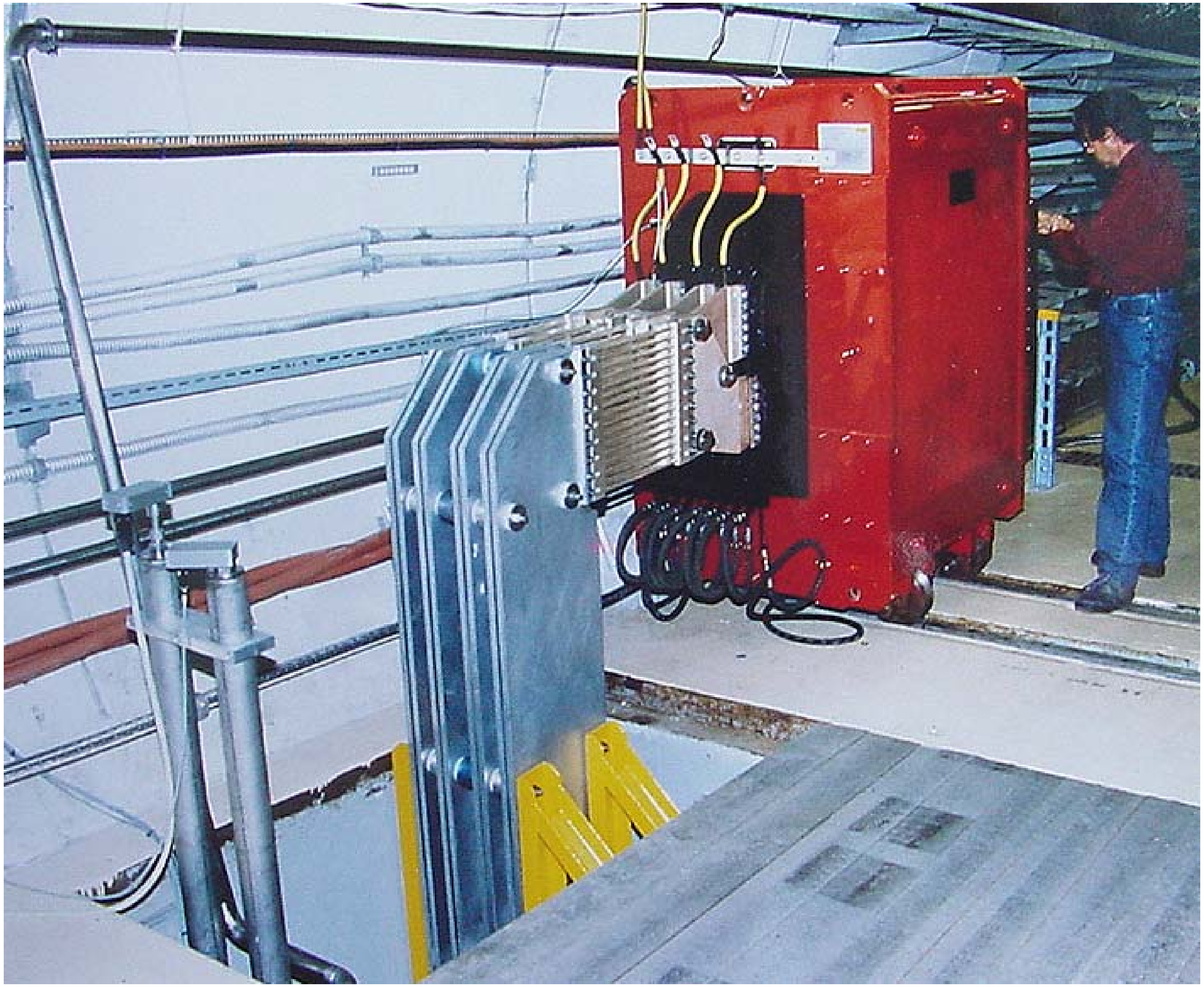
2 reflectors in serie with remote plug-in systems



CHORUS-NOMAD horn (110 kA) installed in 1993

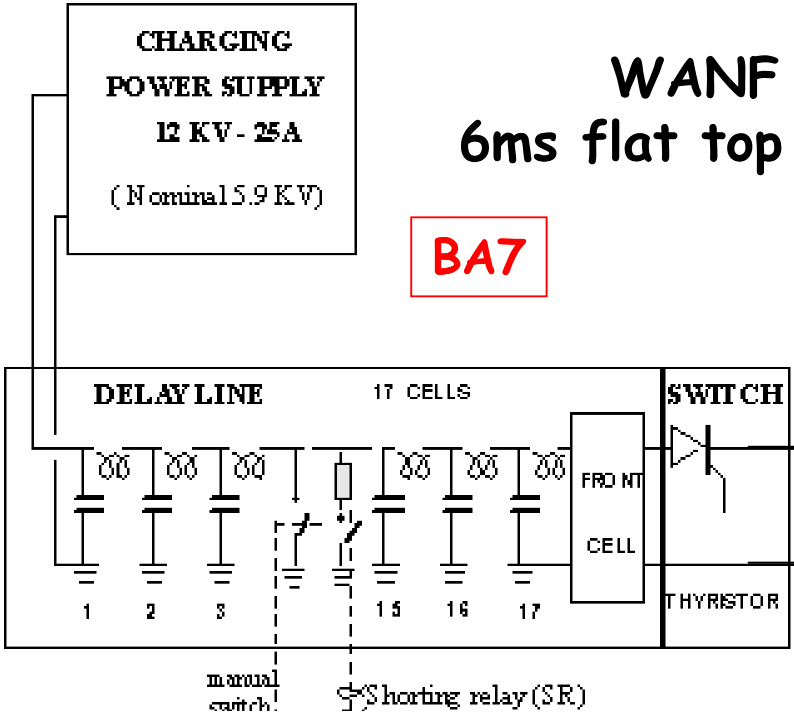


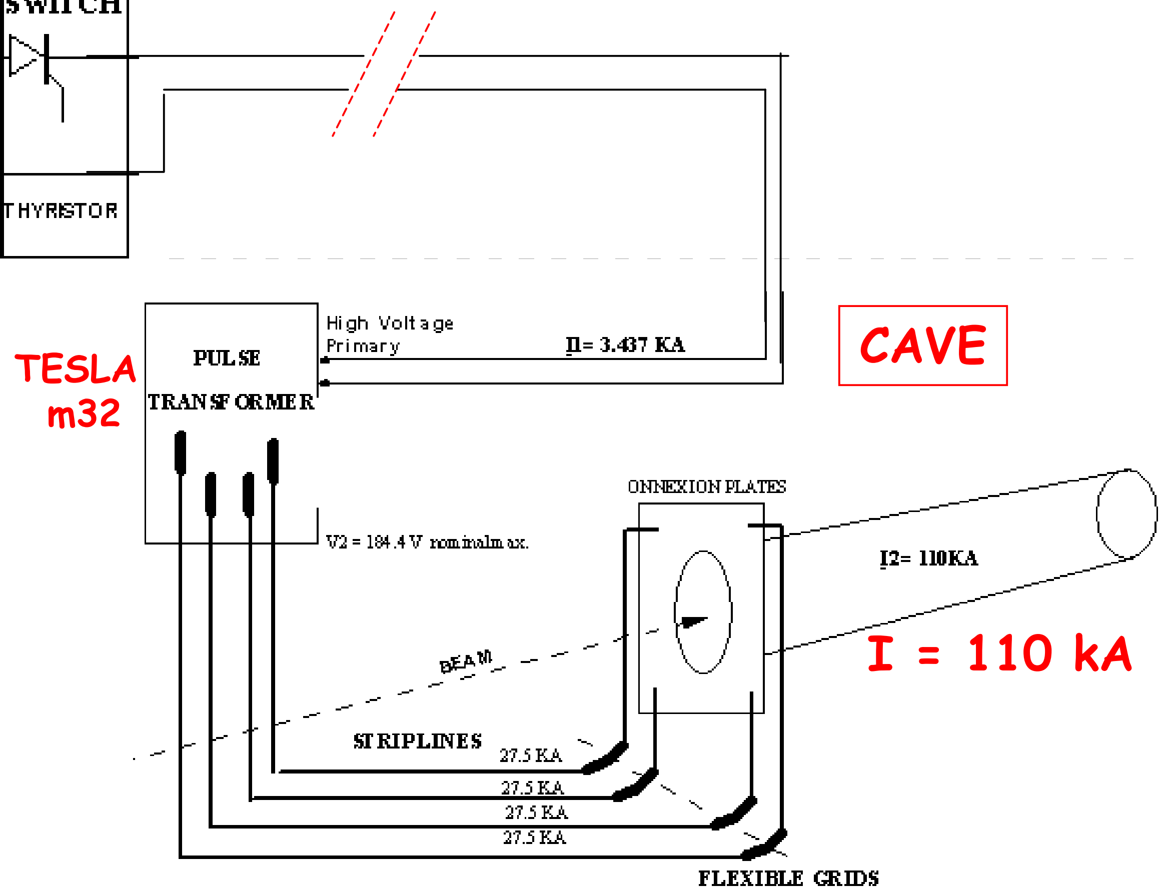
CHORUS-NOMAD reflector (120 kA) installed in 1993



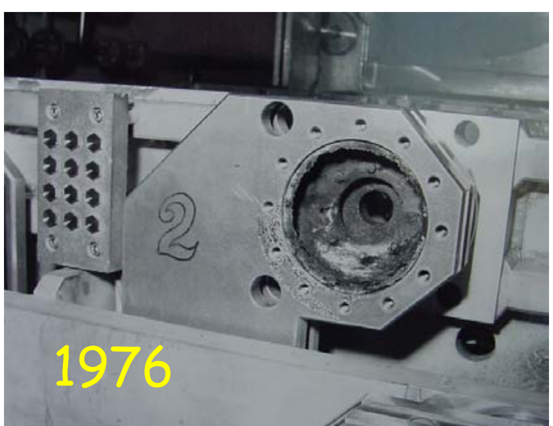
New TESLA transformer installed in 93
-transformer ratio 32-

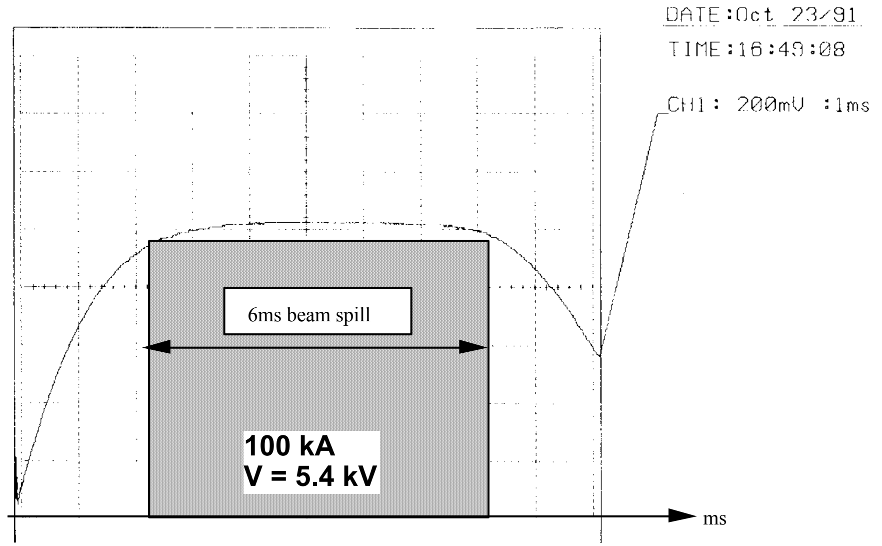
WANF 17 cells delay line
6ms flat top on horn/reflector pulse



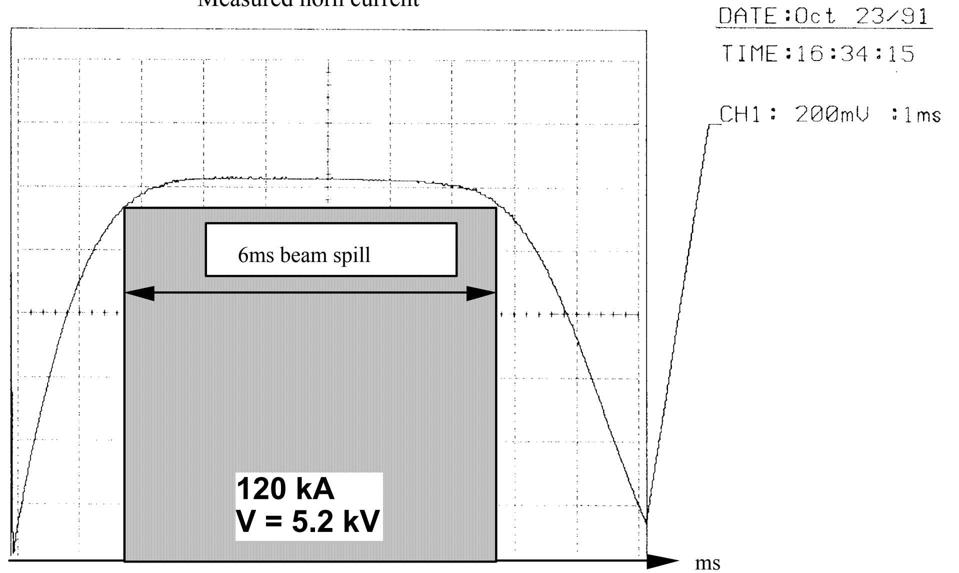


Each cell L = 220 μH
C = 234 μ F





Measured horn current



Measured reflector current

Horn and reflector capacitor banks in BA7

Logbook of 21 years neutrino runs at WANF

High operational reliability

Current on horn kept low ”110 kA

- to ensure run stability
- to avoid accidental horn replacement in very high radiation area

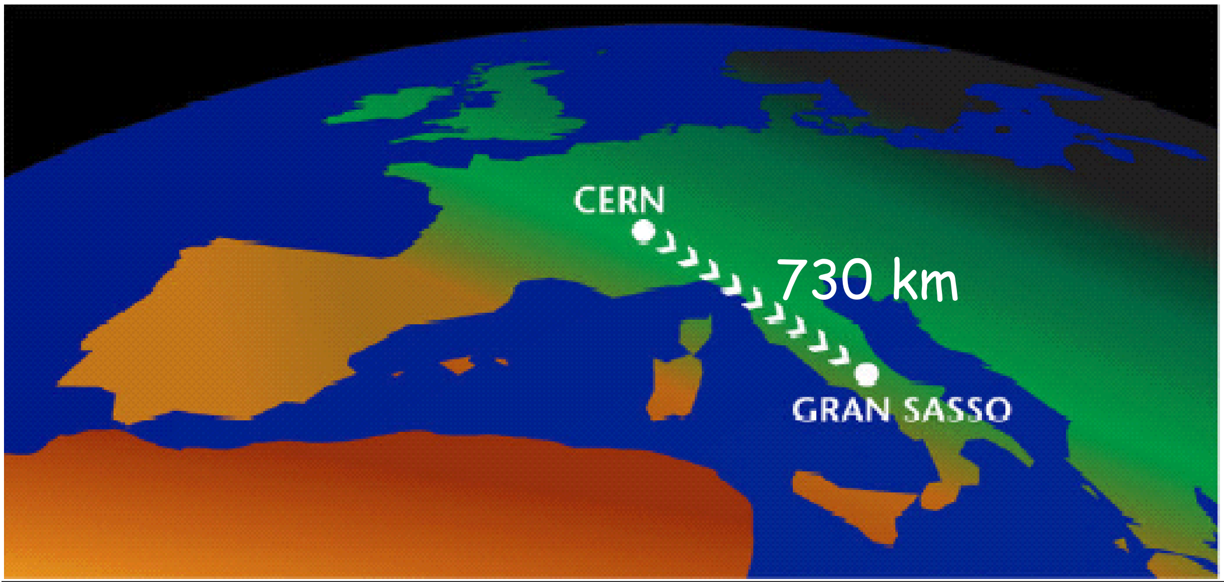
Several horn/reflector configurations have been operating for the succeeding group of experiments.
No accidental horn exchange had to be faced after 77.

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

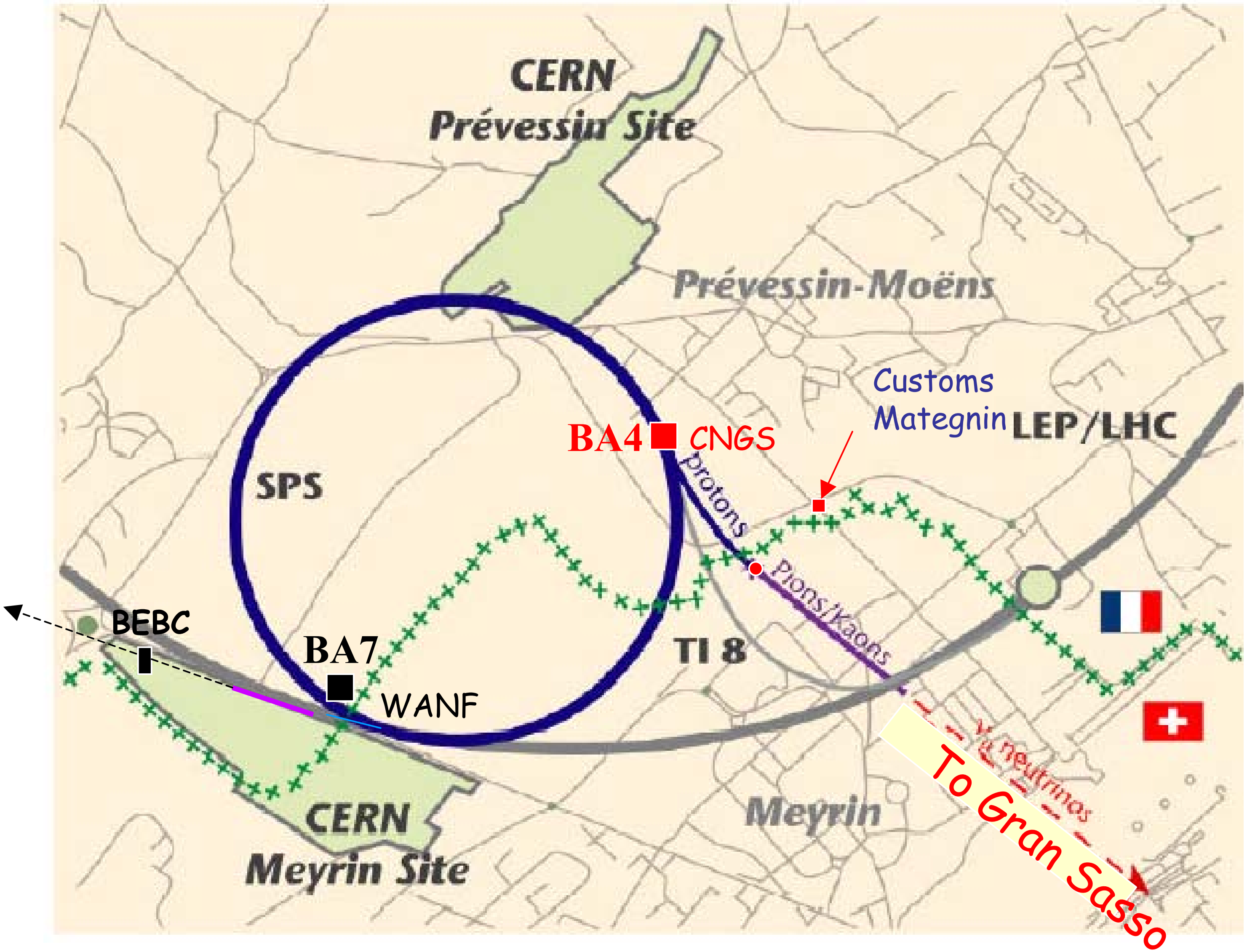
Goal of the CNGS project (F- Pietropaolo – INFN-Padova)



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

- build an intense high energy ν_μ beam at CERN-SPS
- optimized for ν_τ appearance search at Gran Sasso laboratory (730 km from CERN)

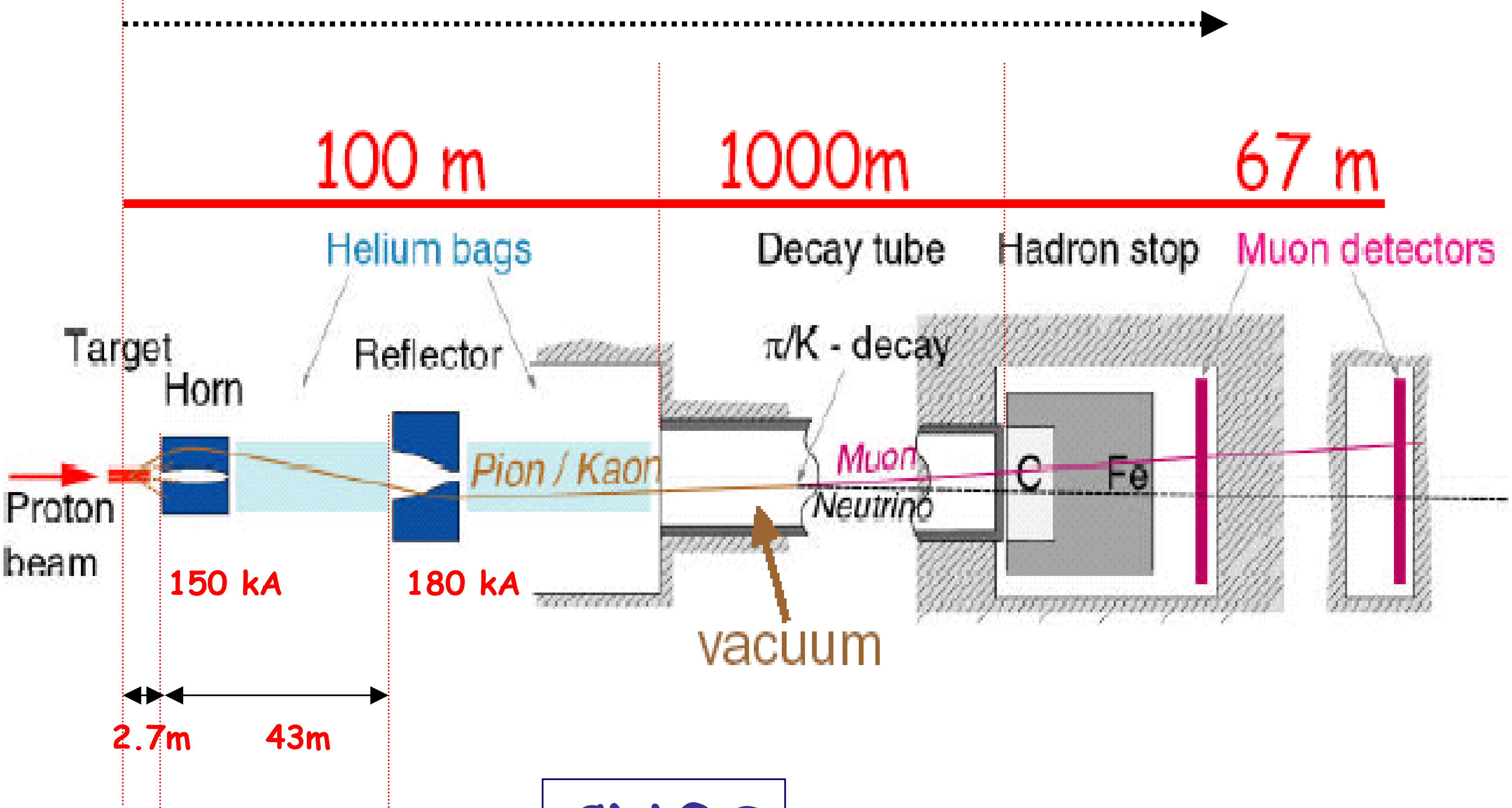
CNGS Layout - F- Pietropaolo – INFN-Padova



450 Gev protons

Gran Sasso 730 km

mean energy 26.7 Gev



CNGS

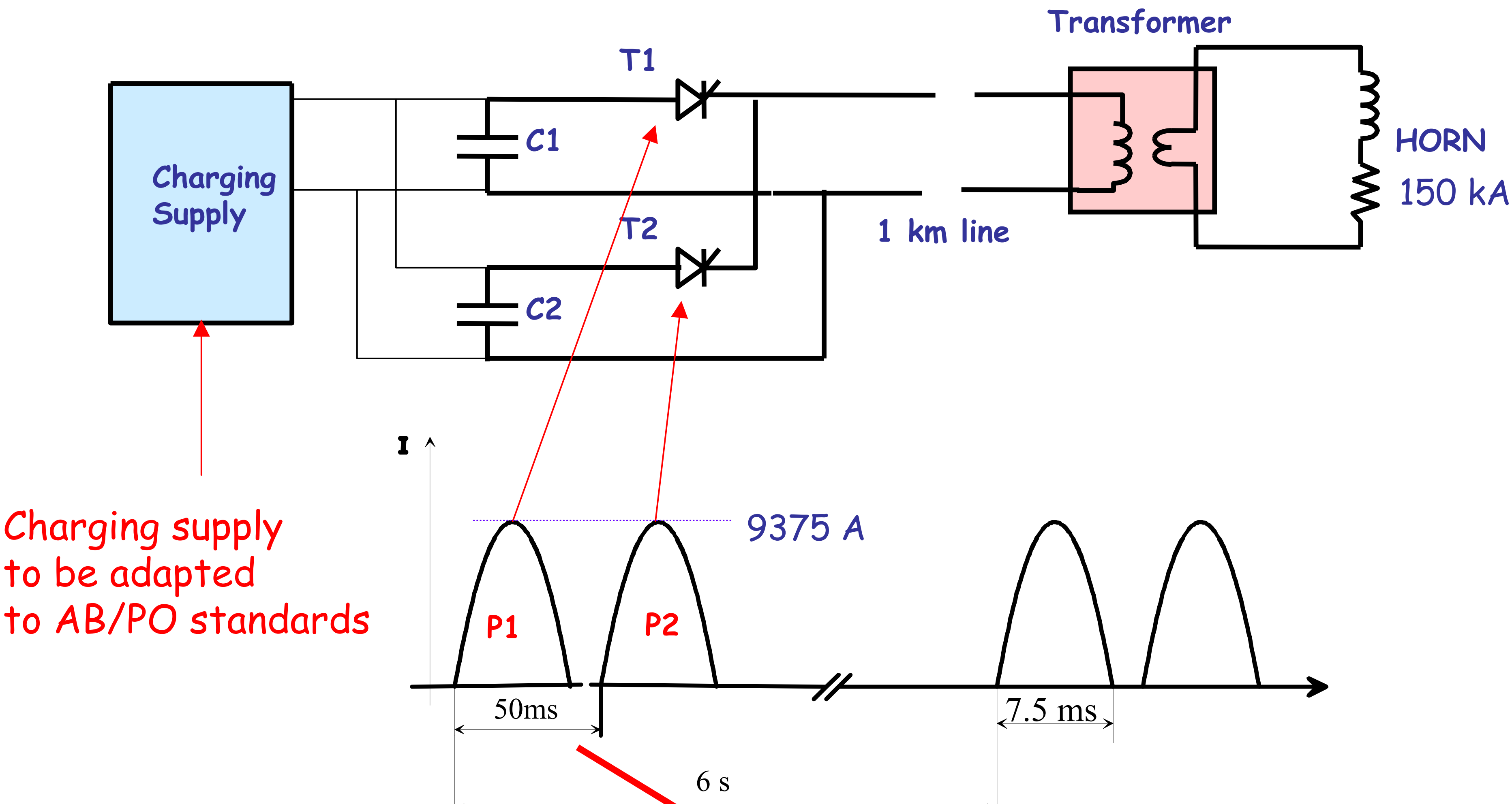
- F- Pietropaolo – INFN-Padova

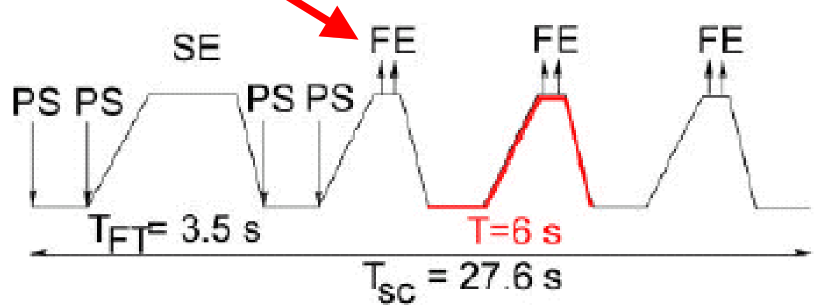
Main design criteria of CNGS horns project

safety

savings maximum re-use of WANF equipment

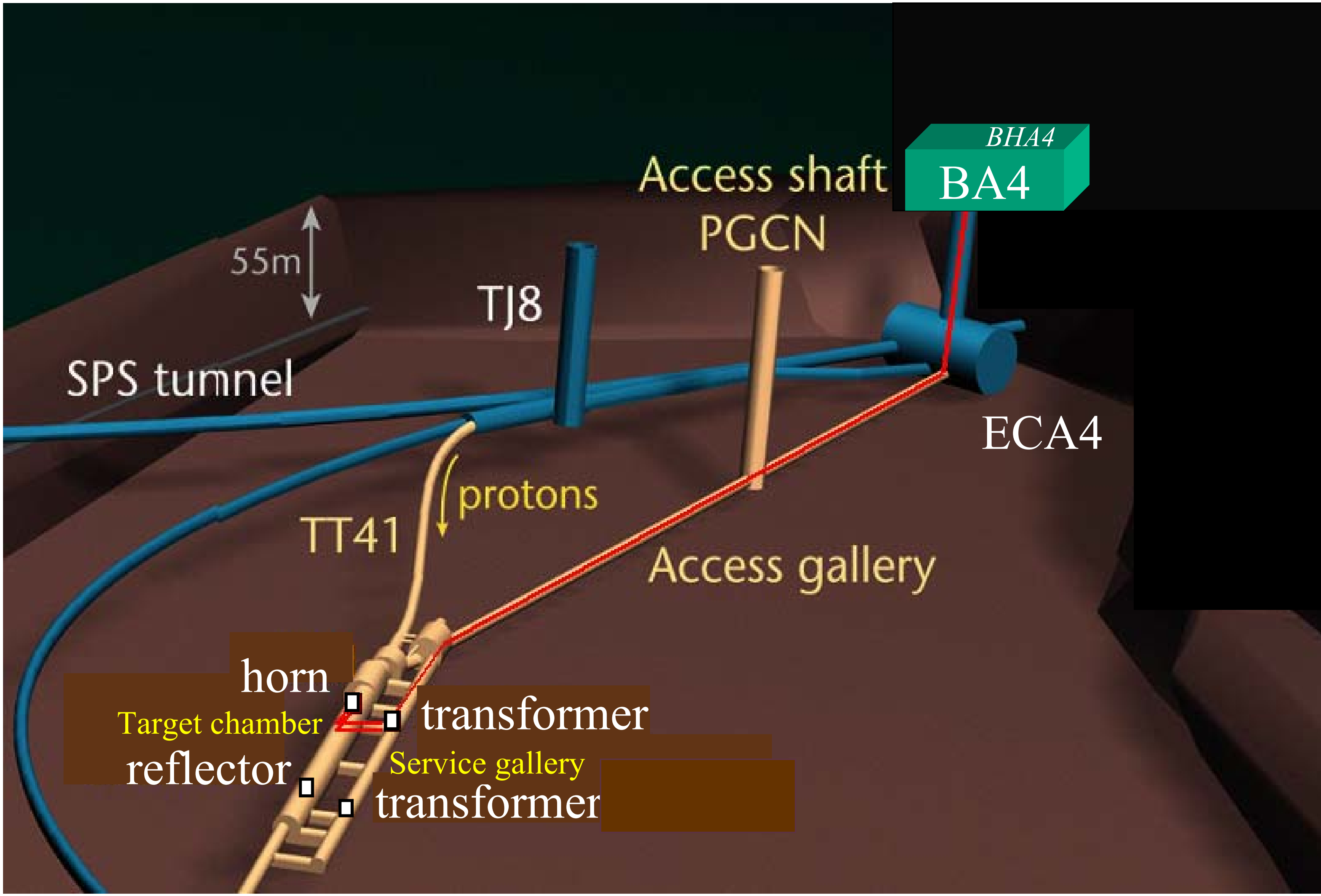
reliability

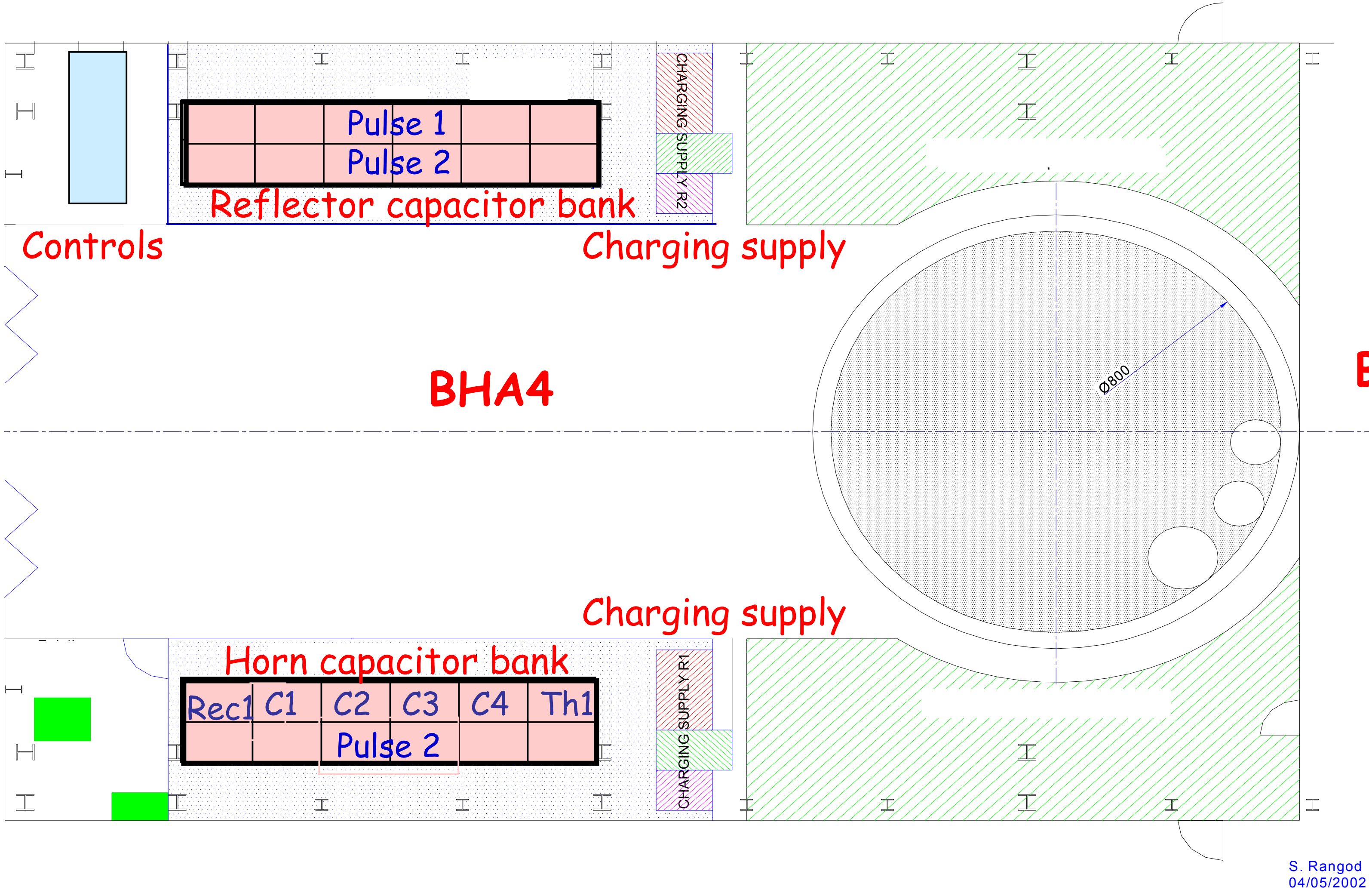


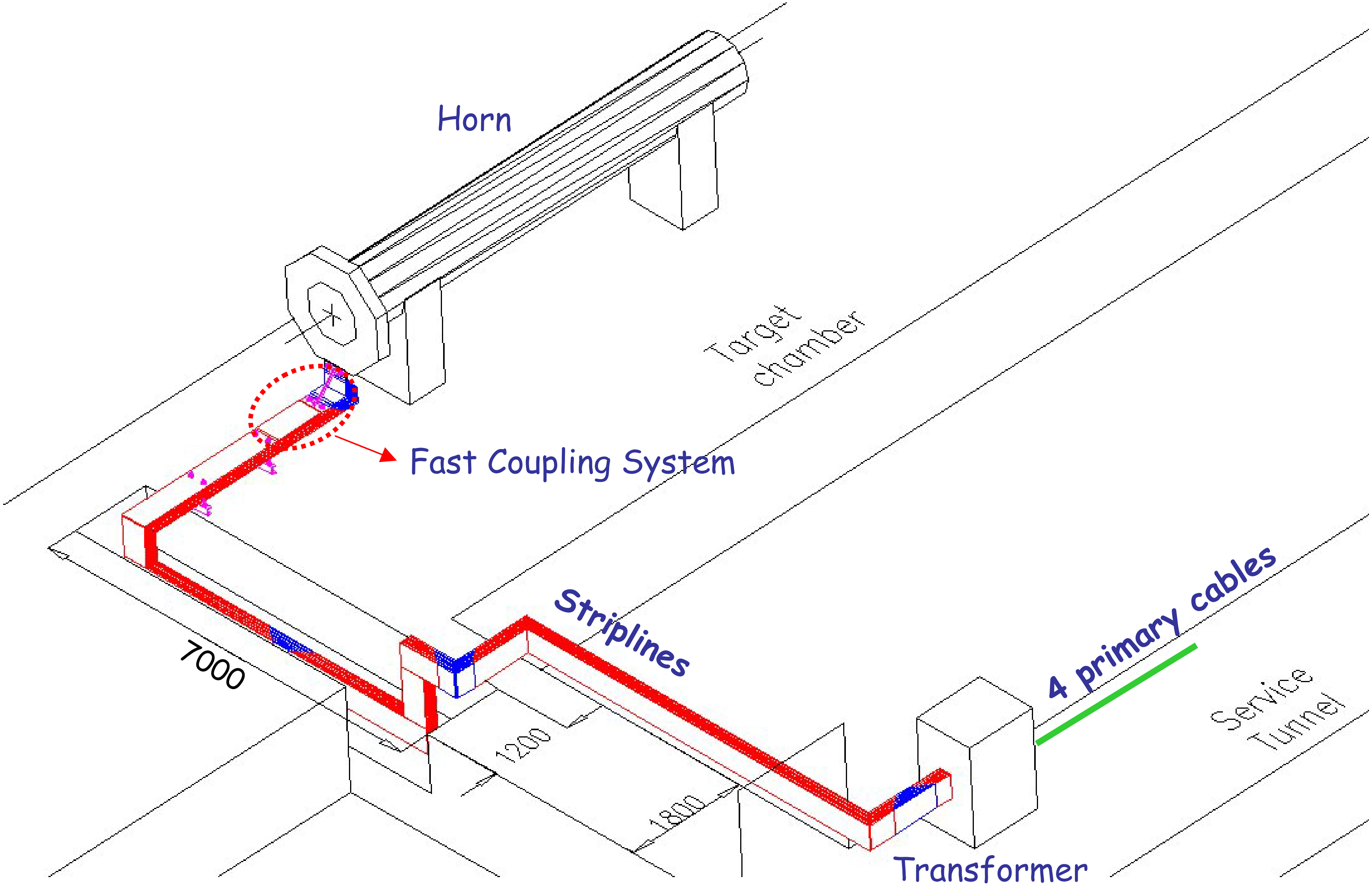


CNGS + Fixed target

Horn electrical circuit layout for CNGS




Pulse 1
Pulse 2
Reflector capacitor bank
CHARGING SUPPLY R2
Controls
Charging supply
BHA4
Ø800
BB4
Charging supply
Horn capacitor bank
Rec1
C1
C2
C3
C4
Th1
Pulse 2
CHARGING SUPPLY R1
S. Rangod
04/05/2002


Horn
Target chamber
Fast Coupling System
7000
Striplines
4 primary cables
1200
1800
Service Tunnel
Transformer

CNGS HORN

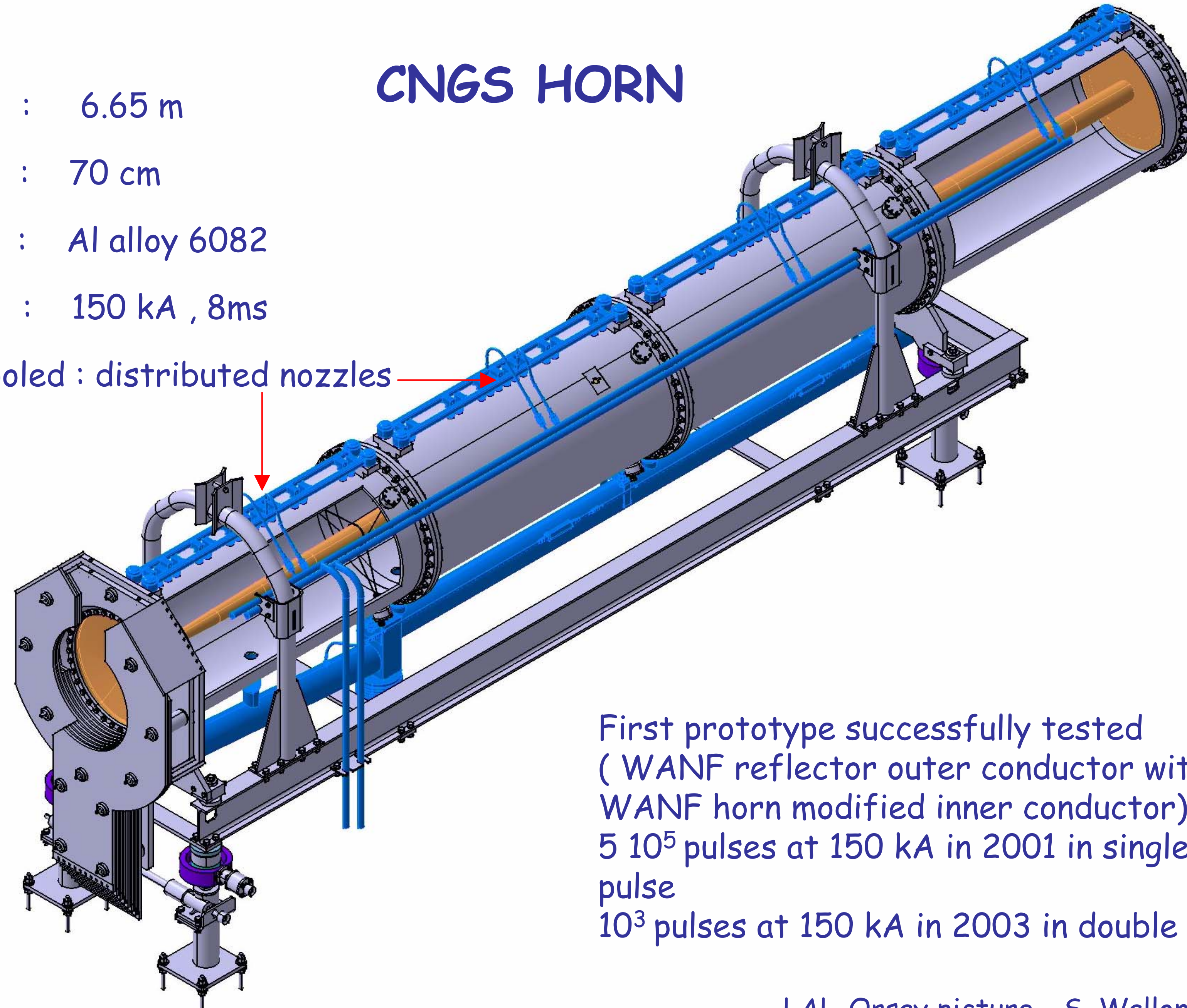
Length : 6.65 m

Diameter : 70 cm

Material : Al alloy 6082

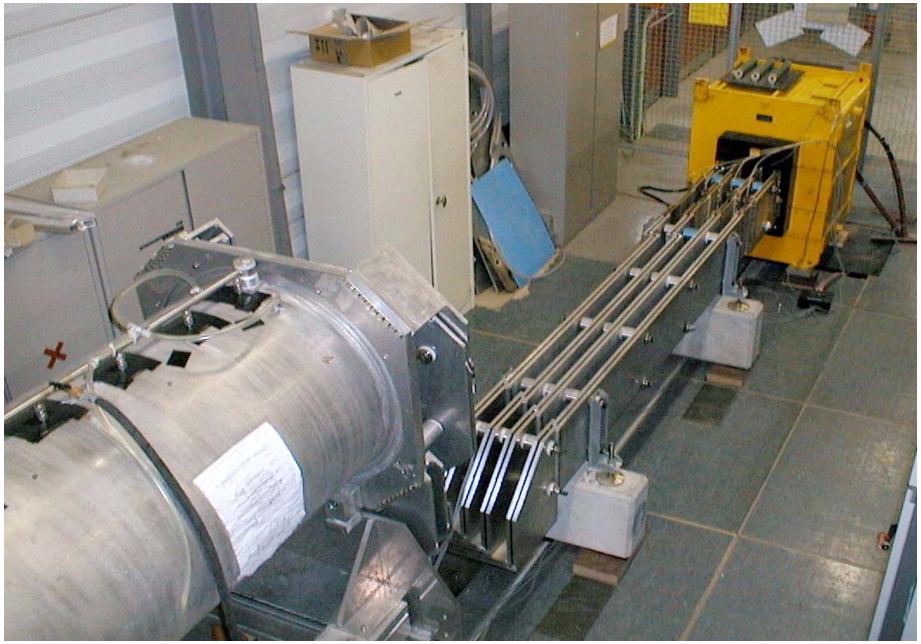
Pulsed : 150 kA , 8ms

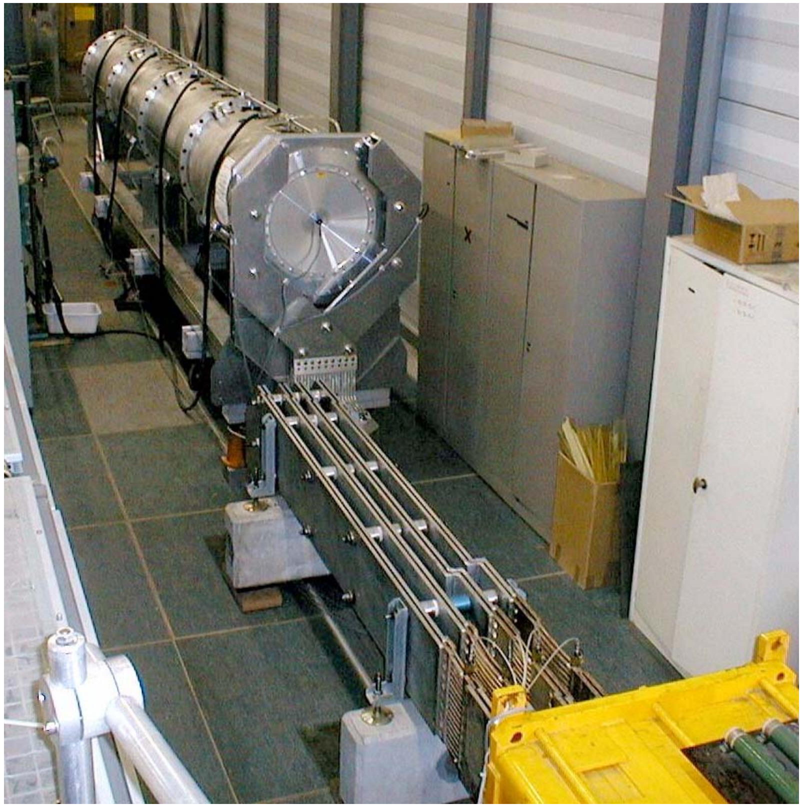
Water cooled : distributed nozzles



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

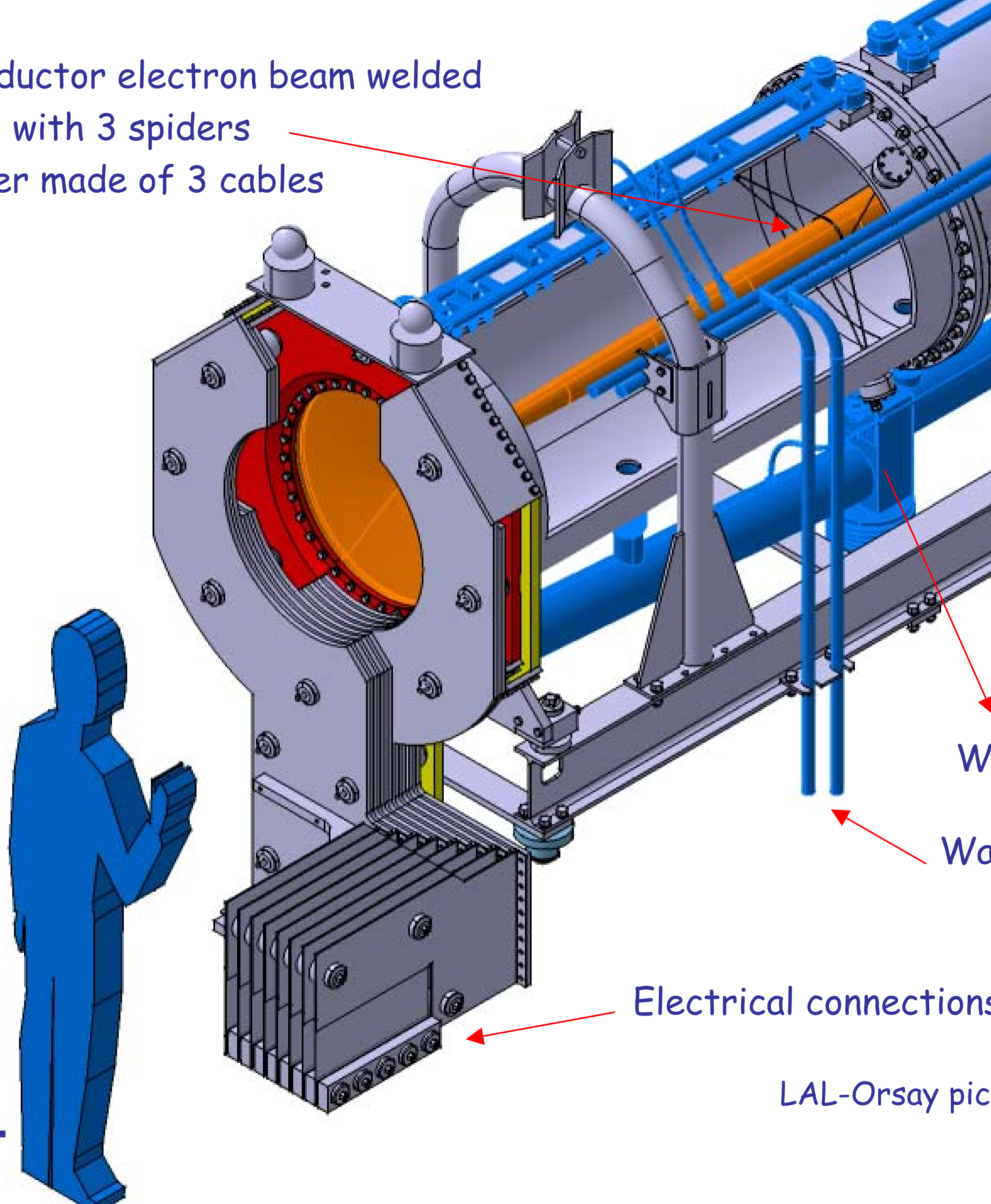
LAL-Orsay picture - S. Wallon





BA7 horn test area (CNGS prototype testing in 2000-2001)
horn with modified wanf inner conductor

Inner conductor electron beam welded
supported with 3 spiders
Each spider made of 3 cables



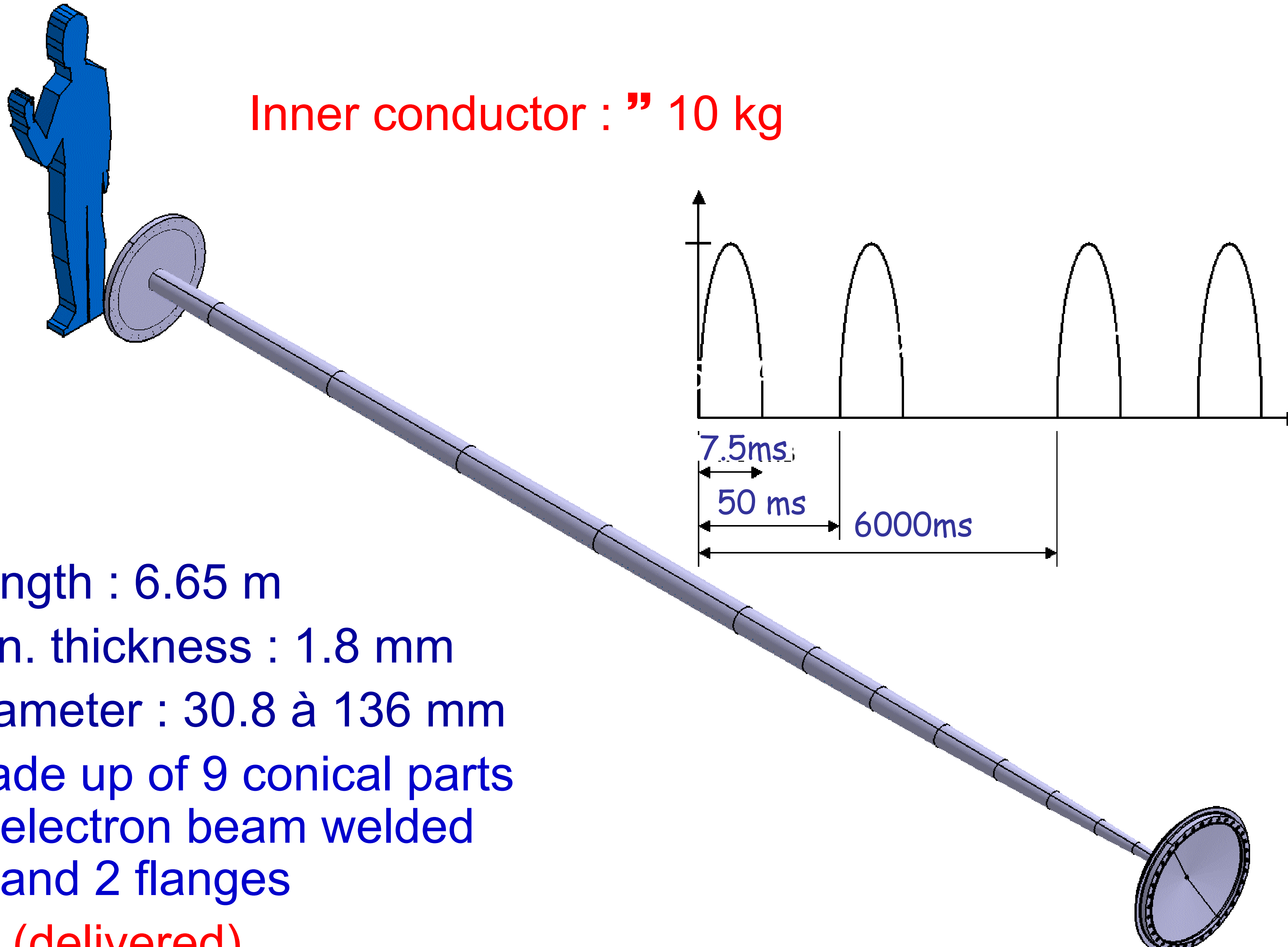
Water supply out

Water supply in

Electrical connections – 4 pairs of plates

LAL-Orsay picture - S. Wallon

Inner conductor : ” 10 kg



Length : 6.65 m

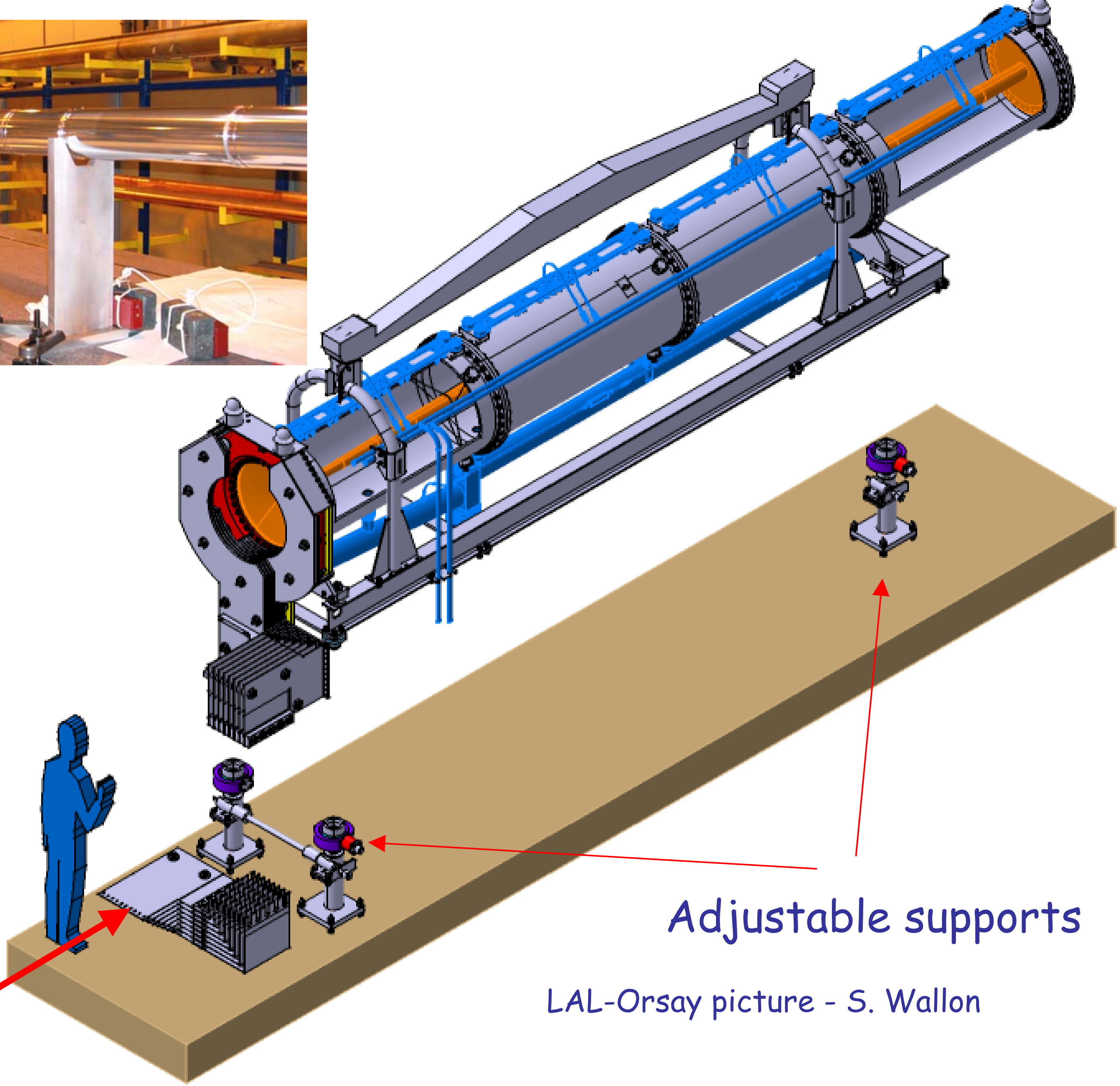
Min. thickness : 1.8 mm

Diameter : 30.8 à 136 mm

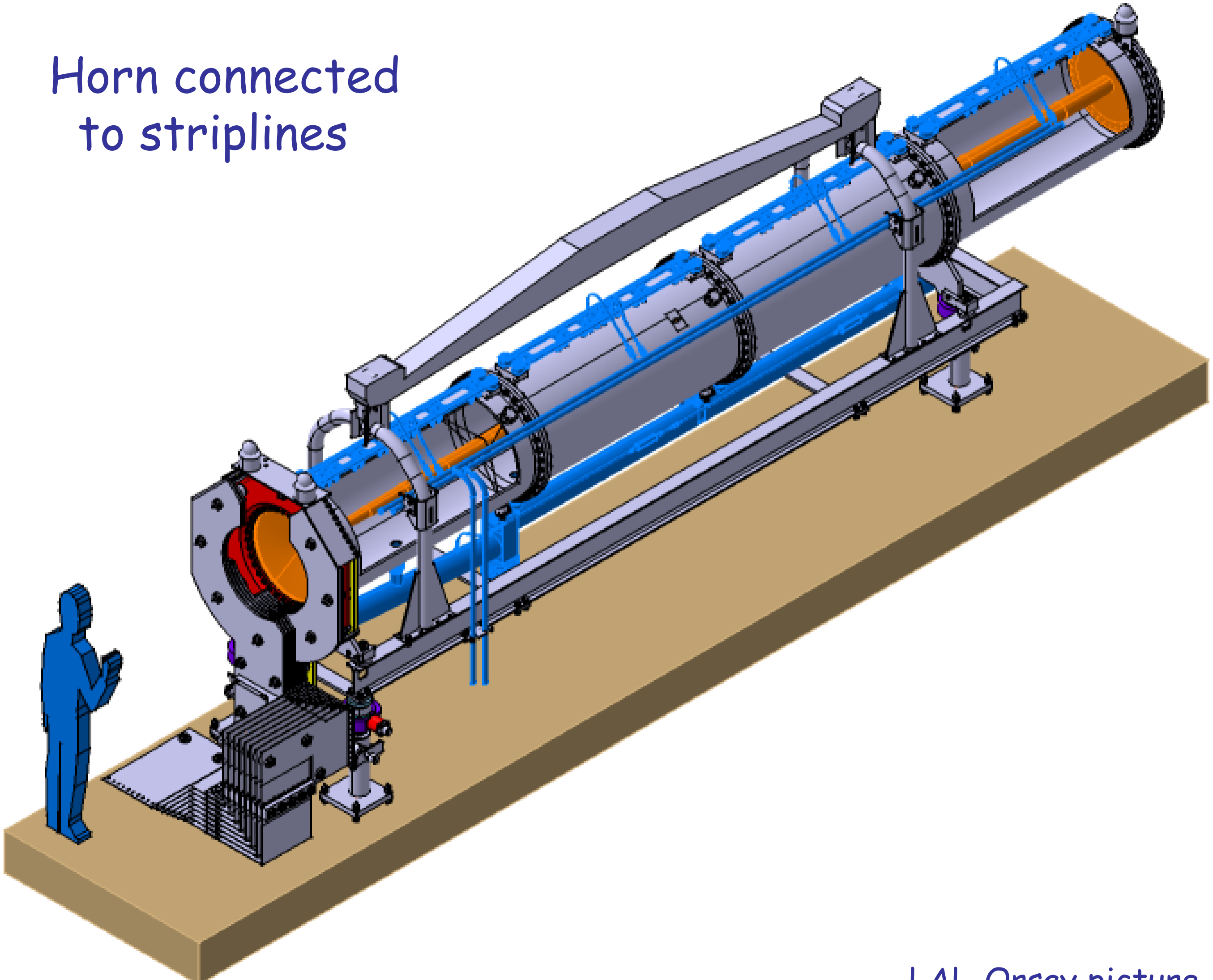
made up of 9 conical parts
electron beam welded
and 2 flanges

(delivered)

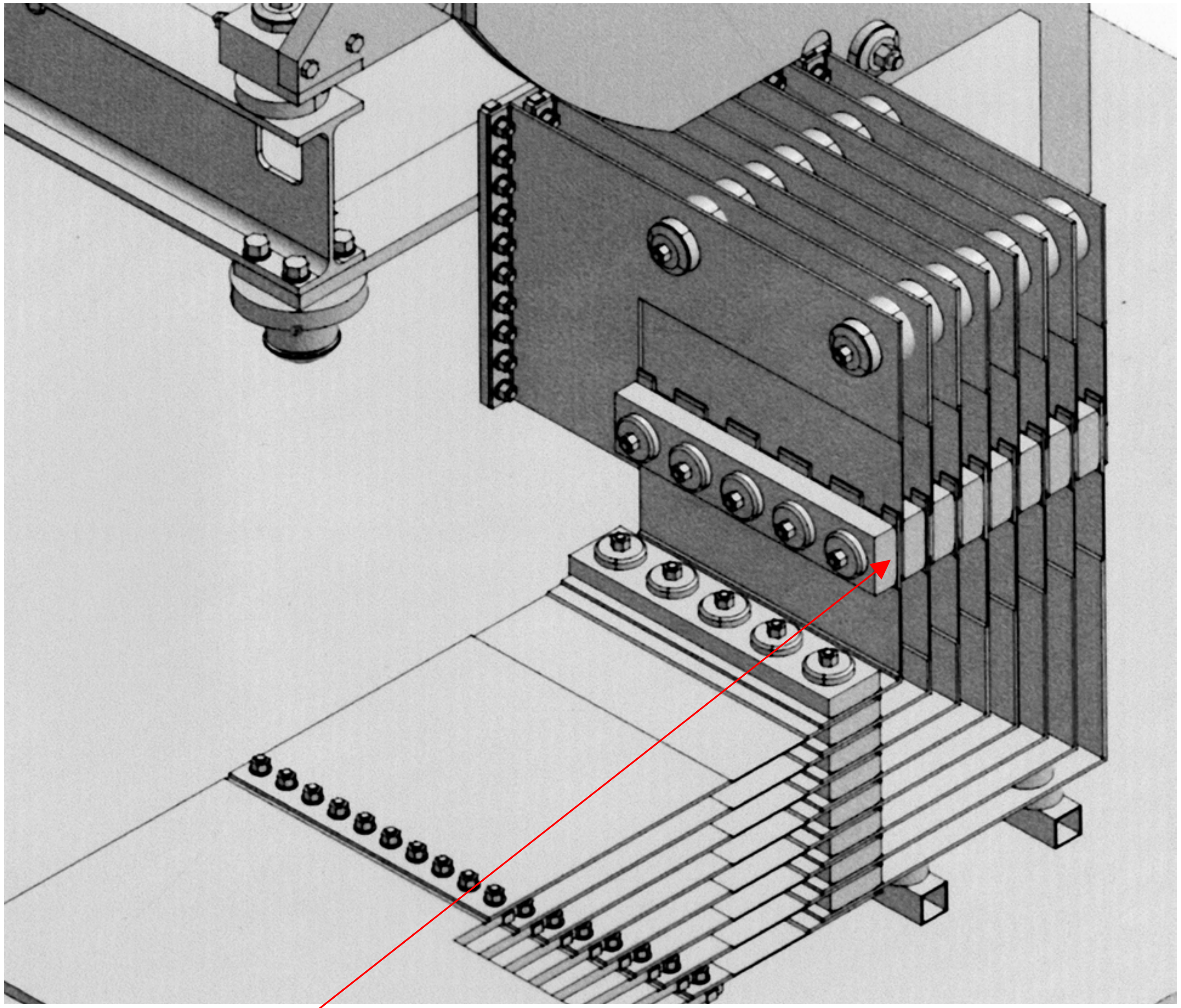
LAL-Orsay picture - S. Wallon


Adjustable supports
LAL-Orsay picture - S. Wallon
striplines

Horn connected to striplines

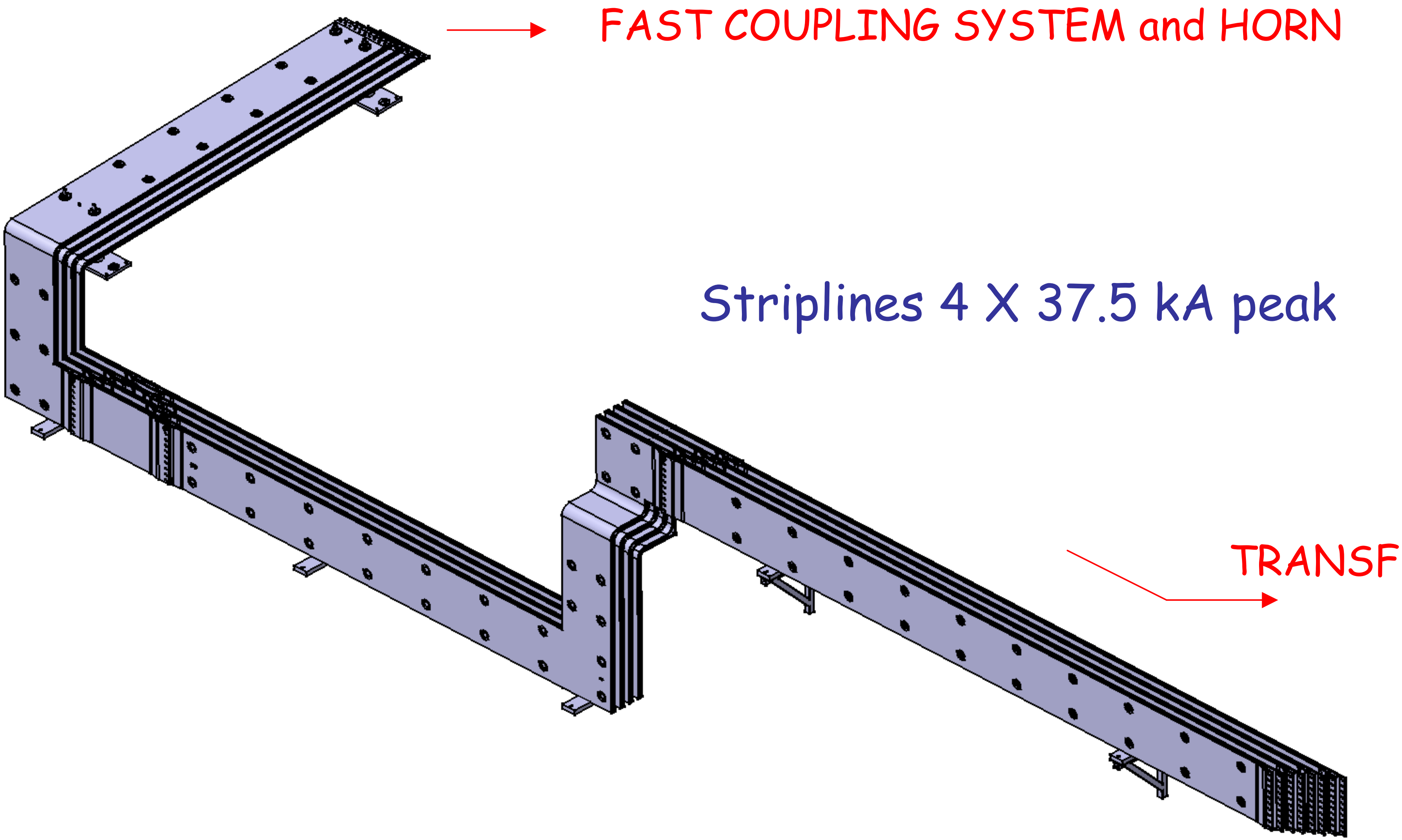


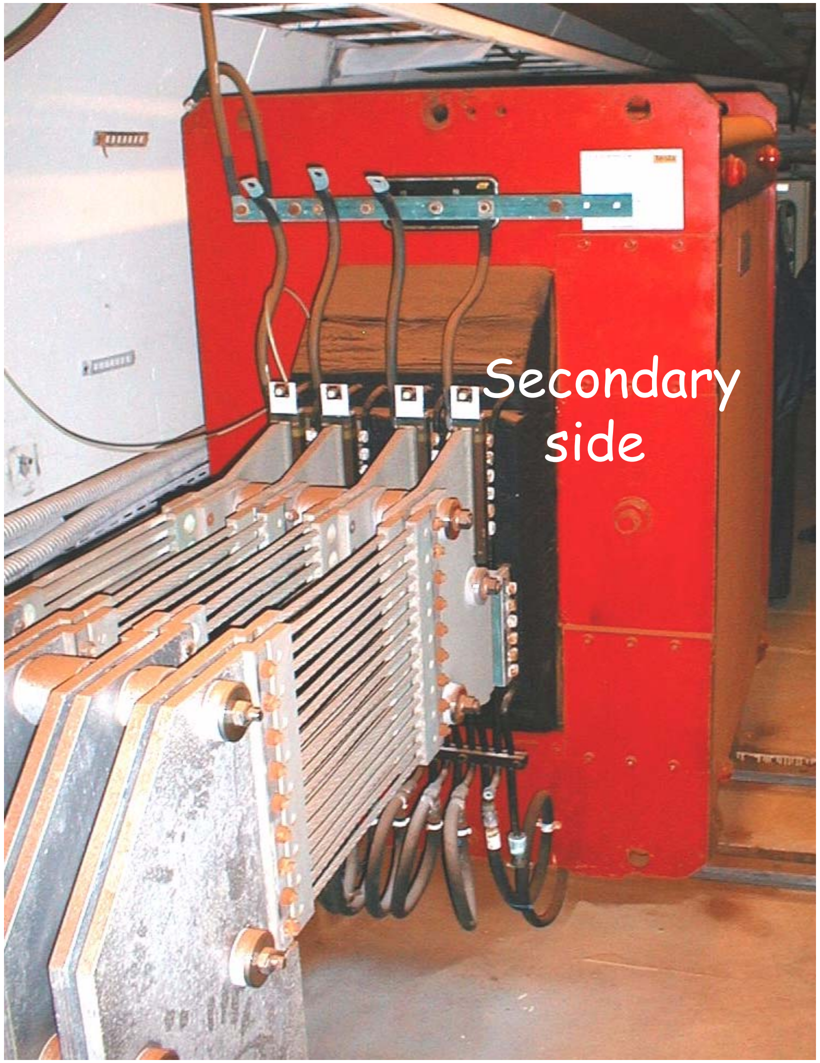
LAL-Orsay picture - S. Wallon



Fast coupling system

LAL-Orsay picture - S. Wallon


FAST COUPLING SYSTEM and HORN
Striplines 4 X 37.5 kA peak
TRANSF.



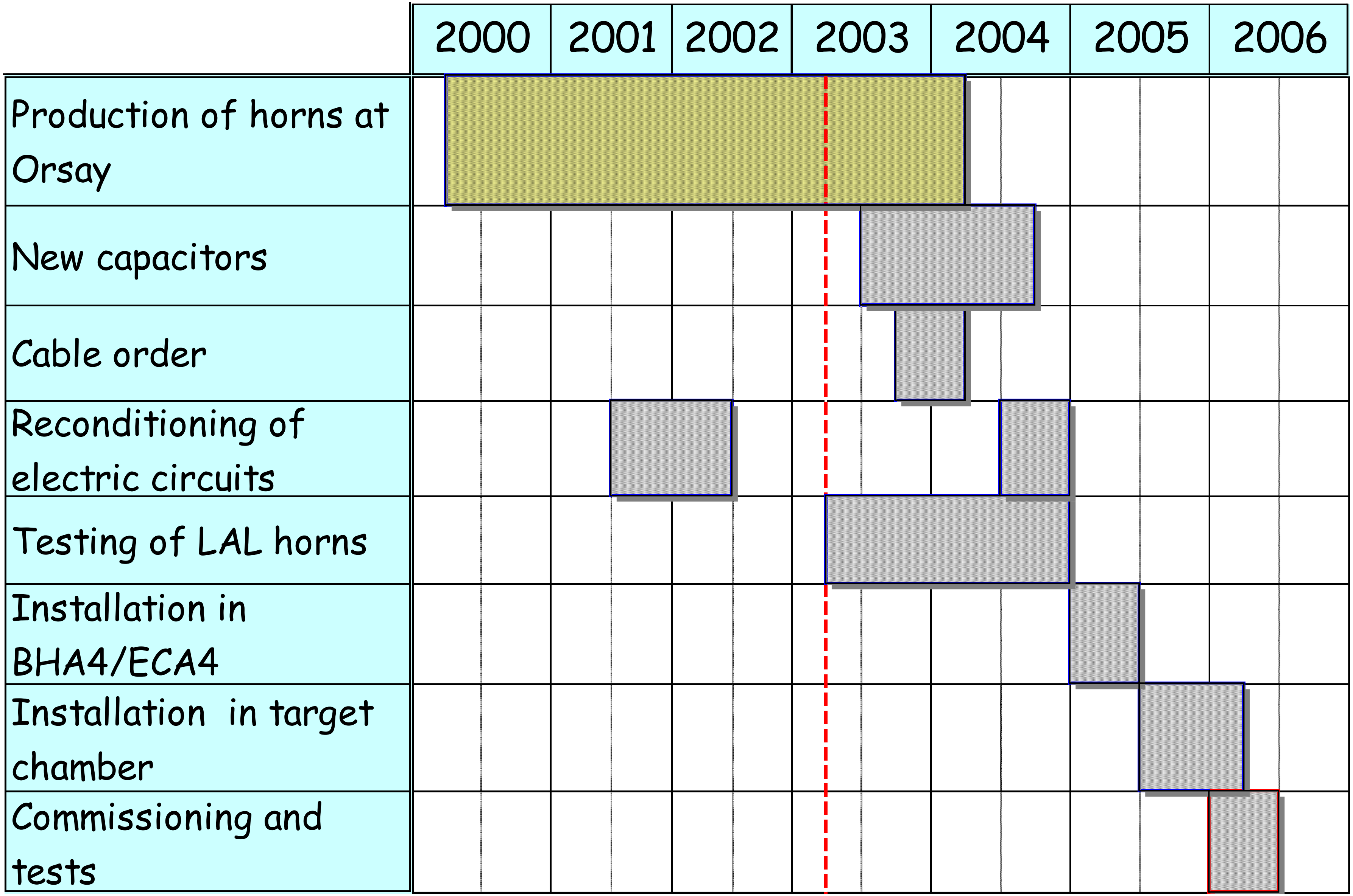
Recuperated WANF TESLA transformers

-transformer ratio 16 (2&2 secondary couplings not mounted)

Operation parameter table updated April 2003

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

Status of CNGS horn project in April 2003

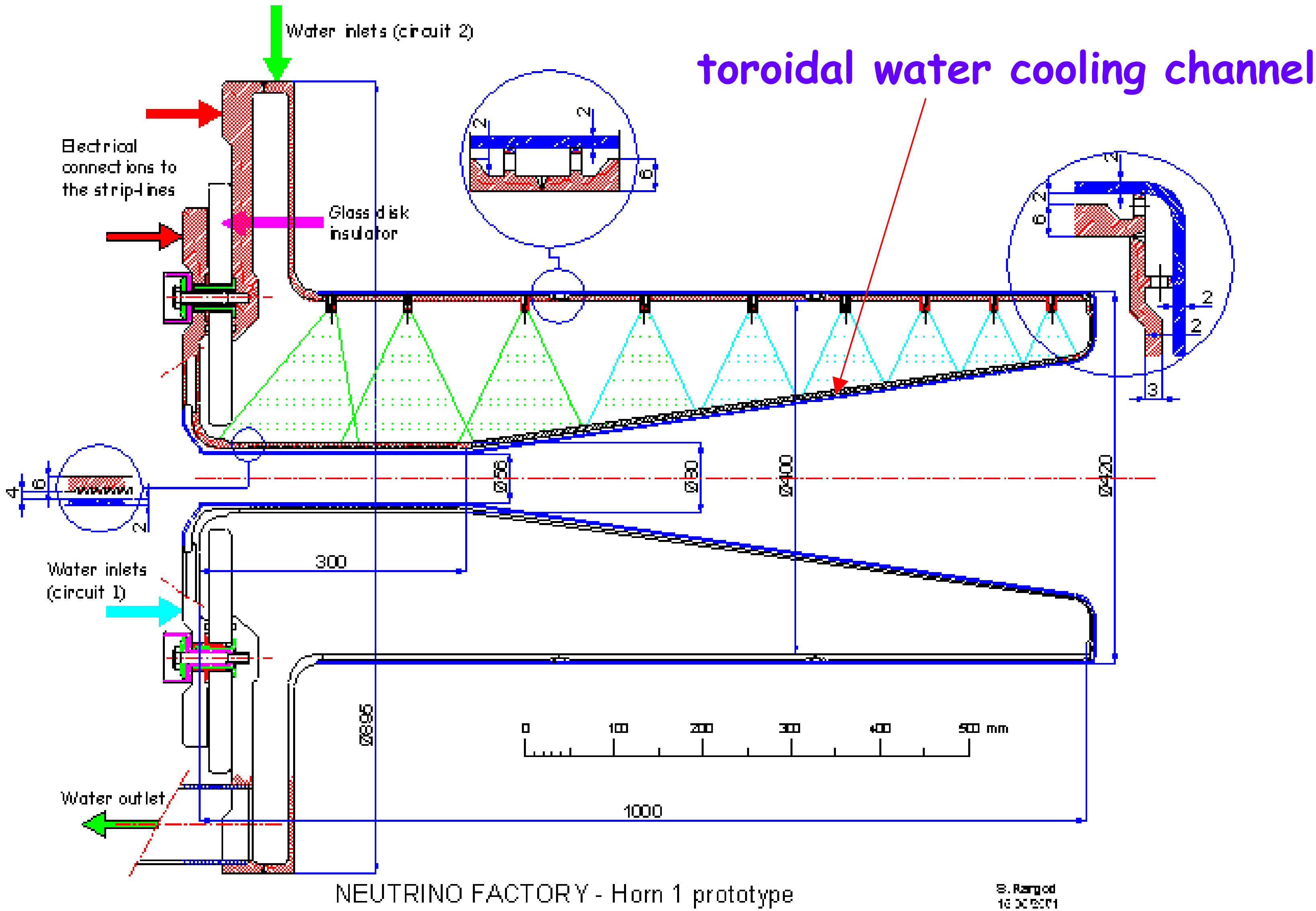


3.5 Neutrino Factory studies for future

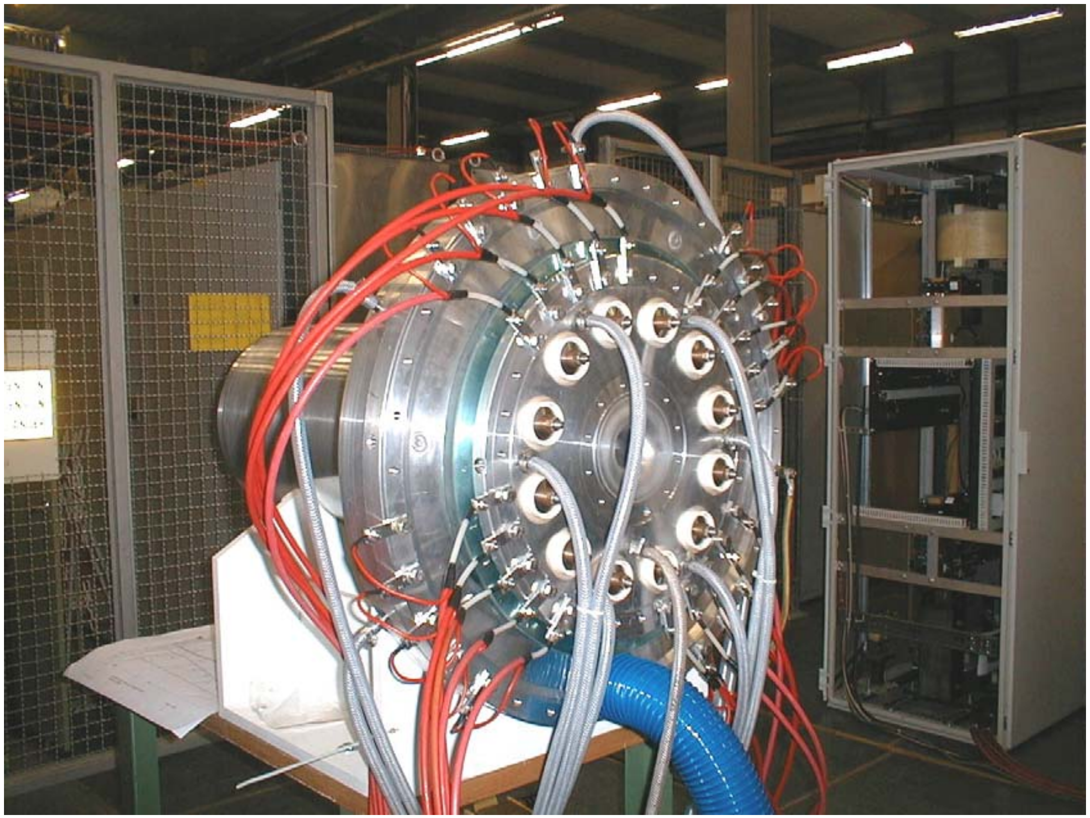
Prototype developed at CERN in 2001

Maximum current	:	300 kA
Pulse repetition rate:		50 Hz
Waist diameter	:	80 mm
Length	:	1030 mm
Life time	:	6 weeks or 2 x 10^8 pulses for the prototype (six months or 8 x 10^8 pulses for a final horn)
Pulse length	:	$\leq$ 100 µs
r.m.s current	:	15 kA (CMS – 20 kA)
Voltage on horn	:	~ 4000 V
Skin depth	:	1.25 mm
Joule losses	:	40 kW

Main technical problems : Cooling, vibrations, irradiation,fatigue



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 responsability 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.

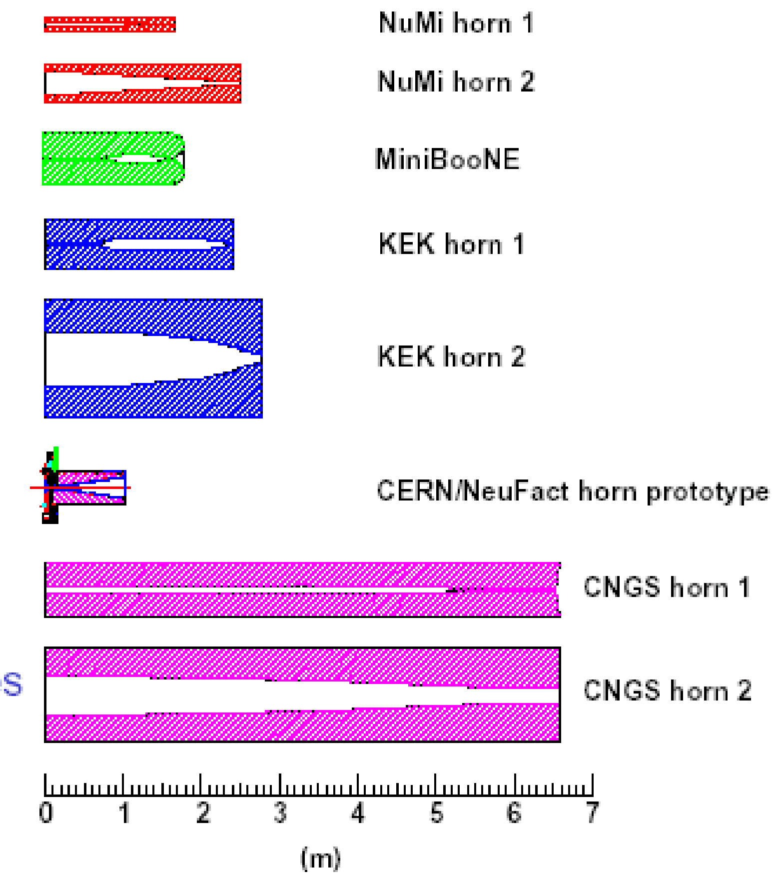
Numi: 200 kA, 0.5 Hz, 6M pulses
1 year

MinibooNe: 170 kA, 5 Hz, 11M pulses
1 year

K2K: 250 kA, 0.5 Hz, 11M pulses
1 year

Nufact: 300 kA, 50 Hz, 200 M pulses
6 weeks

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



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 $\blacksquare_{\tau}$ appearance (τ 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