Horn R&D: present and future

Simone Gilardoni
CERN – PS/PP
DPNC Université de Genève

For the CERN Horn working group

Horn prototype developed in the frame of the NUFACT Target-Collector activity

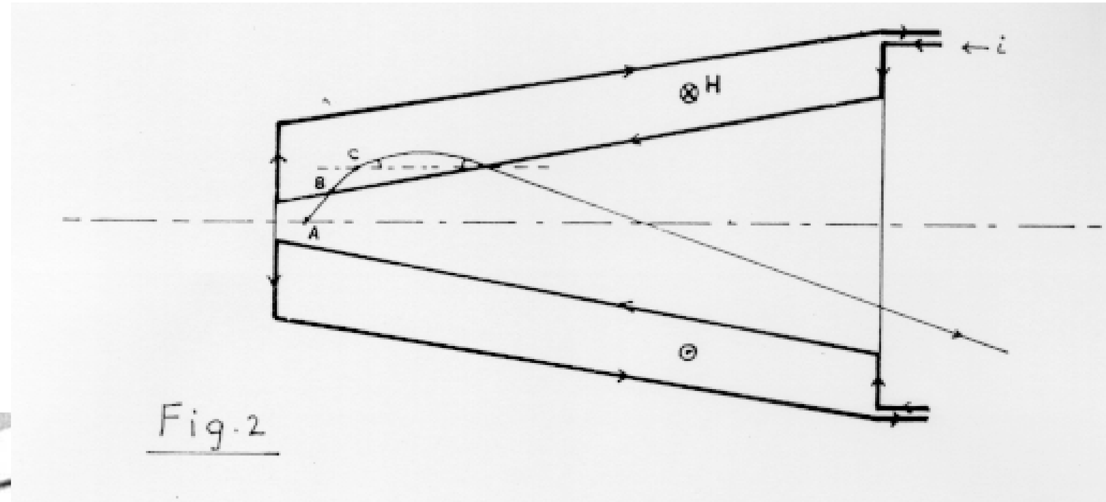
Working Group

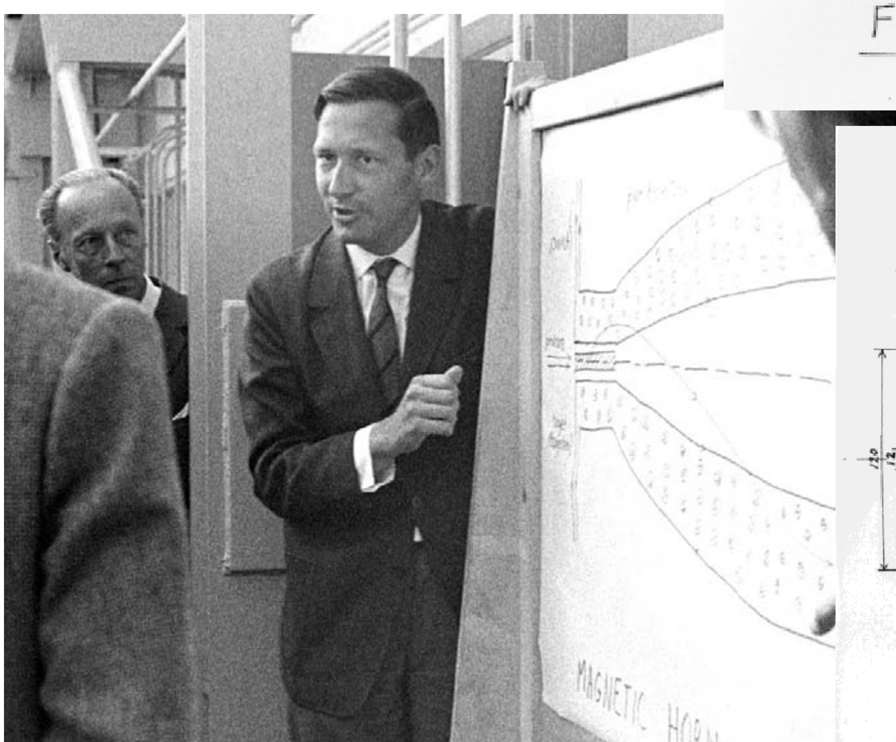
Autin B. - Gilardoni S. - Grawer G - Maire G.
Maugain J-M. - Rangod S. - Sievers P. - Voelker F.

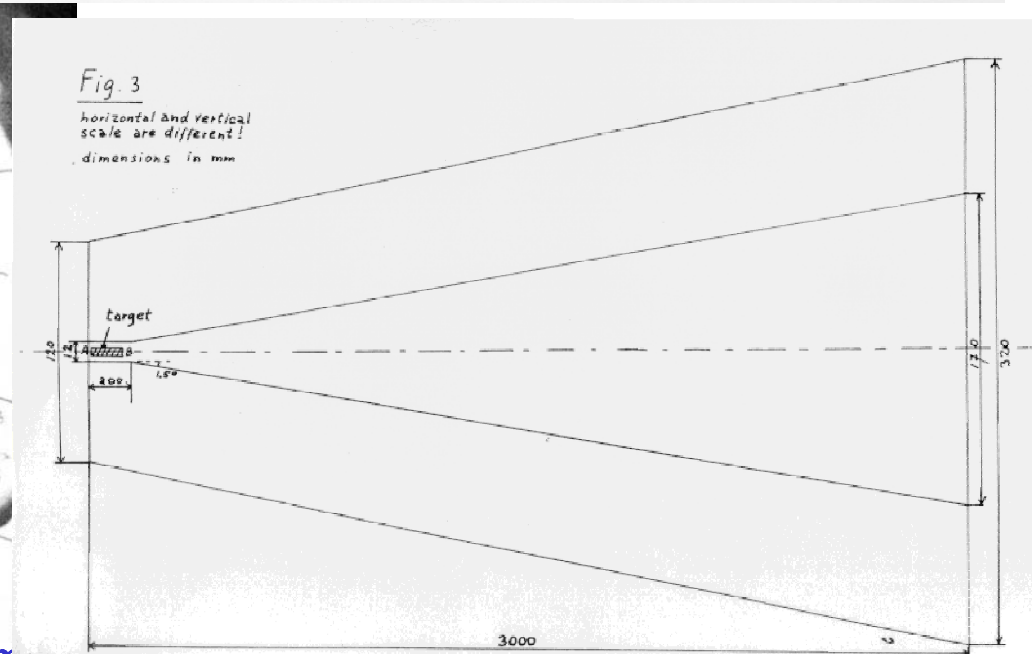
Reference: CERN-NUFACT Note 80

Horn history

Introduced in ≈ 1961
by S. Van der Meer

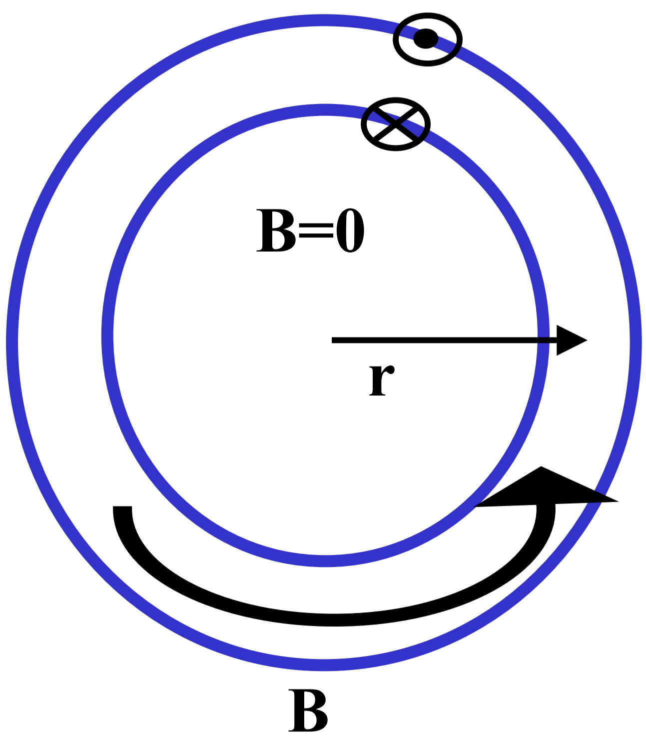






How it works, nothing magic

From the lecture "Physique de Base" the Ampere law:



$$\oint B \cdot dl = 2\pi r B = \mu_0 I$$

$$B = \frac{\mu_0 I}{2\pi r}$$

⊗ Current OUT

⊙ Current IN

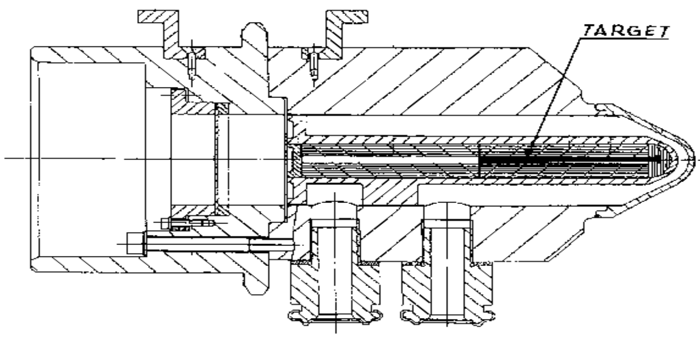
First horn built

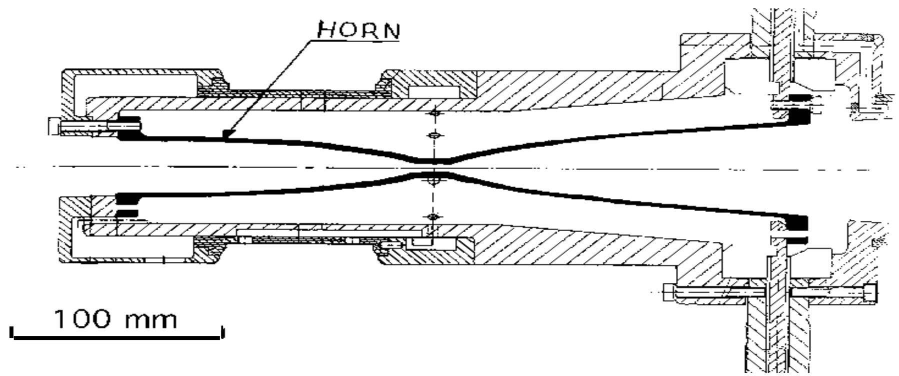
Horn features:

- Focus only one particle sign
- Compact element
- Radiation hard
- Low Cost

Horn in use at CERN

AD horn (see Microcosm) 300 kA, 0.5 Hz, 1M pulses

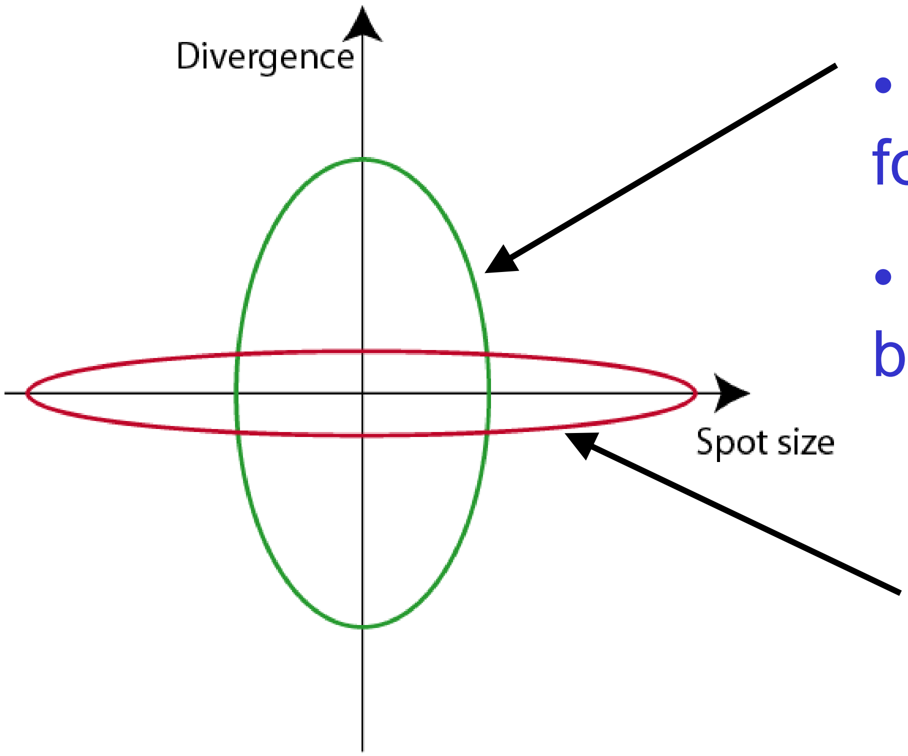




AD Target station

Horn optic design

Maximization of secondary flux into a given acceptance:



Accelerator acceptance

- Max divergence fixed by focusing in the channel
- Max radius fixed by the beam pipe aperture

Neutrino beam experiment

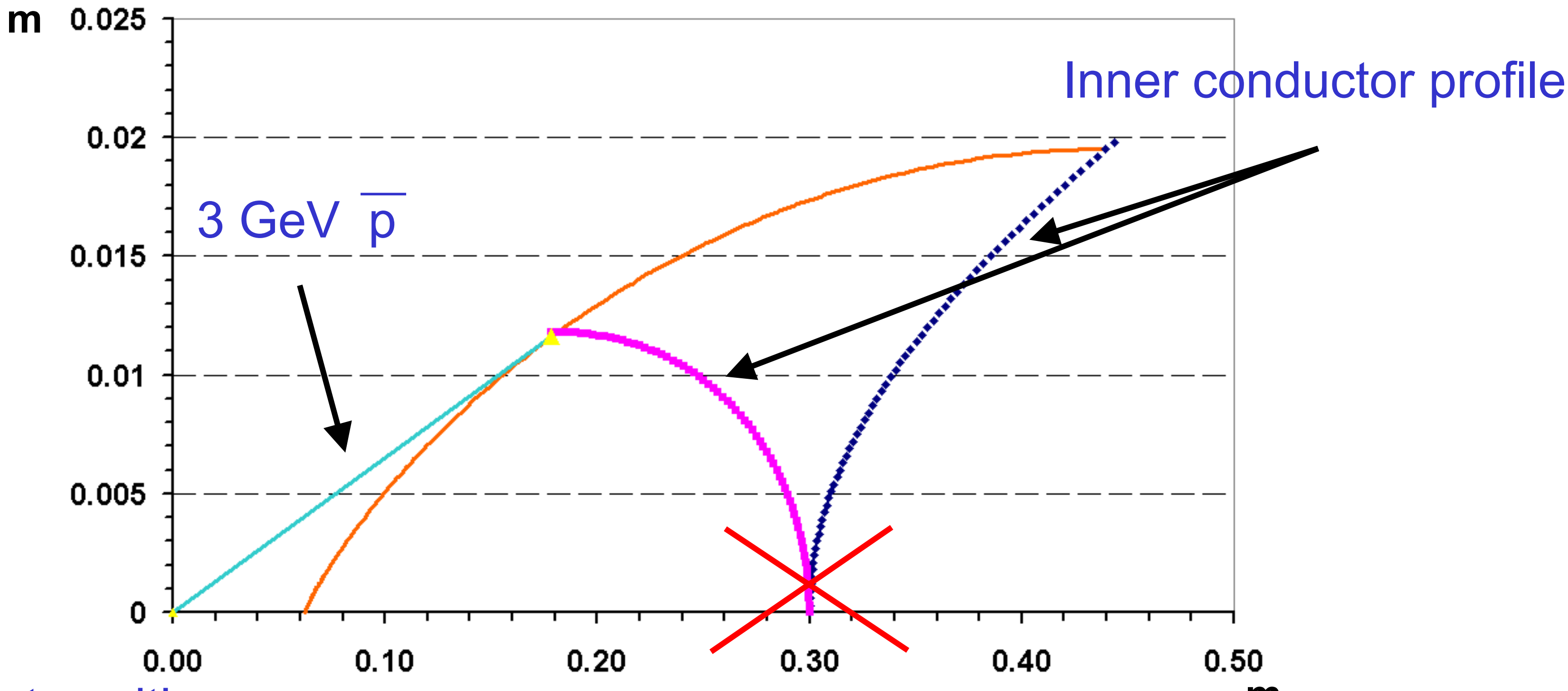
- Max divergence small to have a small spot size at the experiment site
- Max radius doesn't matter

AD horn design

From equation of motion in 1/R field:

For a monoenergetic beam and a point like source

Theoretical shape to have a point to parallel beam

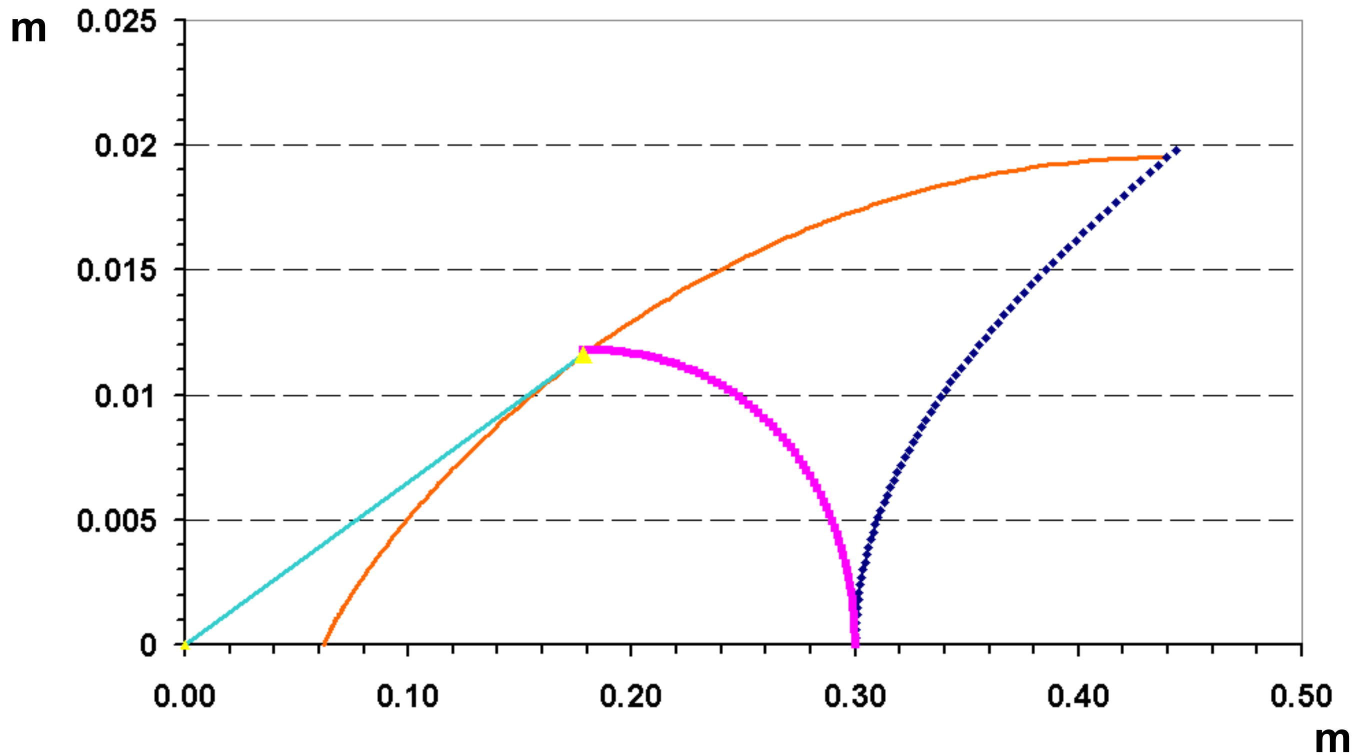


Target position

Cut away

Design choices

- Shape both the profiles: AD, Numi
- Approx the theoretical profiles with straight lines: NuFact
- Fix one and shape the other: CNGS
- Combine the first two approaches: MiniBoone



Horns available from the shelf

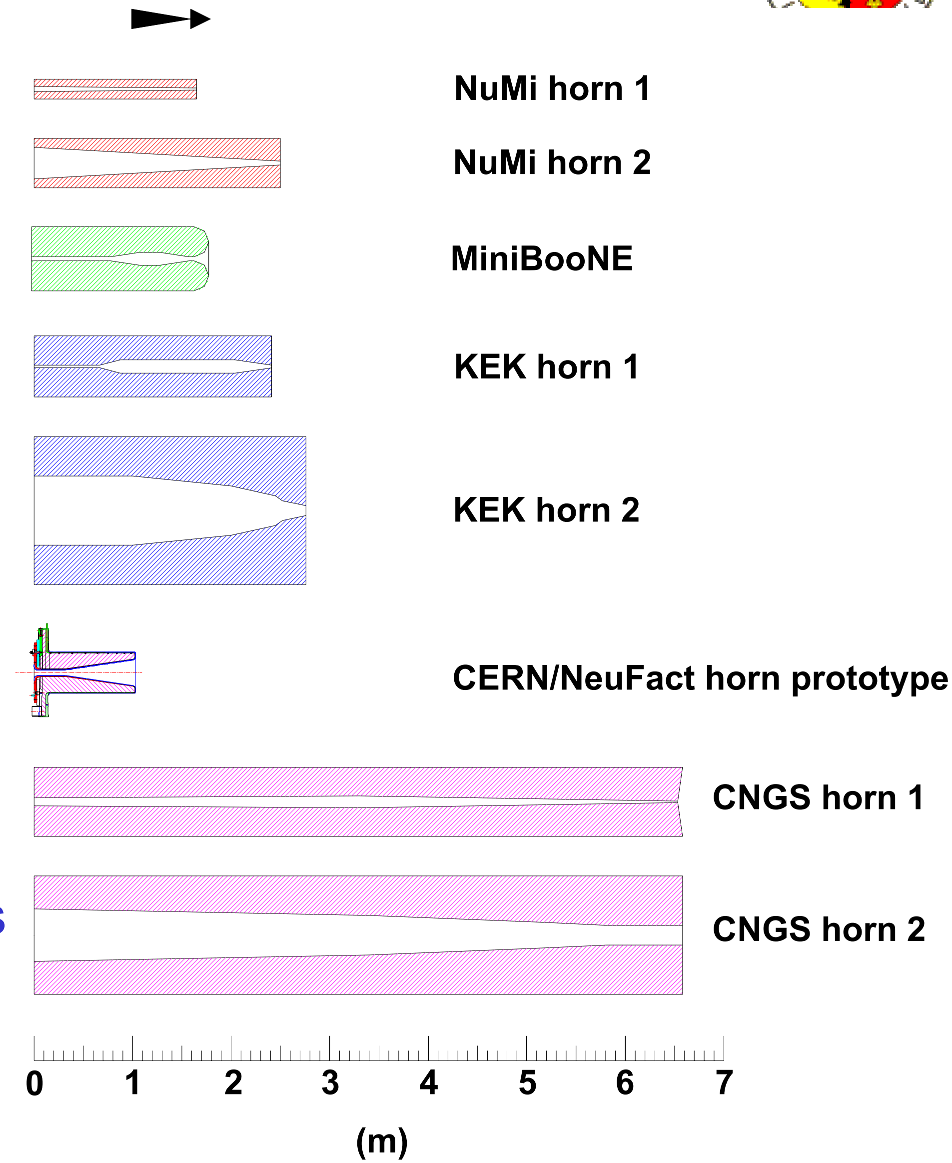
Numi: 200 kA, 0.5 Hz, 6M pulses
1 year

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

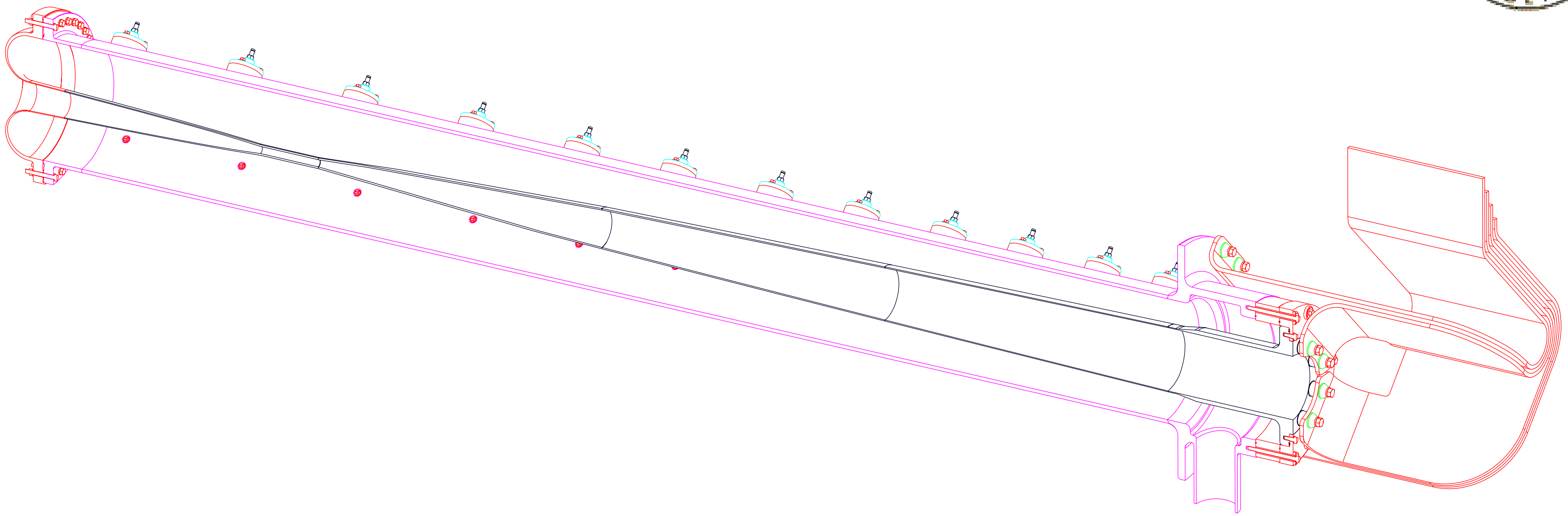
K2K: 250 kA, 0.5 Hz, 11M pulses
1 year

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

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

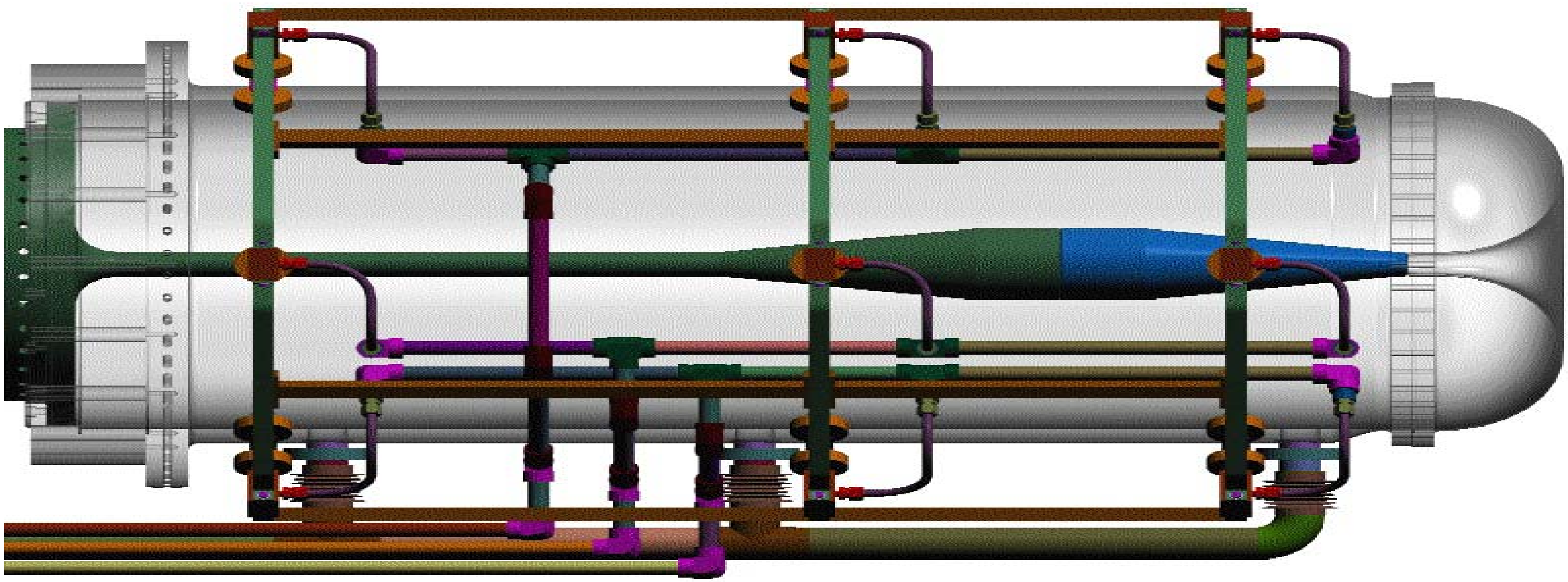


Numi horn inner conductor



Miniboone

- From trasp. of Ioanis Kourbanis



Caveats

- The target is not point-like:
  - Normally 1-2 interaction lengths
    - Order 1 m for light targets (Be)
    - Order 20-30 cm for heavy targets (Hg)

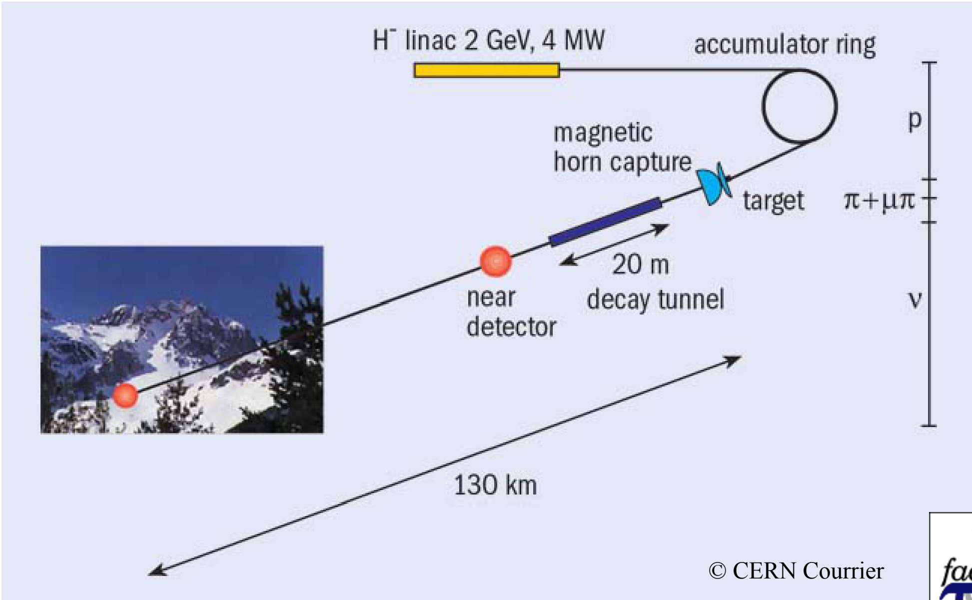
- Particle produced with large energy spread

- In any case, as Van der Meer dixit:
  - Max angle for a given momentum depends only on the <u>square root</u> <u>of the current</u>

$$\theta_{MAX} = \sqrt{\frac{\mu_0 I}{2\pi \frac{p}{0.3}}}$$

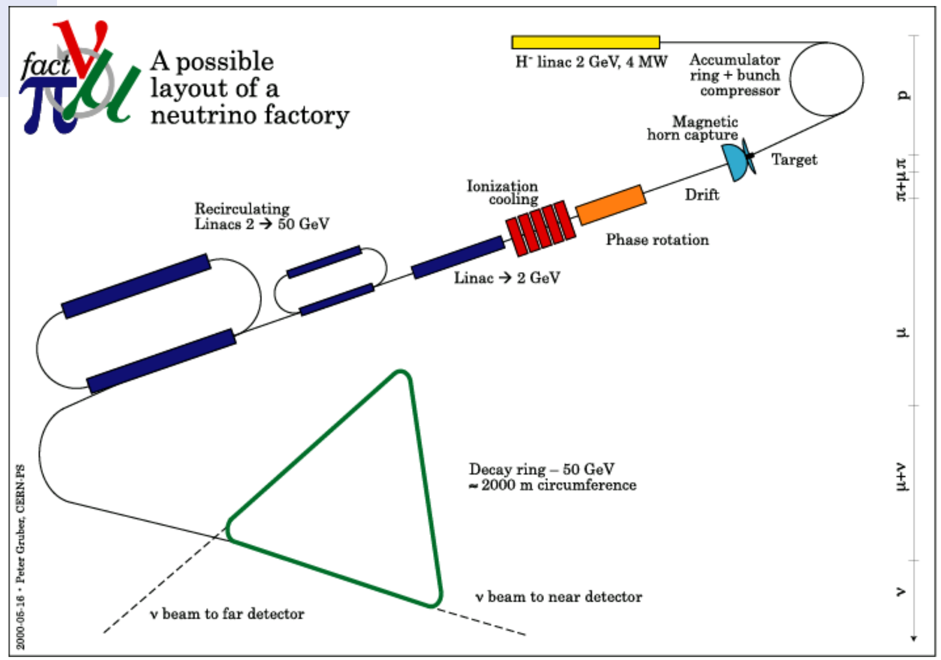
Optimisation criterium = Physics reach

Nufact + SuperBeam



Same Inner horn for SuperBeam & Nufact

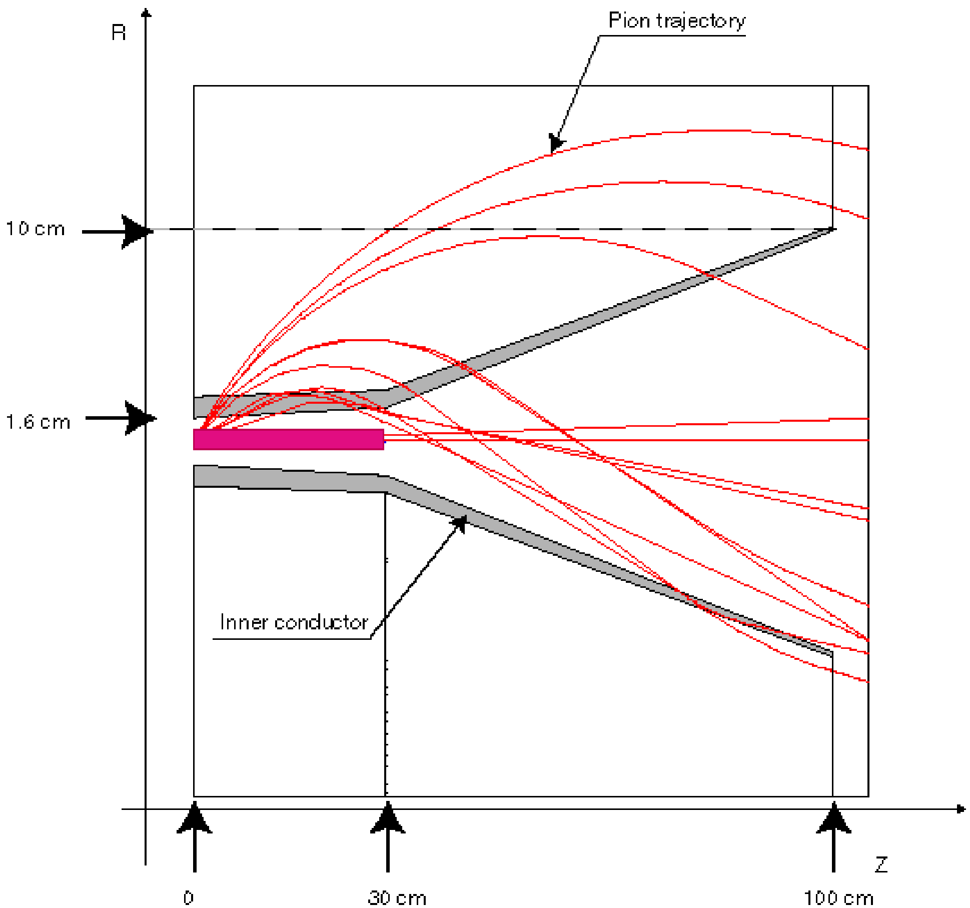
Different optimisation of the outer horn for the two cases

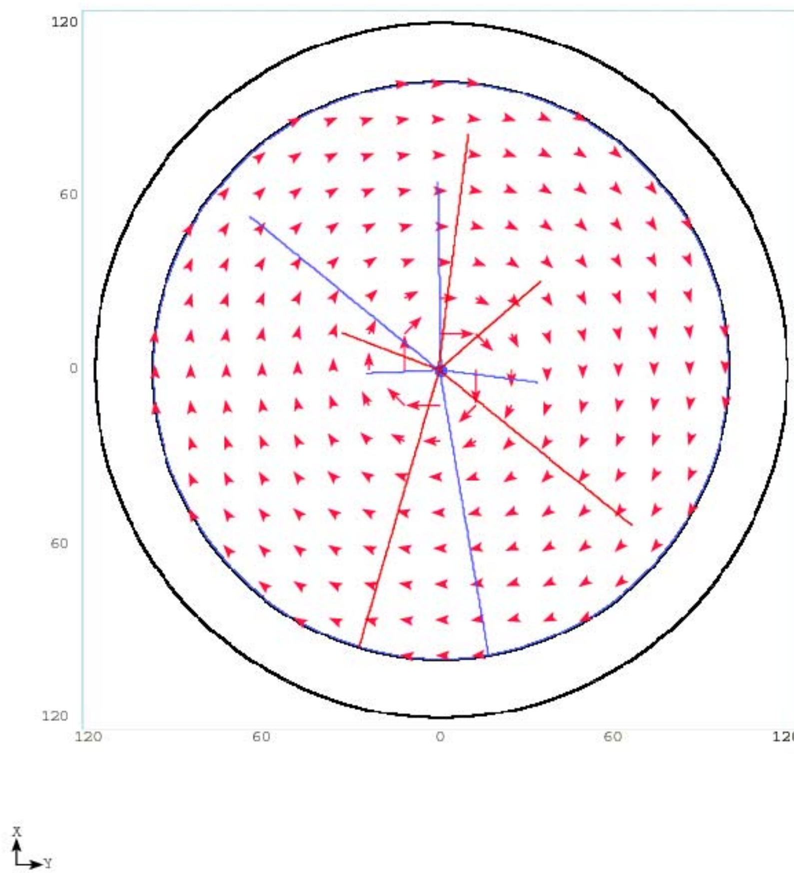


Same Horn operation mode:

- 4 MW proton beam
- 50 Hz rep. rate
- Current as high as possible

Old horn Nufact

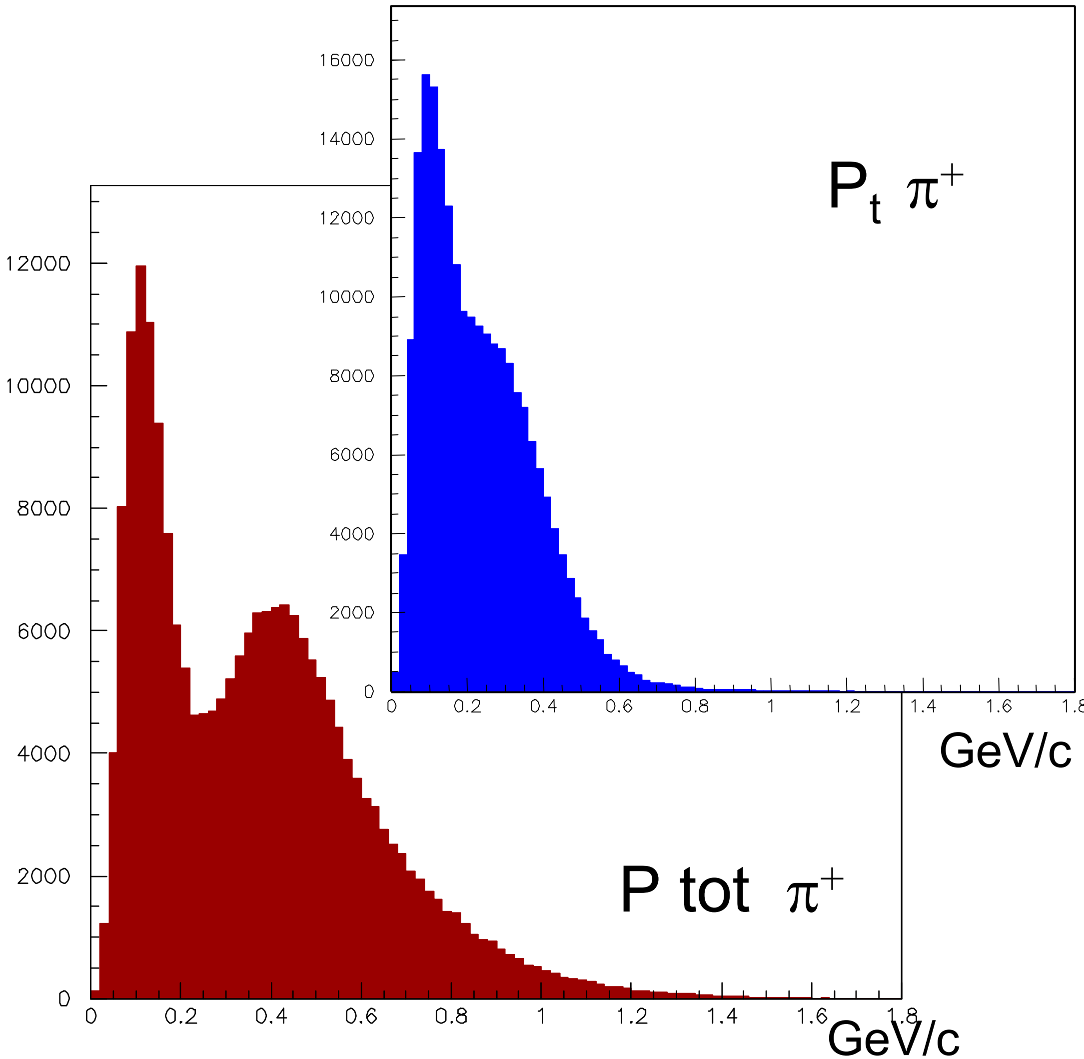


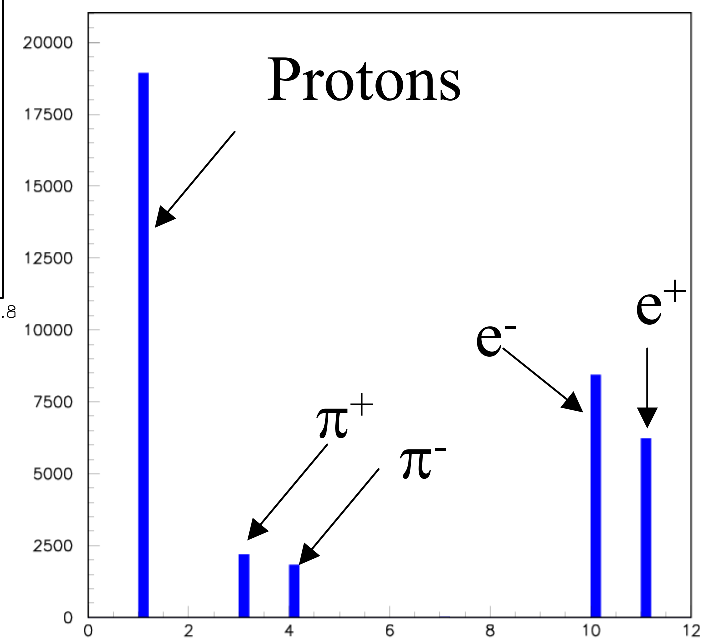


Horiz.+ Vert. scale different

Particles at target

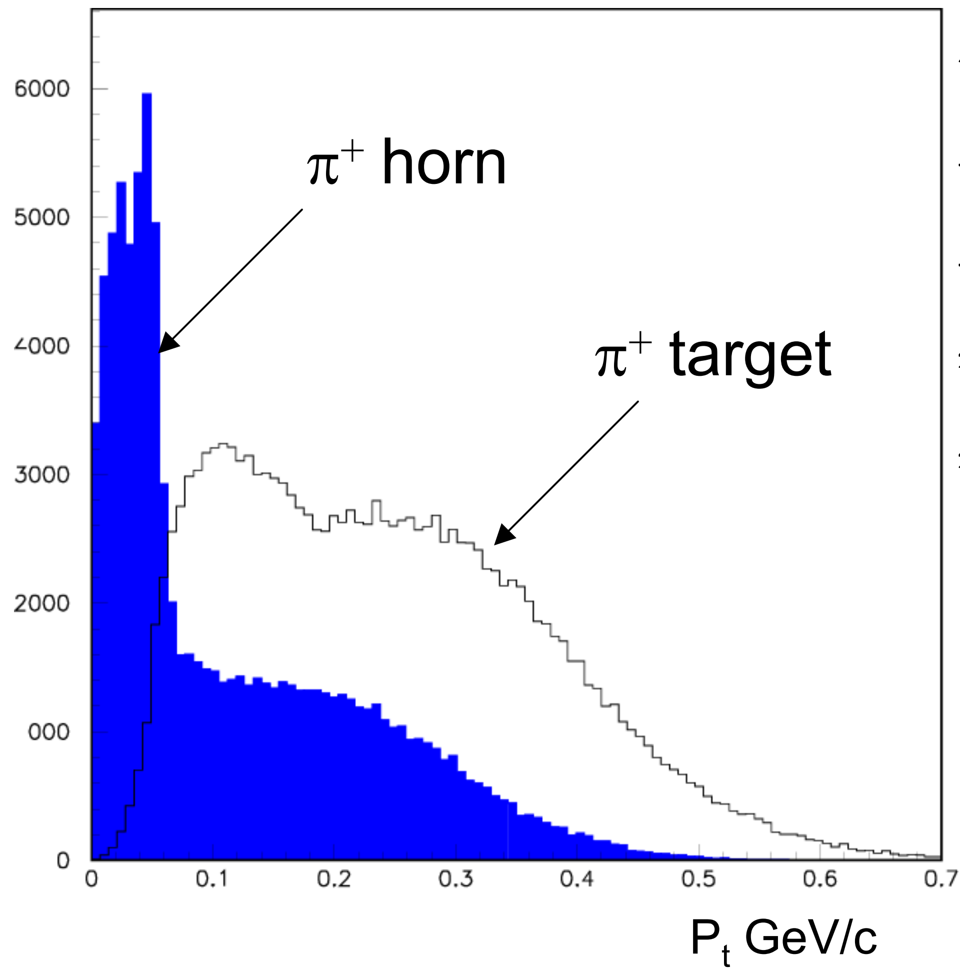
- Hg target
  - 26 cm (2 λ_I)
  - 2.2 GeV p beam
- 20% more π^+ Vs π^-



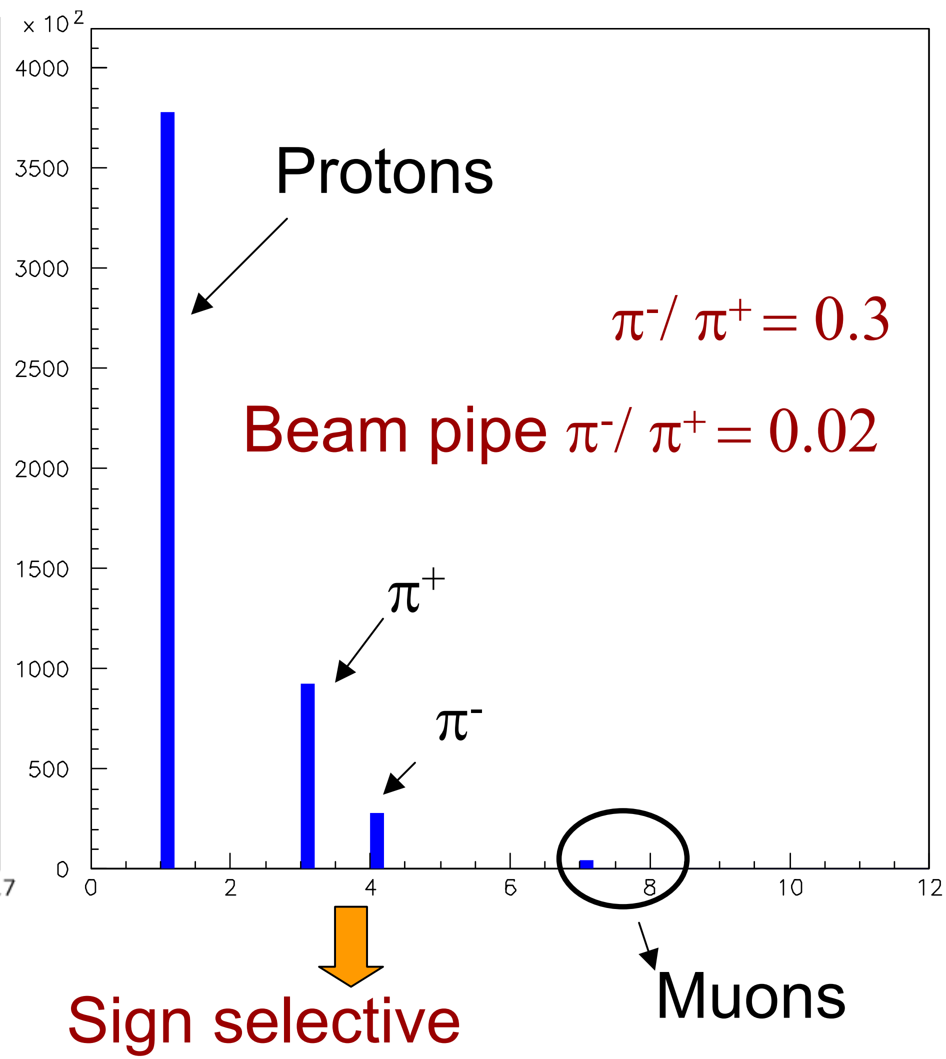


After the horn

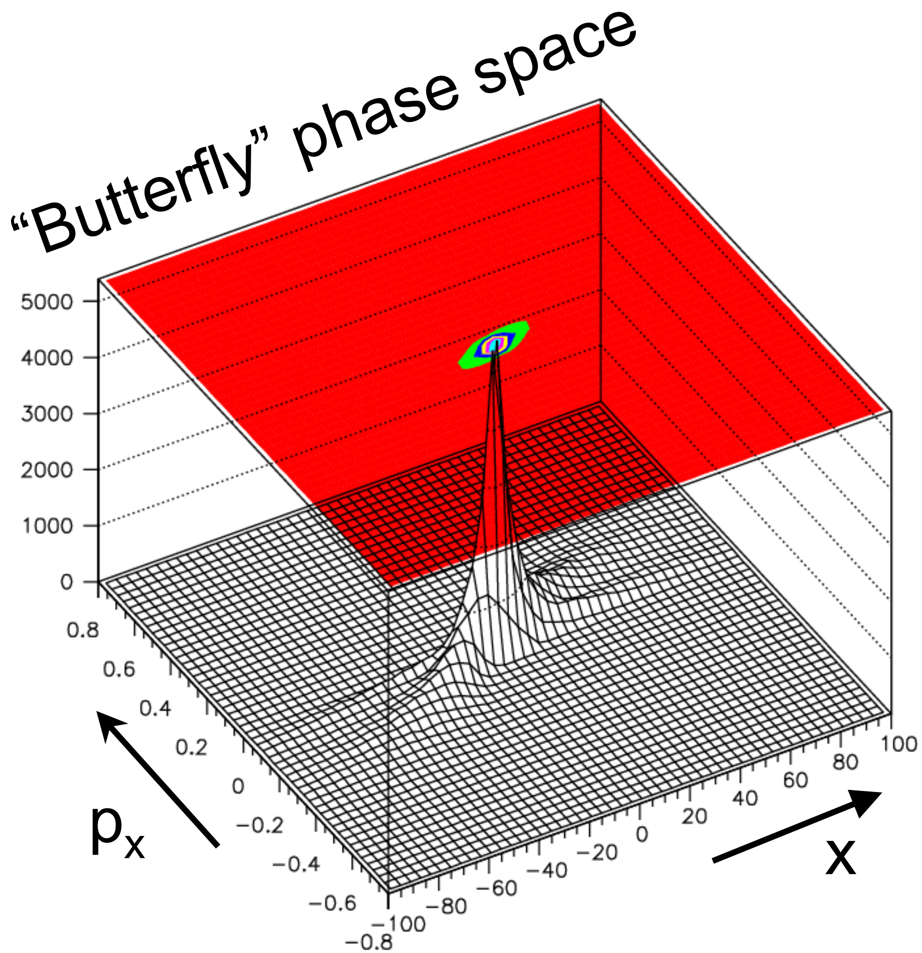
P_t distribution

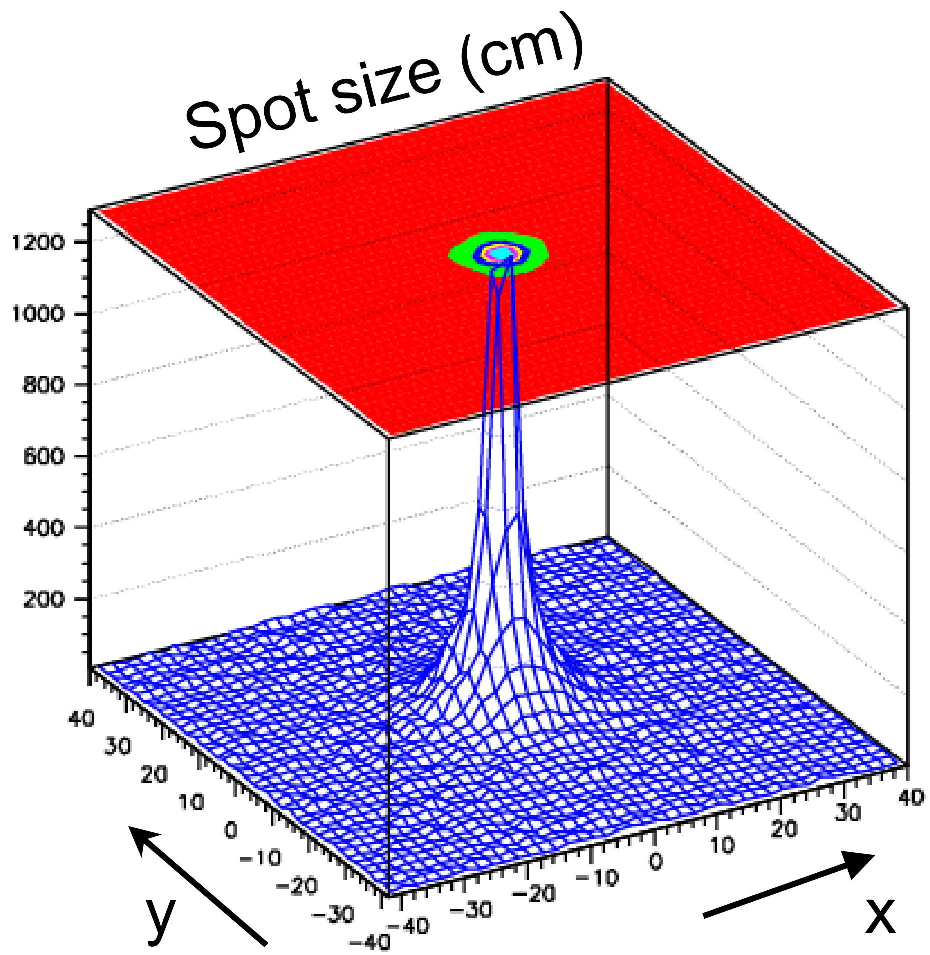


Population



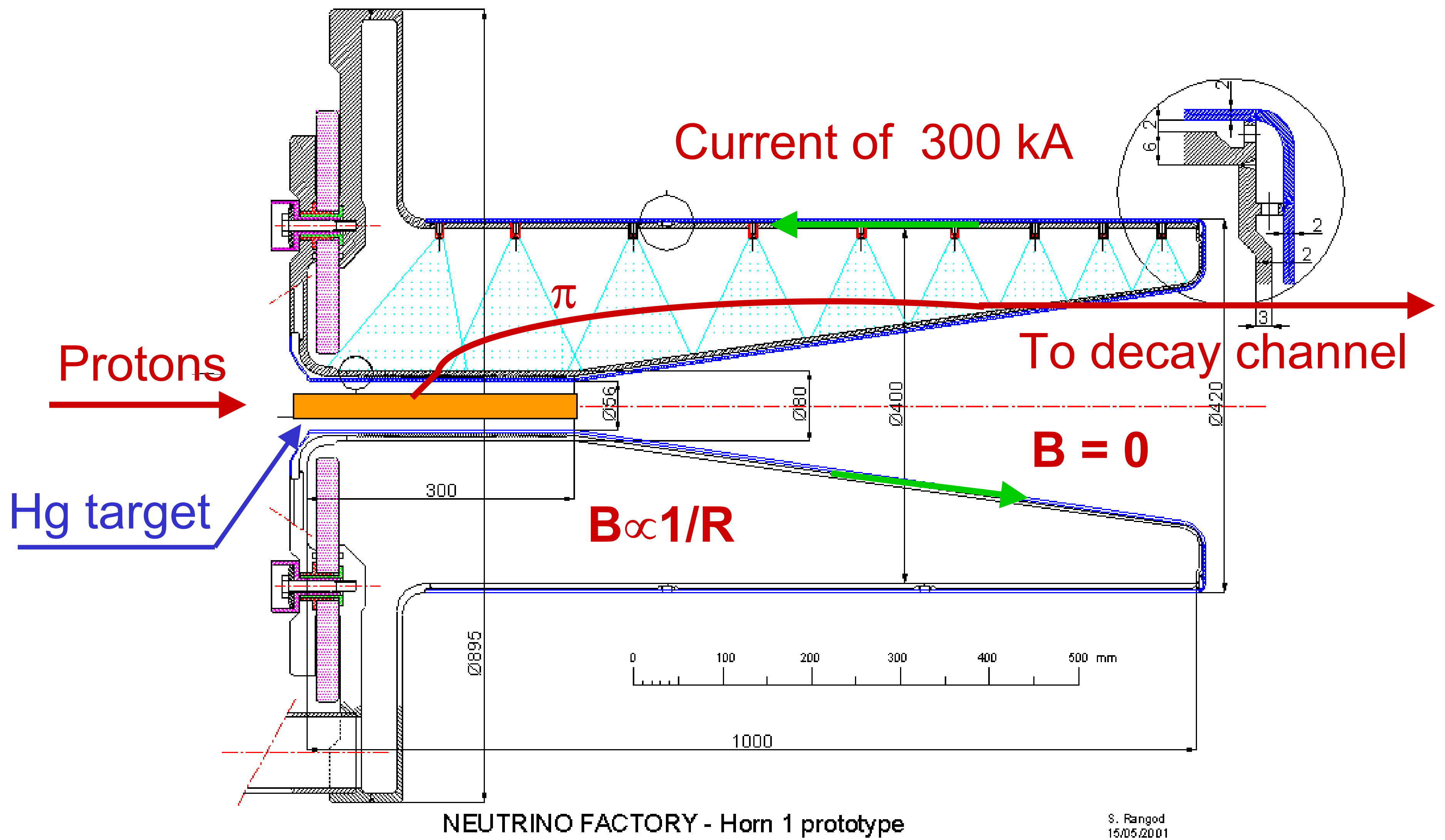
After the horn II



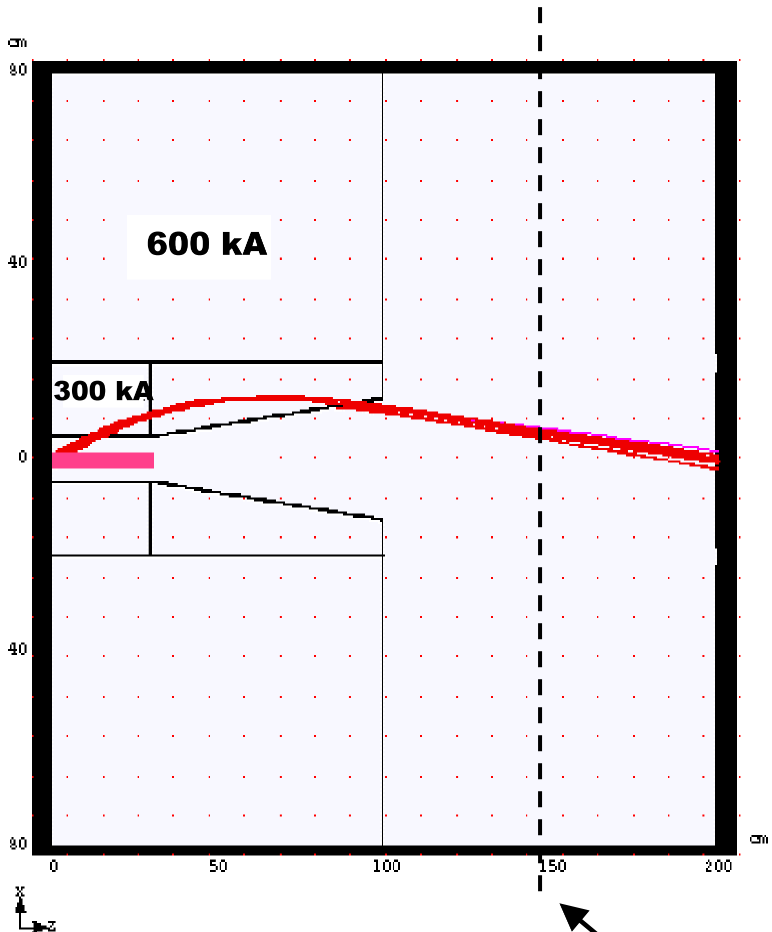


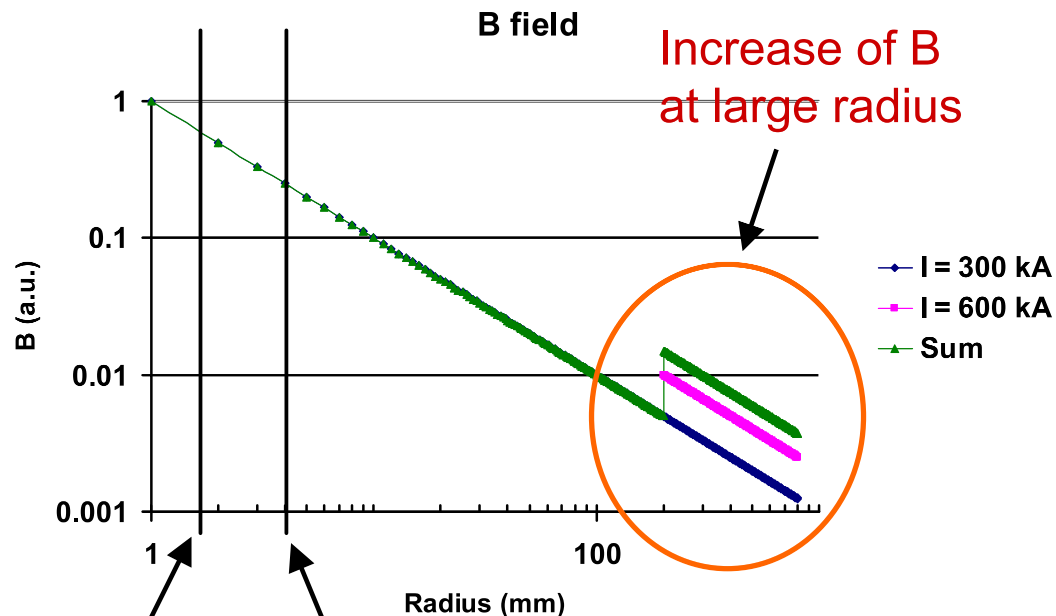
Horn designed to fit the beam in a R = 30 cm beam pipe

Horn focusing system



Double Horn





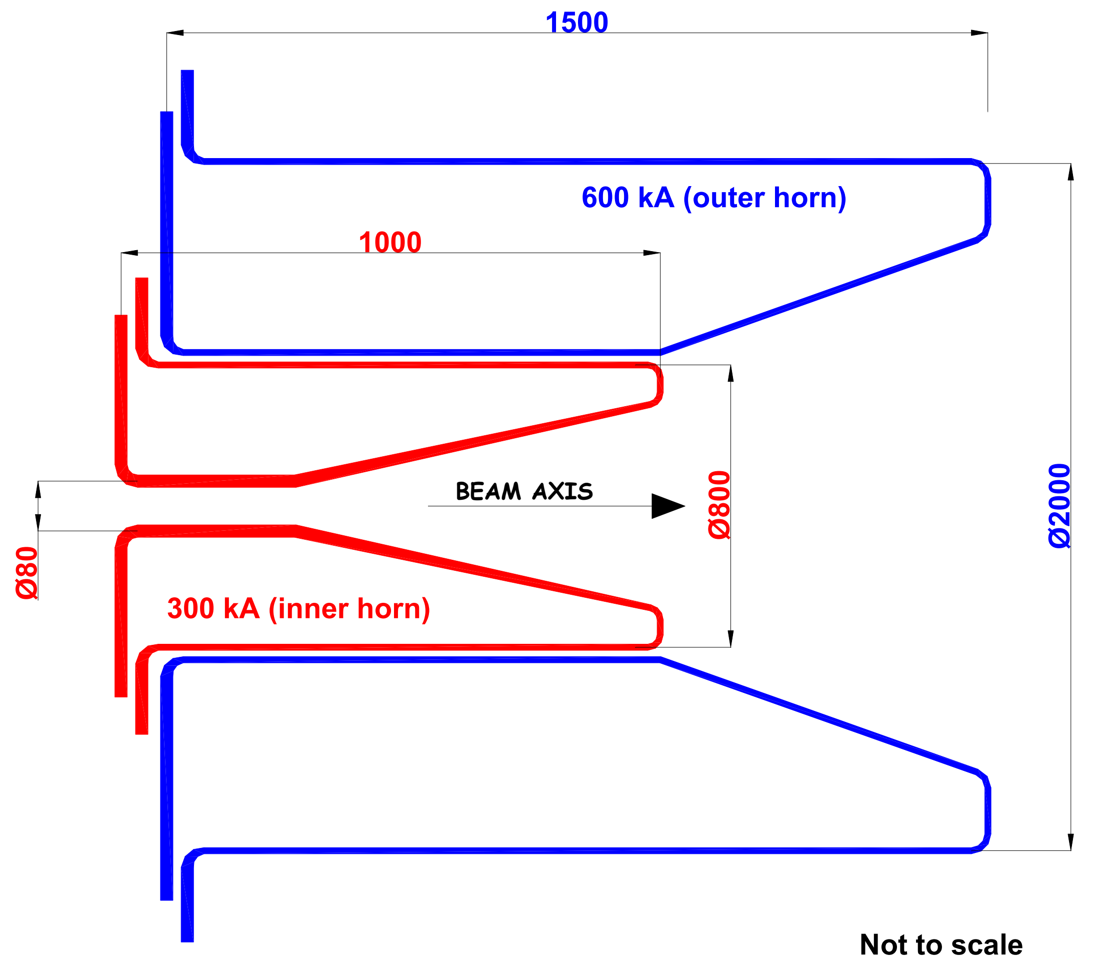
Increase of B at large radius

Old horn neck
R = 1.6 cm

New horn neck
R = 4 cm
B field is 2.5 times smaller !

First decay channel solenoid

Double horn concept



Beam dynamics study

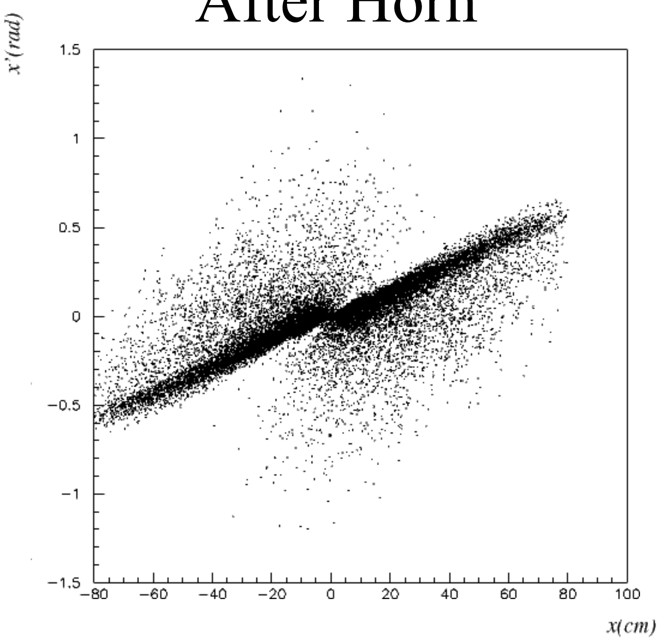
Transverse phase space:

•Simulation and tracking by MARS

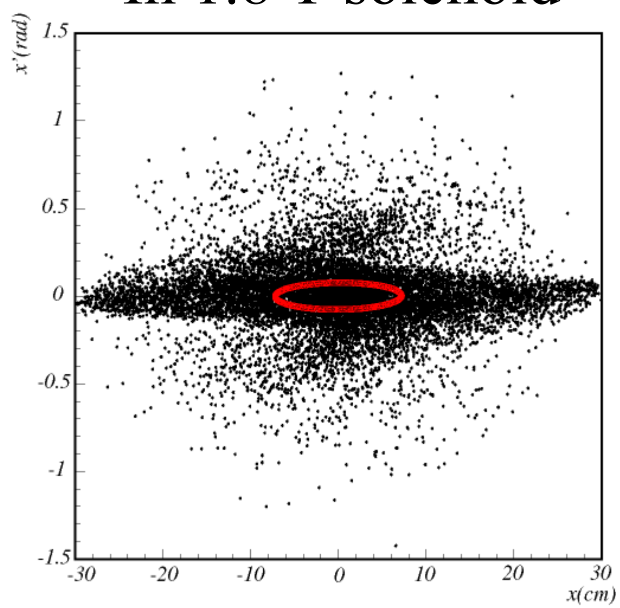
Pion Yield: 0.0013 π/POT with CUT ε_n =1.5 cm rad

0.3 GeV < Et <0.6 GeV

After Horn



In 1.8 T solenoid



Horns available from the shelf

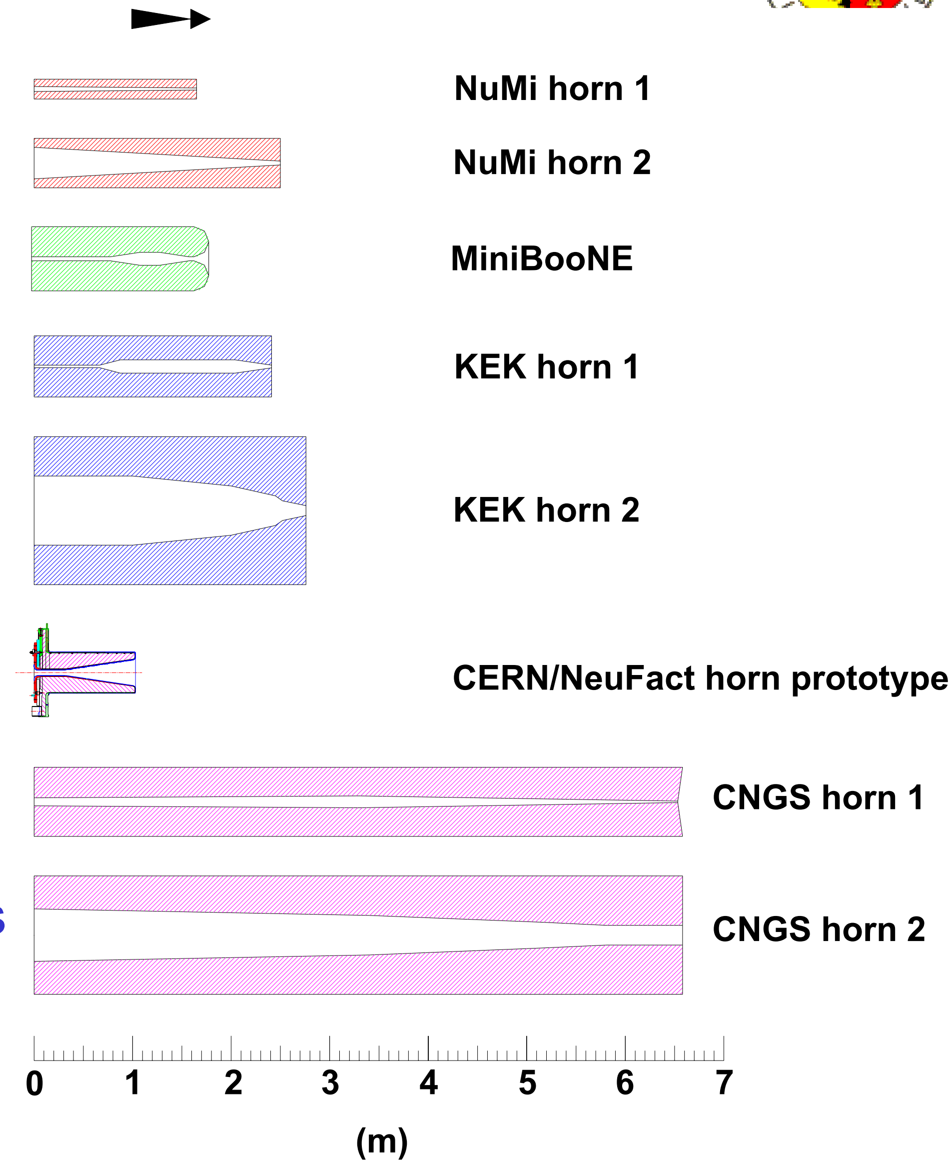
Numi: 200 kA, 0.5 Hz, 6M pulses
1 year

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

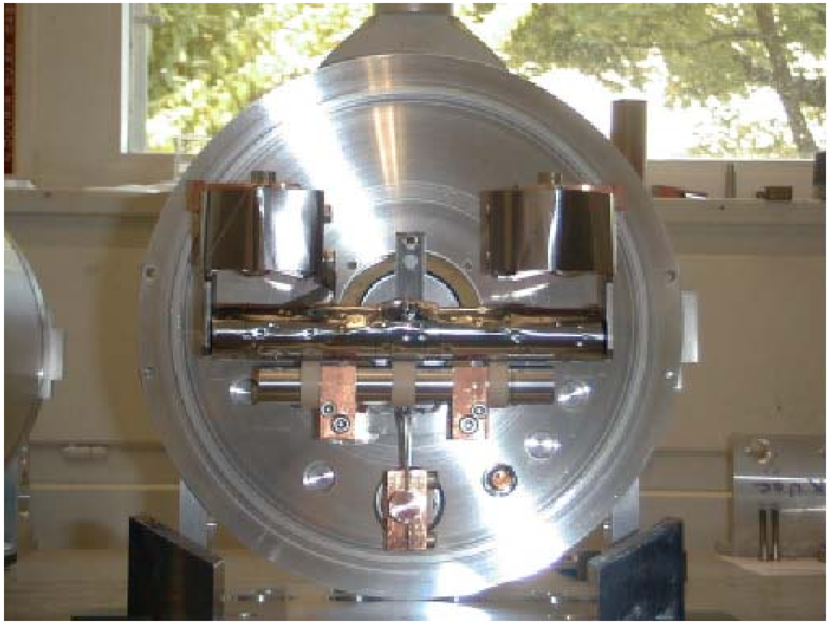


Experiment	curr	freq	Neck radius (cm)	Wall thickness neck(mm)	Out cond radius (cm)	Inductance (nH)	Resist (microhom)	Temprise at neck	A g F fr c t p k
Numi	200	1.87 sec	0.9	4.5	14.9	685-690	208ms	22.8	1
Miniboone	170	5.0 hz	2.2				0.24milli		2
k2k	250	2.18s	3.0				2.5ms	15	6

Mechanical study Goal

- Verify the reliability of a **300kA-50Hz** horn built according the conventional technique of pulsed horns and providing a minimum lifetime of one month.

- In the same period one has to change 2 or 3 ISOLDE Uranium-Carbide targets



Main Parameters

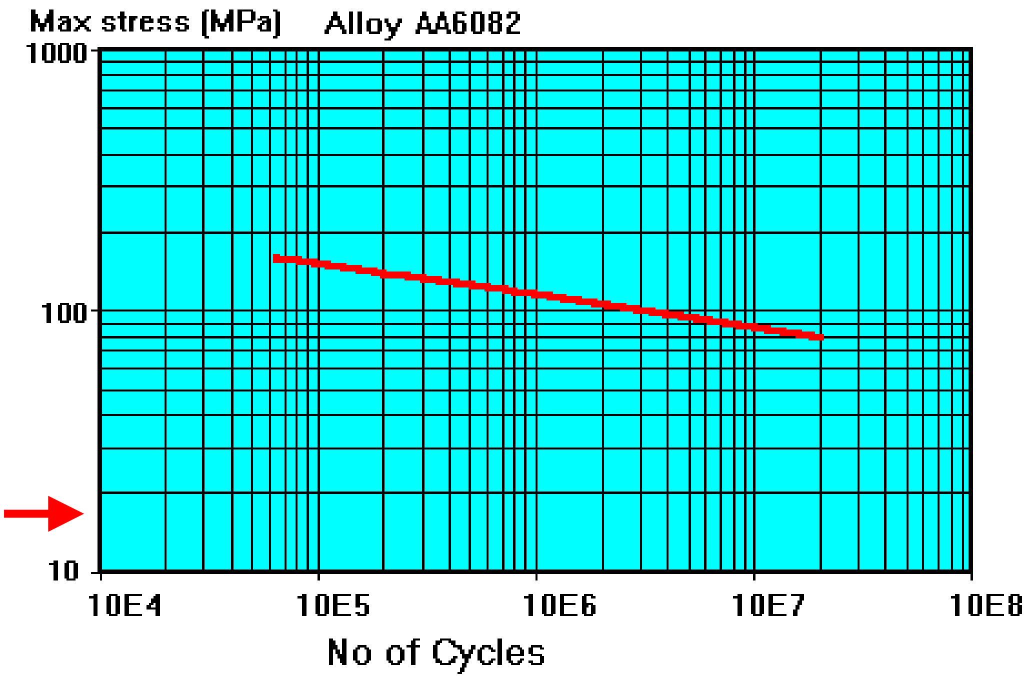
•Radius of the waist	40 mm
•Peak current	300 kA
•Repetition rate	50 Hz
•Pulse length	93 μs
•Voltage on the horn	4200 V
•rms current in the horn	14.5 kA
•Power dissipation (by current)	39 kW
•Skin depth	1.25 mm

•Total length	1030 mm
•Outer diameter	420 mm
•Max diameter (electrical connection flange)	895 mm
•Free waist aperture	56 mm
•Waist outer diameter	80 mm
•Average waist wall thickness	6 mm
•Double skin thickness	2 mm

Material choices

- **AA 6082-T6 / (AlMgSi1) is an acceptable compromise between the 4 main characteristics:**
  - Mechanical properties
  - Welding abilities
  - Electrical properties
  - Resistance to corrosion

Max. allowed stress →



Not compatible with Mercury

What we had planned to do

- First "inner" horn 1:1 prototype
- Power supply for Test One:
  30 kA and 1 Hz, pulse 100 μs long
  - ✓ First mechanical and thermal stresses measurements
  - ➢ Test of numerical results for vibration
  - ✓ Test of cooling system

More or less done

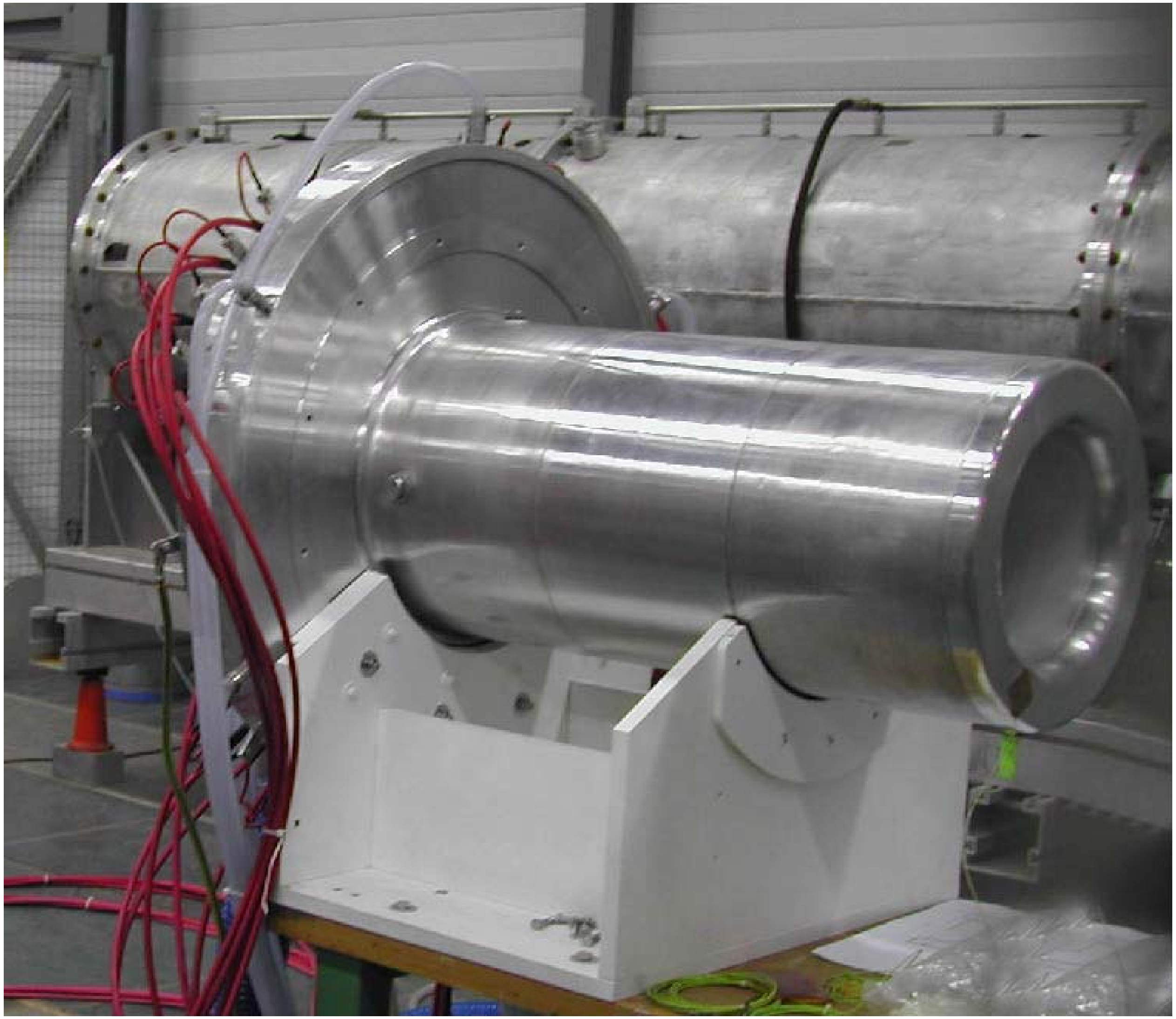
- Test Two: 300 kA and 1 Hz
- Last test: 300 kA and 50 Hz

Unknown schedule

Goal: Horn Life-Time 6 weeks ($2*10^8$ pulses)

Very good news

Horn prototype ready for tests

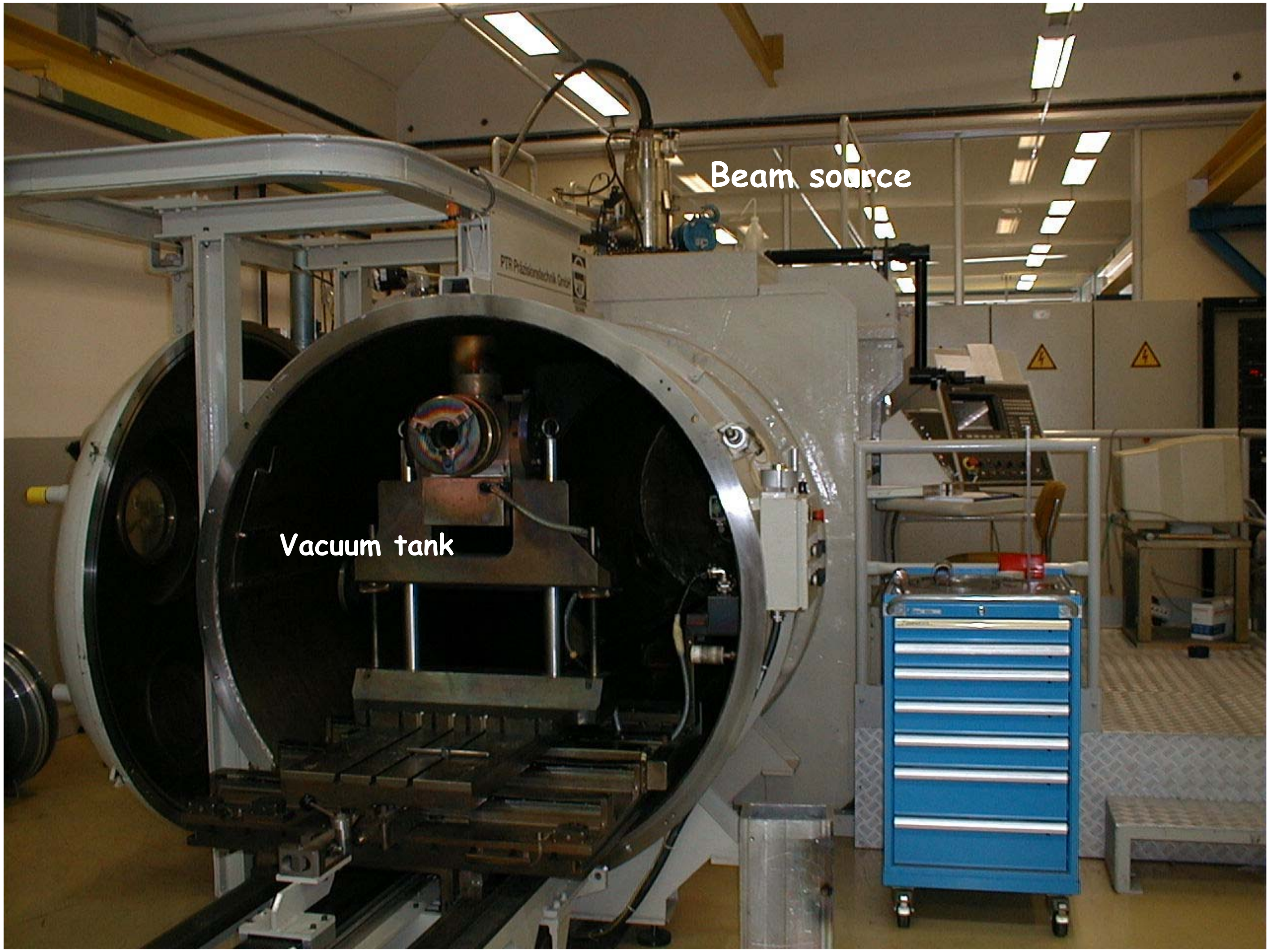


Mechanical design

- **Main features:**
  - Staying in conventional mechanical technology
  - Thickness of the walls calculated for a minimum absorption.
  - Improvement of the cooling efficiency.
  - Low cost radiation hardness insulation.

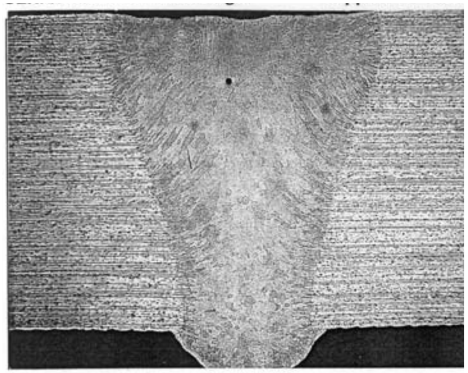
- **Highlights:**
  - Creation of a double skin.
  - Sprayers directly feed by an annular low pressure water film.
  - Cooling circuit shared out for the waist zone
  - Inner waist exchange surface magnified by a factor 2 (round shape inner screw thread)
  - Ceramic balls used as spacers between inner conductor and double skin to ensure the concentricity of the both components.
  - Use of a glass disc insulator.

EBW – CERN INSTALLATION

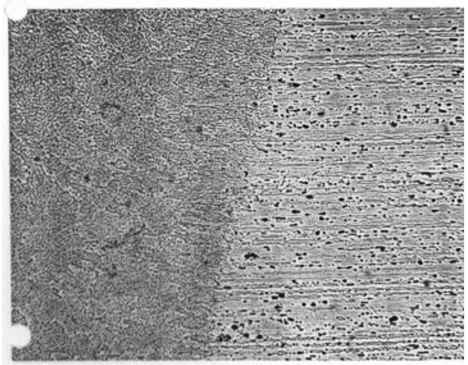


E.B. Welding

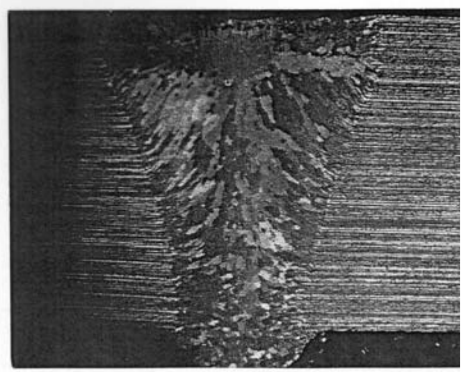
Magnification: x25



Magnification: x25

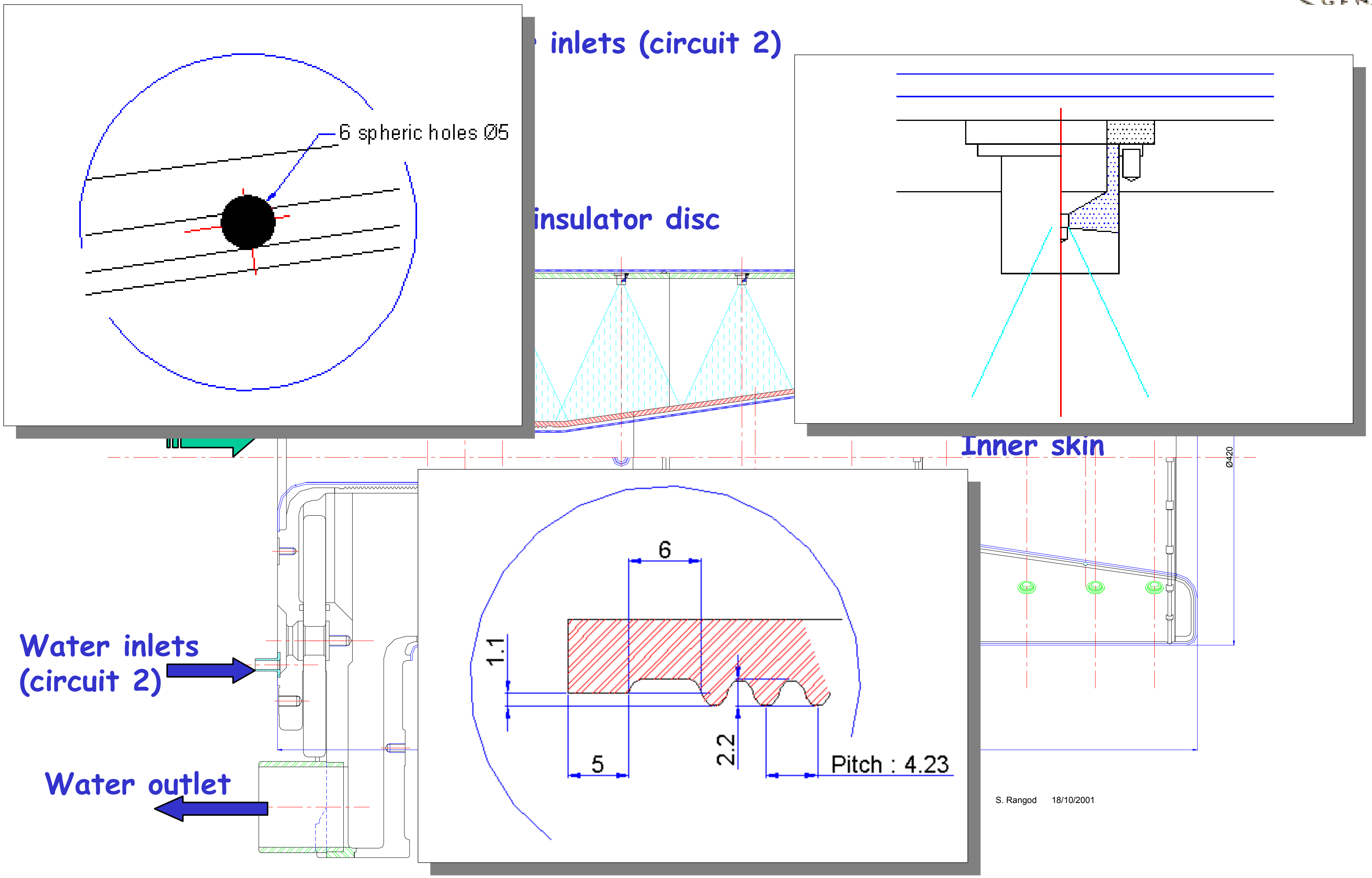


Magnification: x25
Under polarized light



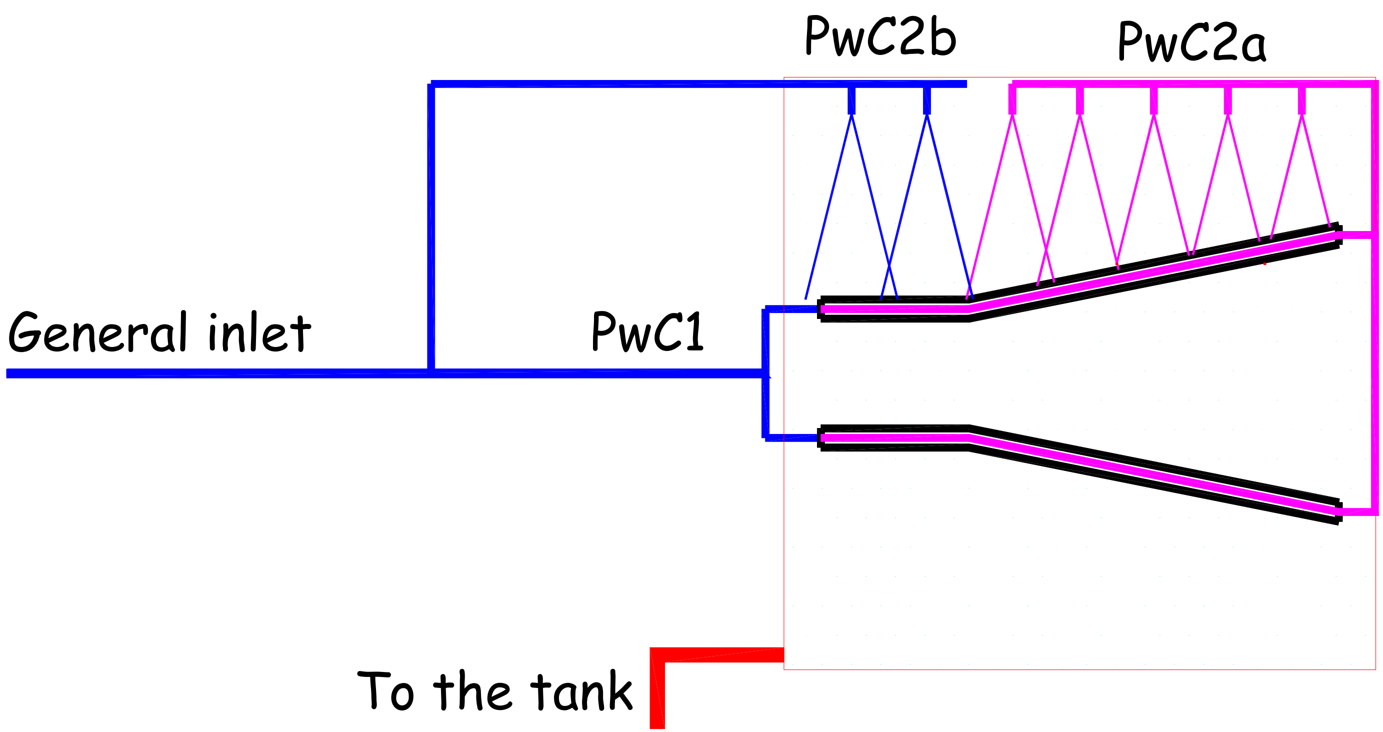
CERN/EST document

Longitudinal section



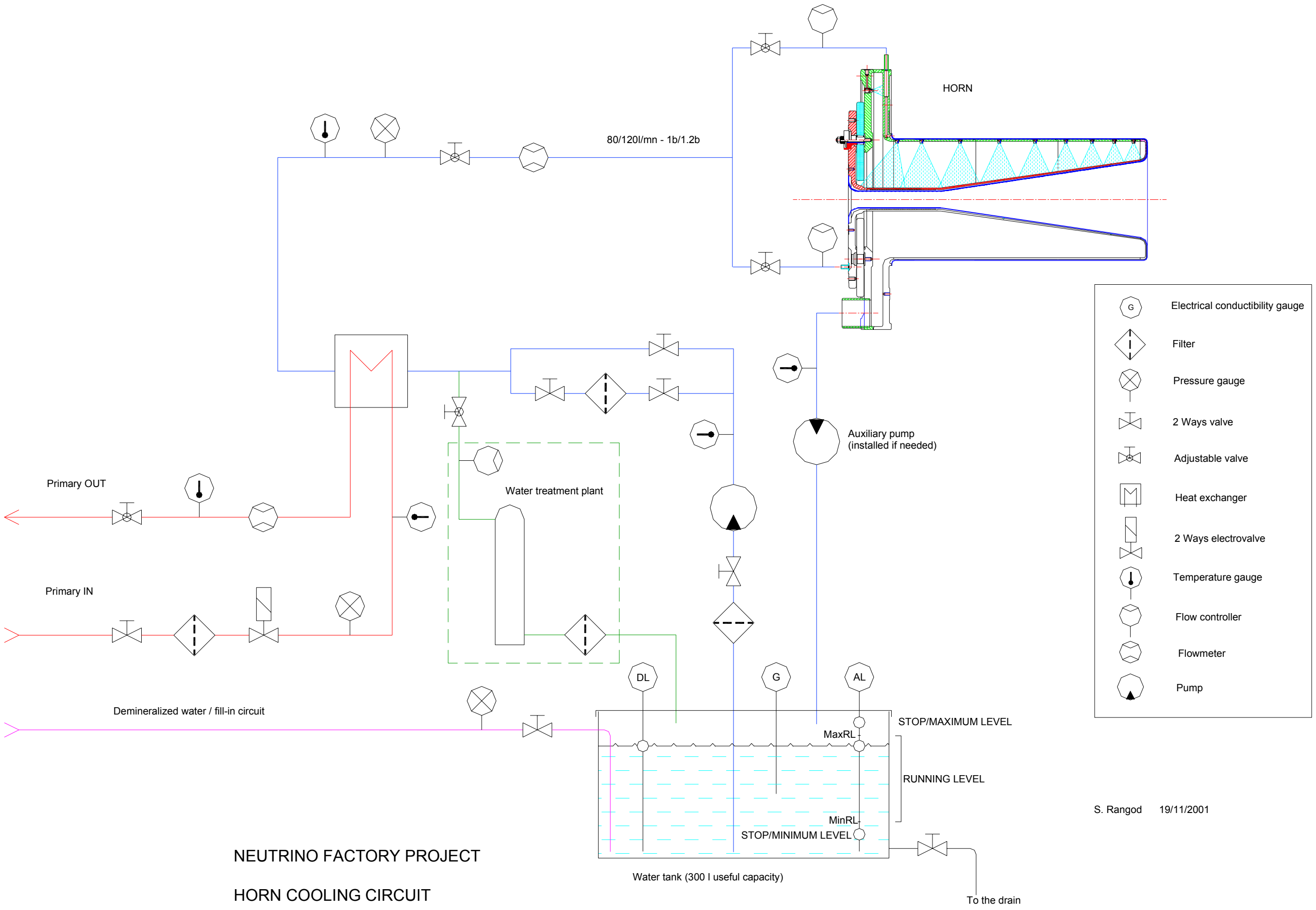
Water cooling circuit 1

- Mean power dissipation in the horn by current (kW) 39

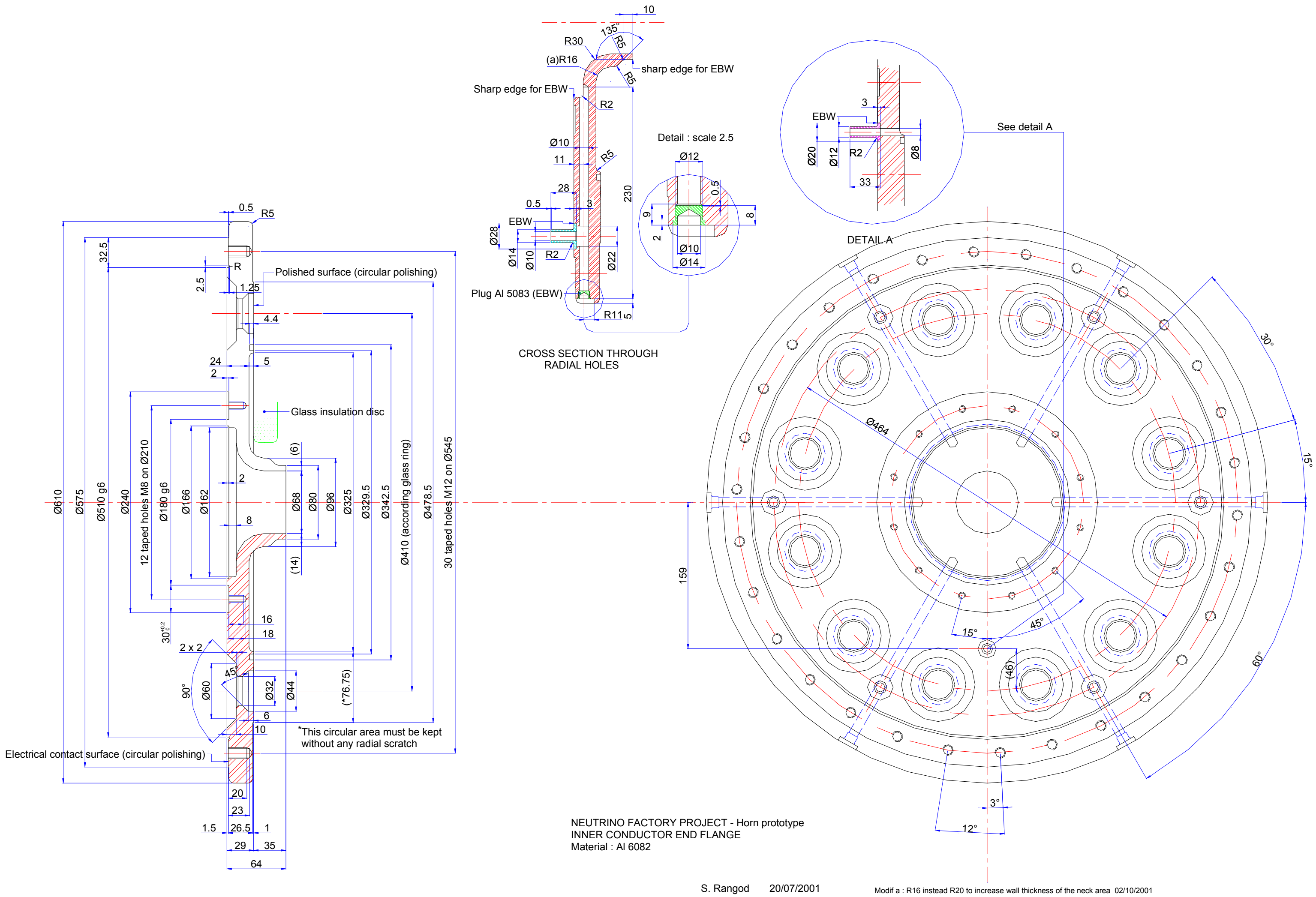


SCHEMATIC WATER CIRCUIT

Water cooling circuit 2



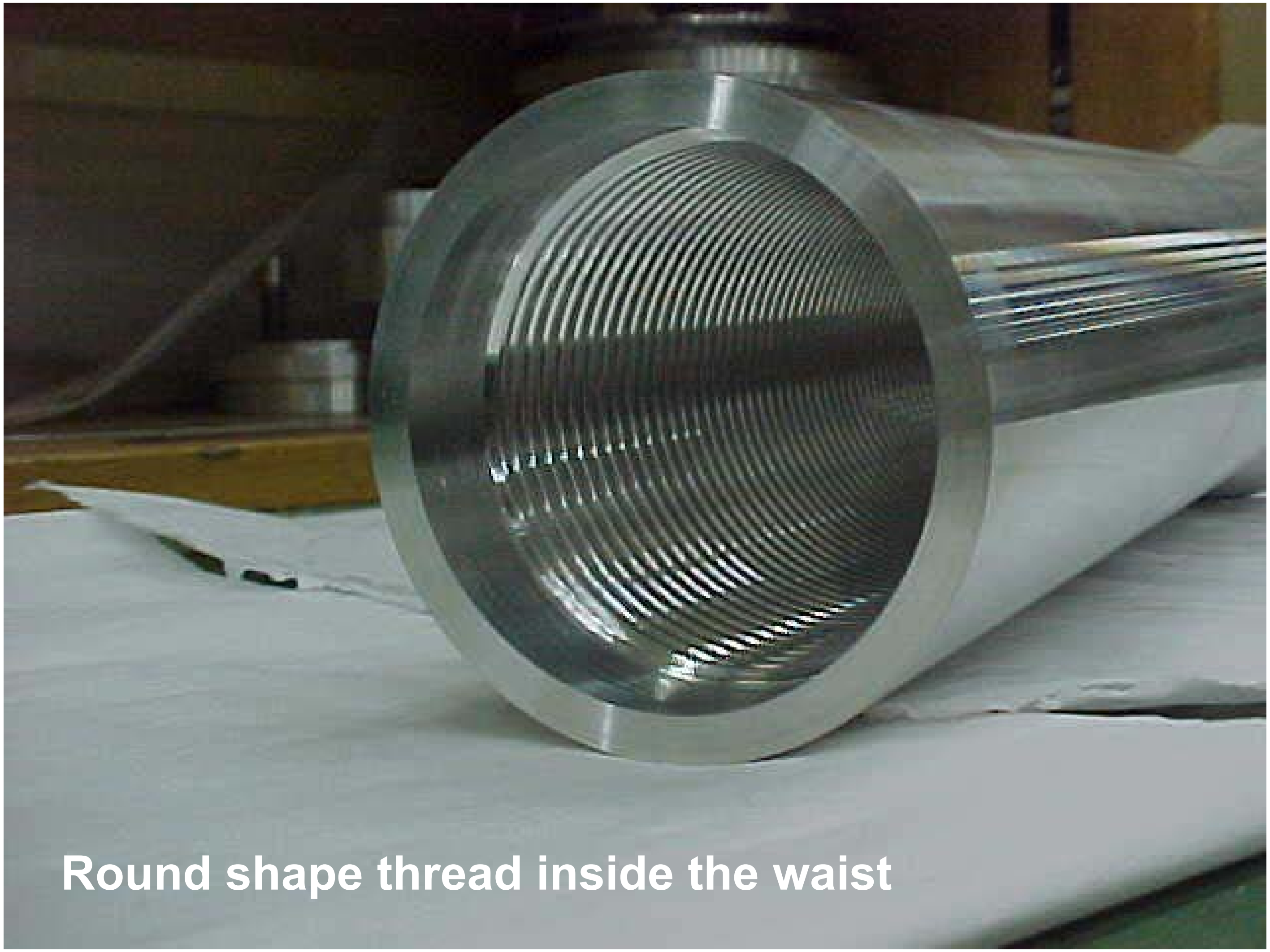
Inner conductor flange



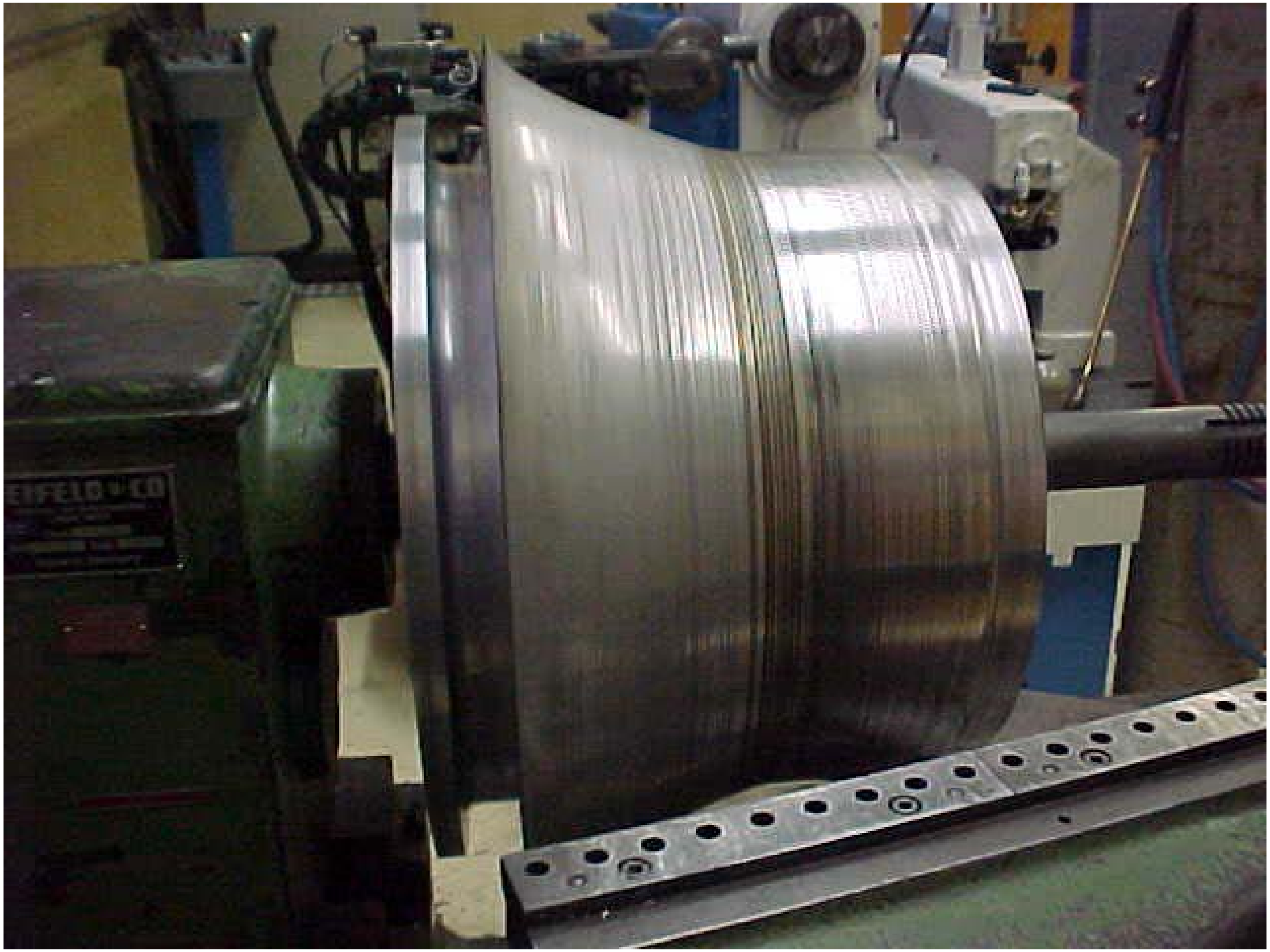
Construction of horn at CERN

Drilling operation
for radial holes

Construction of horn at CERN

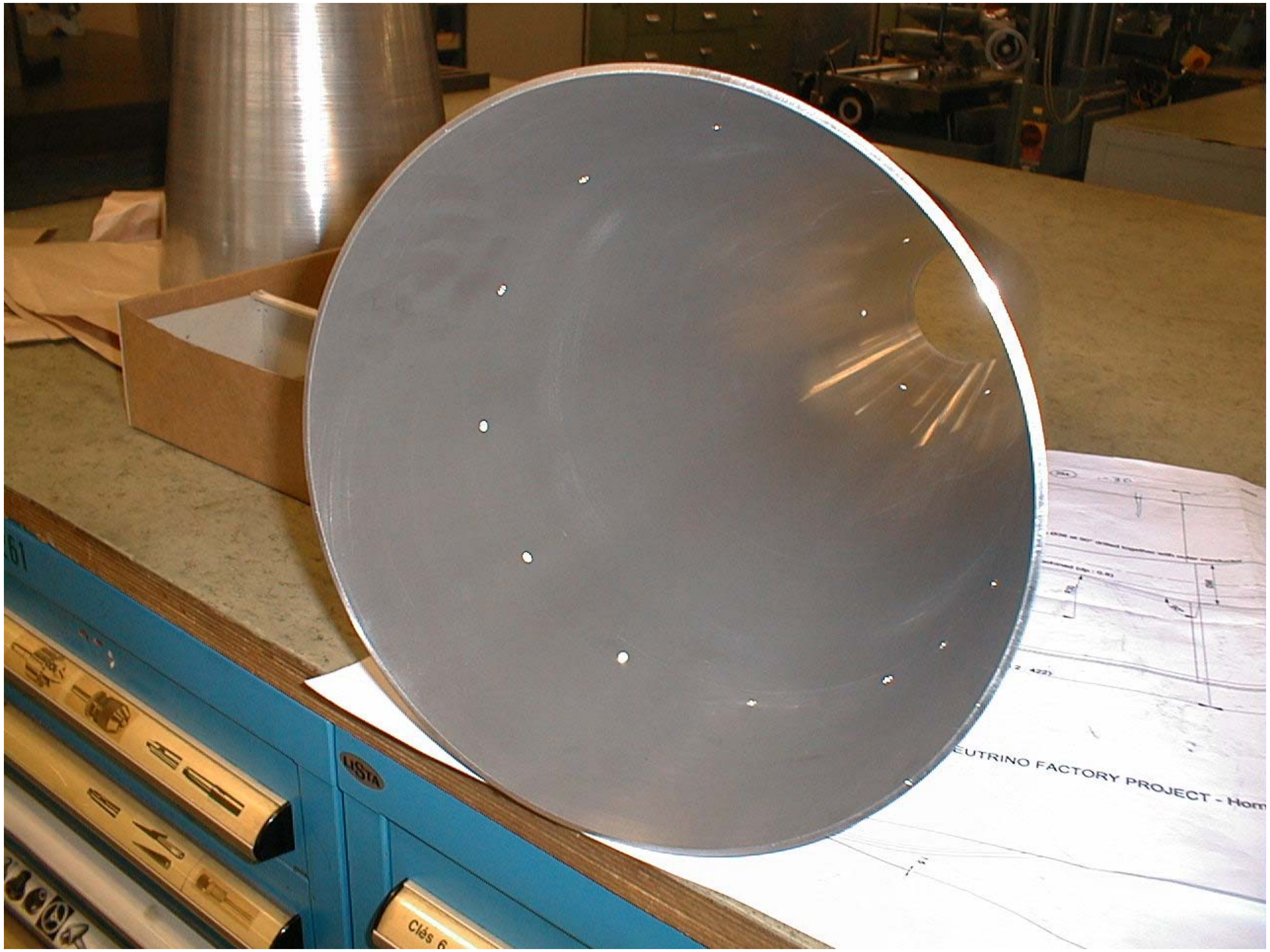


Construction of horn at CERN



Punching of the outer skin

Construction of horn at CERN



Spherical blind holes for ceramic balls spacers

Construction of horn at CERN

Inner conductor

Construction of horn at CERN

Inner and outer skins

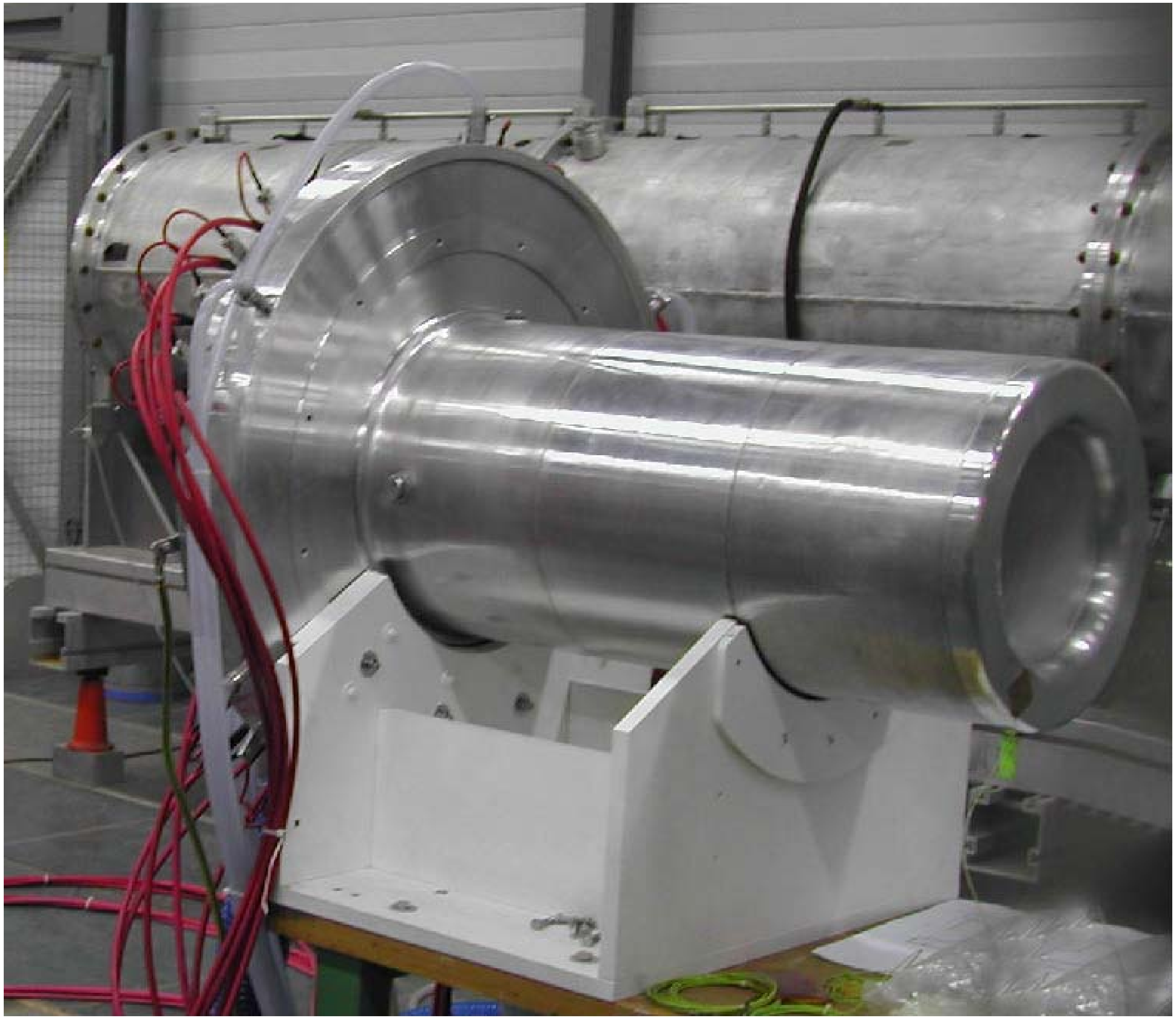
Construction of horn at CERN

- Glass insulator disc

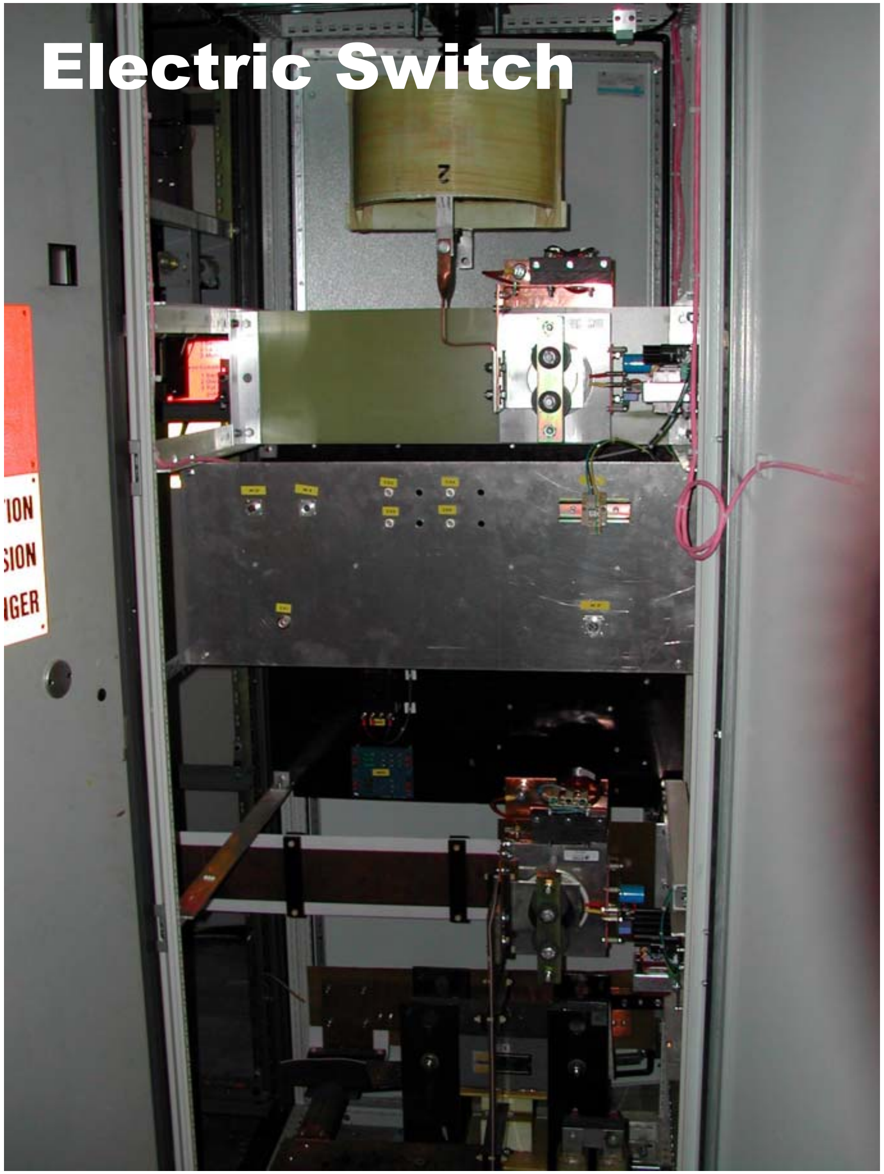
Construction of horn at CERN

Front side assembly

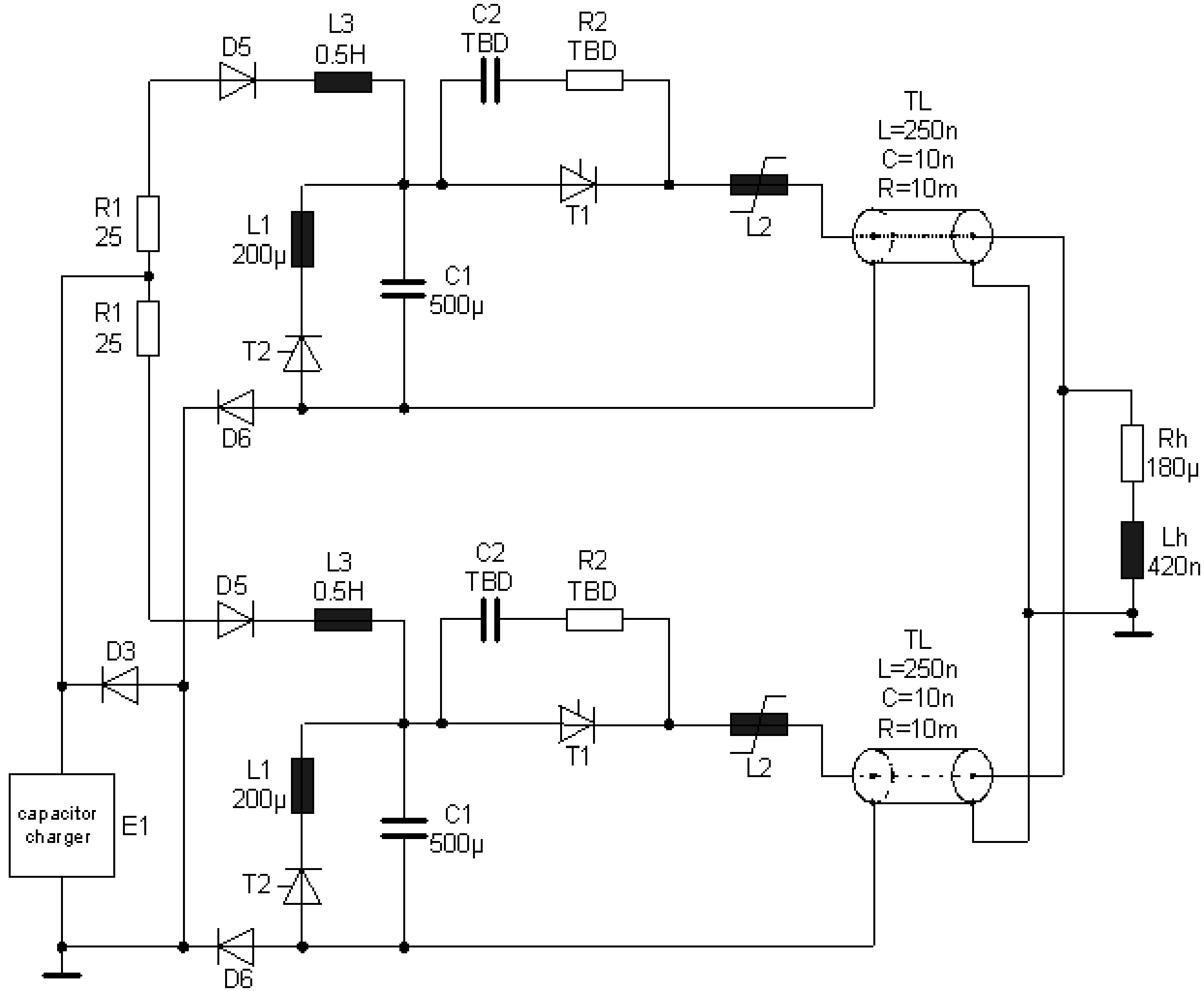
Horn prototype ready for tests



Discharger Unit



Power supply scheme

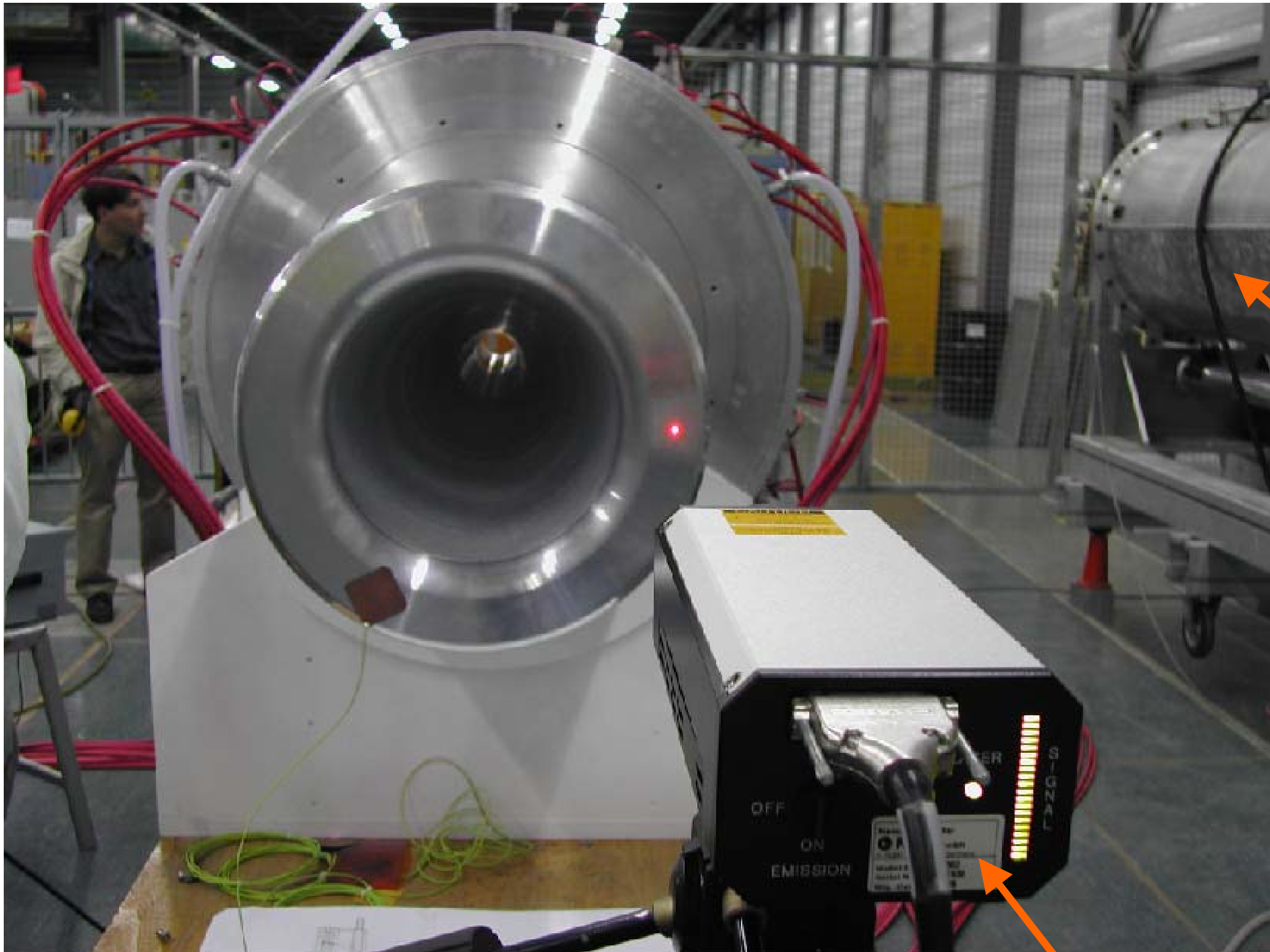


What we are doing

- Building a new power supply
  - 70 kA, 120 μs, 1 Hz
  - Mechanical vibration tests
- Studying how to connect the CNGS power supply
  - 100-120 kA, few ms, 0.5 Hz

- Looking for someone interested in developing the final power supply
  - 300 kA, 100 μs (better less), 50 Hz
- Looking for someone to develop a numerical model for horn vibration

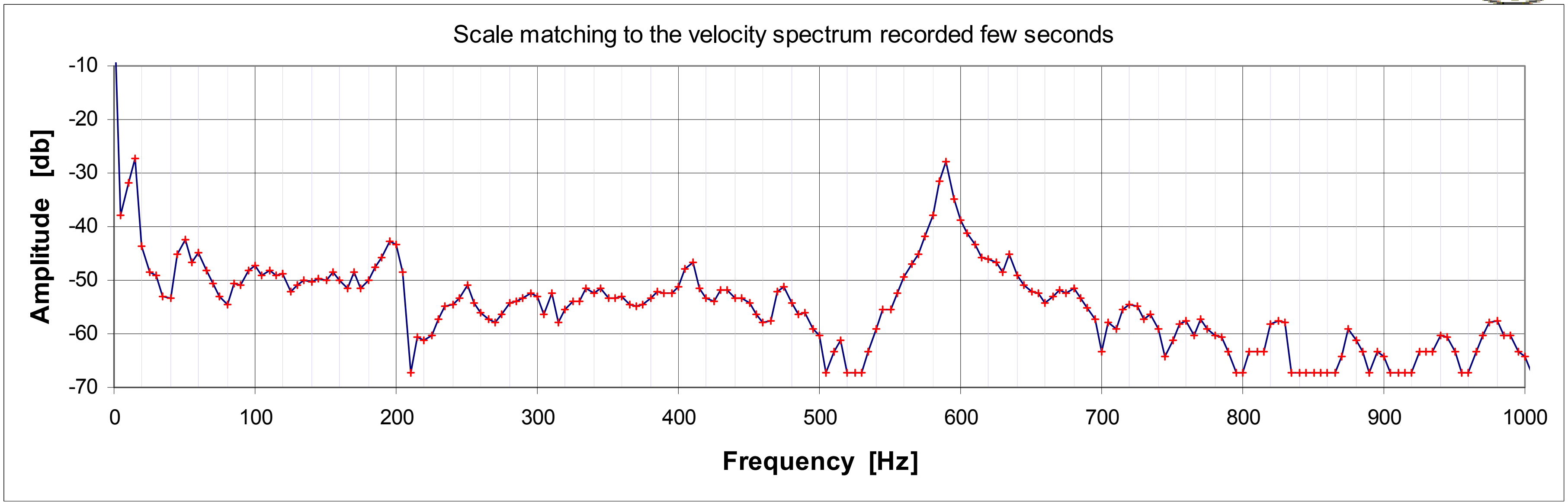
Laser Measurements



CNGS horn

Laser vibrometer

Preliminary vibration meas.



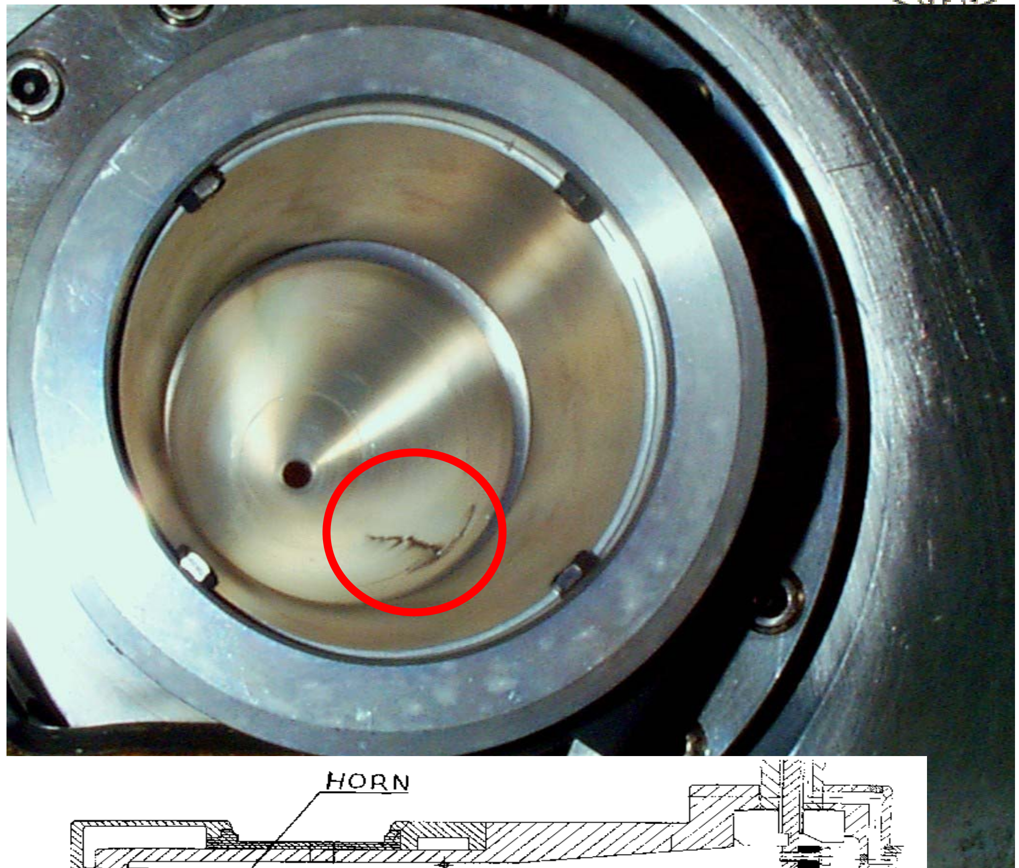
New campaigns of measurements with laser vibrometer and a microphone as the new power supply ready.

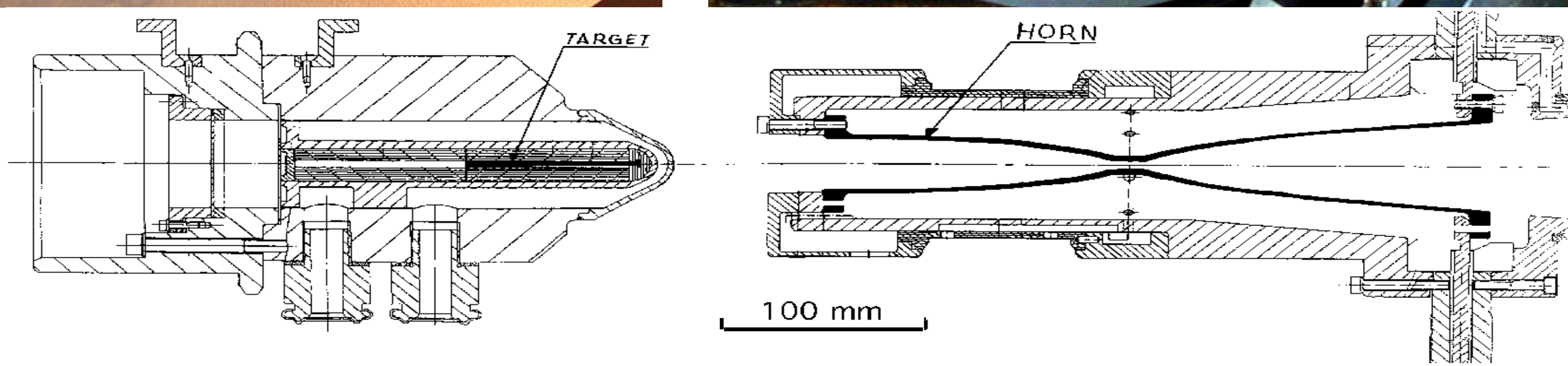
Would you like to hear a laser?

Any suggestions how to measure a surface that you cannot touch, the INNER conductor ?

Horn failures ...When? Why?

AD horn (see Microcosm)
300 kA, 0.5 Hz, 1M pulses

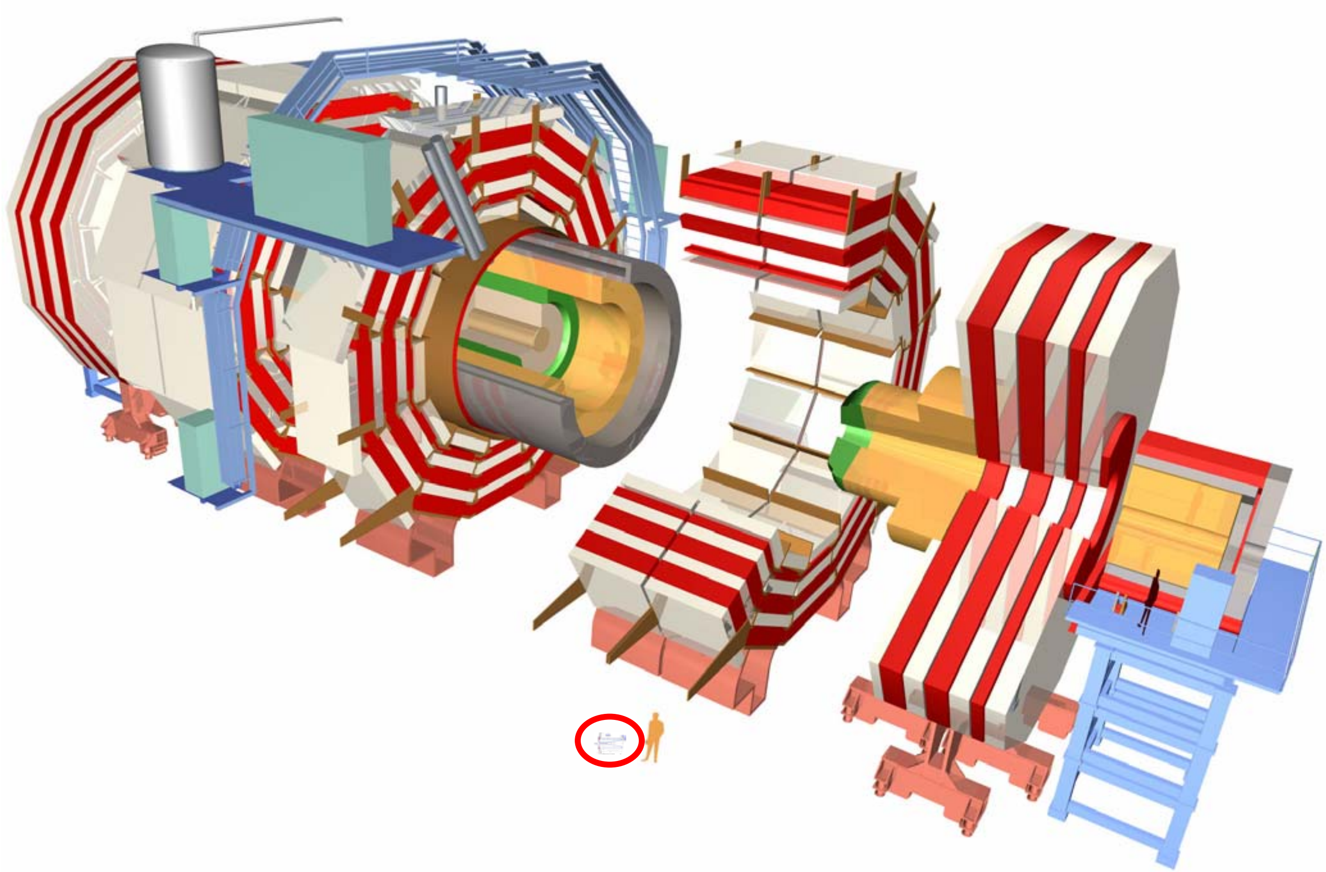




Reasons for horn failure

- Fatigue limit
  - stress due to electro-magnetic forces
  - Max pressure: ≈14 MPa (140 kg/cm^2)
  - Operation always in material elastic regime
- Thermal stresses
  - joule losses: 39 kW
  - particle energy deposition (still to be evaluated)
- Neutron irradiation
  - Swelling
  - Mechanical properties variation

CMS Magnets Power supply



- Total RMS current for CMS magnets: 19 kA DC
- Ramping in 5h
- Horn RMS current: 14.5 kA

Pulse length optimisation

- Proton beam pulse length 3.2 μs
  - Why a current pulse length of 100 μs ?
- Power dissipated in horn $\propto \sqrt{\tau_0}\, I_M^2$
  - τ_0 pulse duration = half sine wave
  - I_M peak current
    - ➢ Shorter current pulse length wanted
- Voltage across the capacitor banks $\propto I_M / \tau_0$
  - Limit now is 6 kV

30 times shorter pulse length reduces the power by a factor of 5 but increase the voltage to 180 kV

How produce a shorter pulse length ?

Optimum to be found or a new idea …

Target Nufact

- Target:
  - Mercury: Z = 80 → short target
    Liquid → easy to replace
    ($v_{//} \approx$ 20 m/s)
  - Dimensions: L ≈ 30 cm, R ≈ 1 cm

→ 4 MW of proton into a pint of beer

4 MW

=

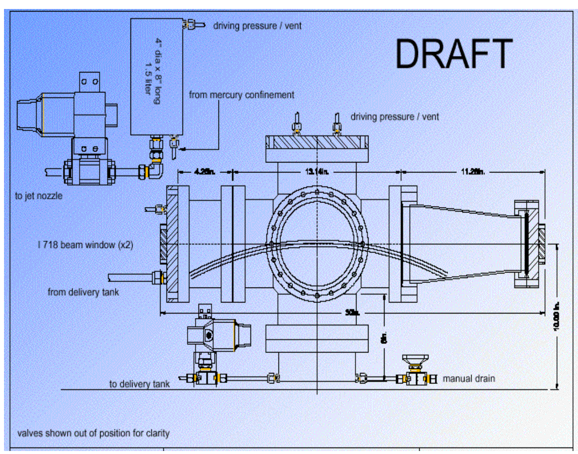
40000 ×

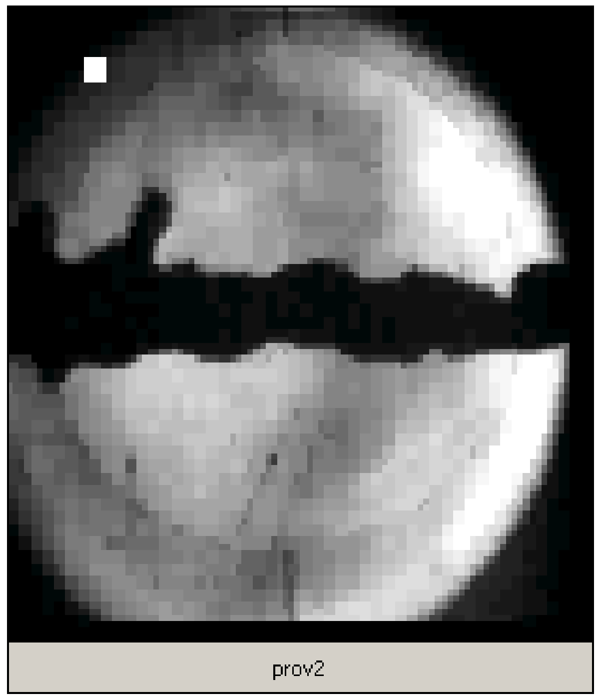
→

Target experiment

Experiments @BNL and @CERN

- Measurements of Hg explosion speed
  - Speed of protons >> Speed of sound
- Maximum $v_{\perp} \approx$ 20 m/s
- $v_{//} \approx 3$ m/s



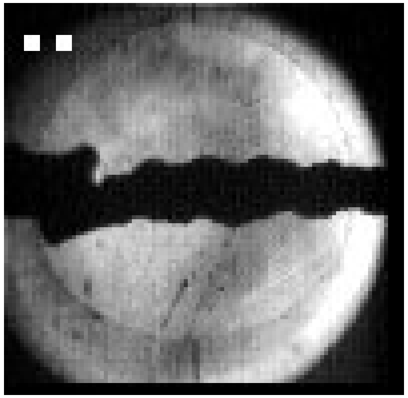


1 cm

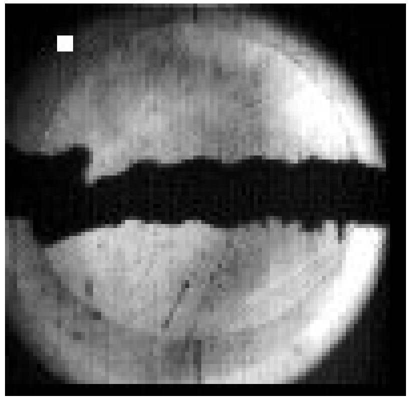
Protons

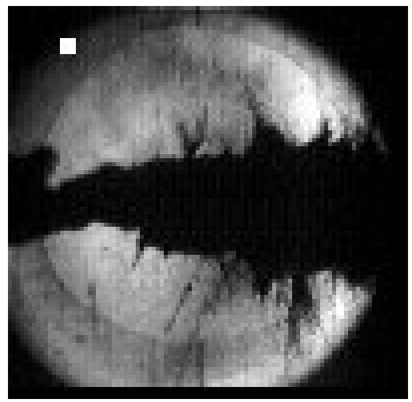
Jet test a BNL E-951

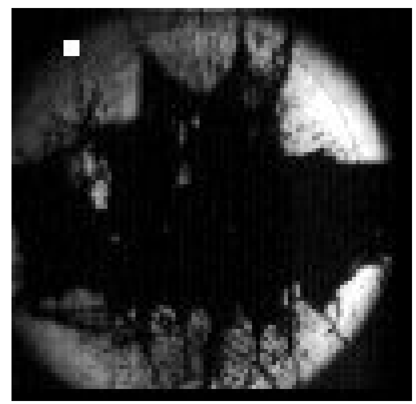
Event #11   25th April 2001

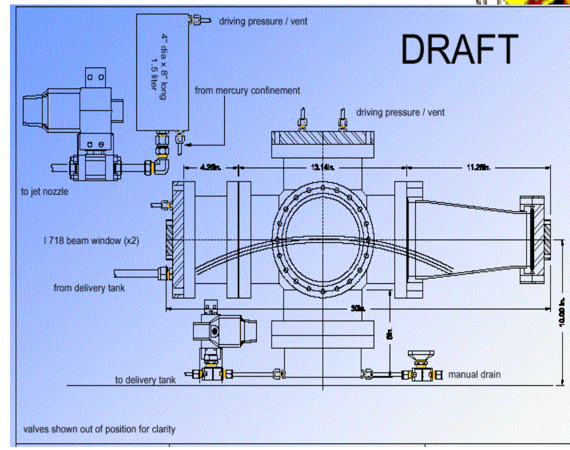


Protons ←









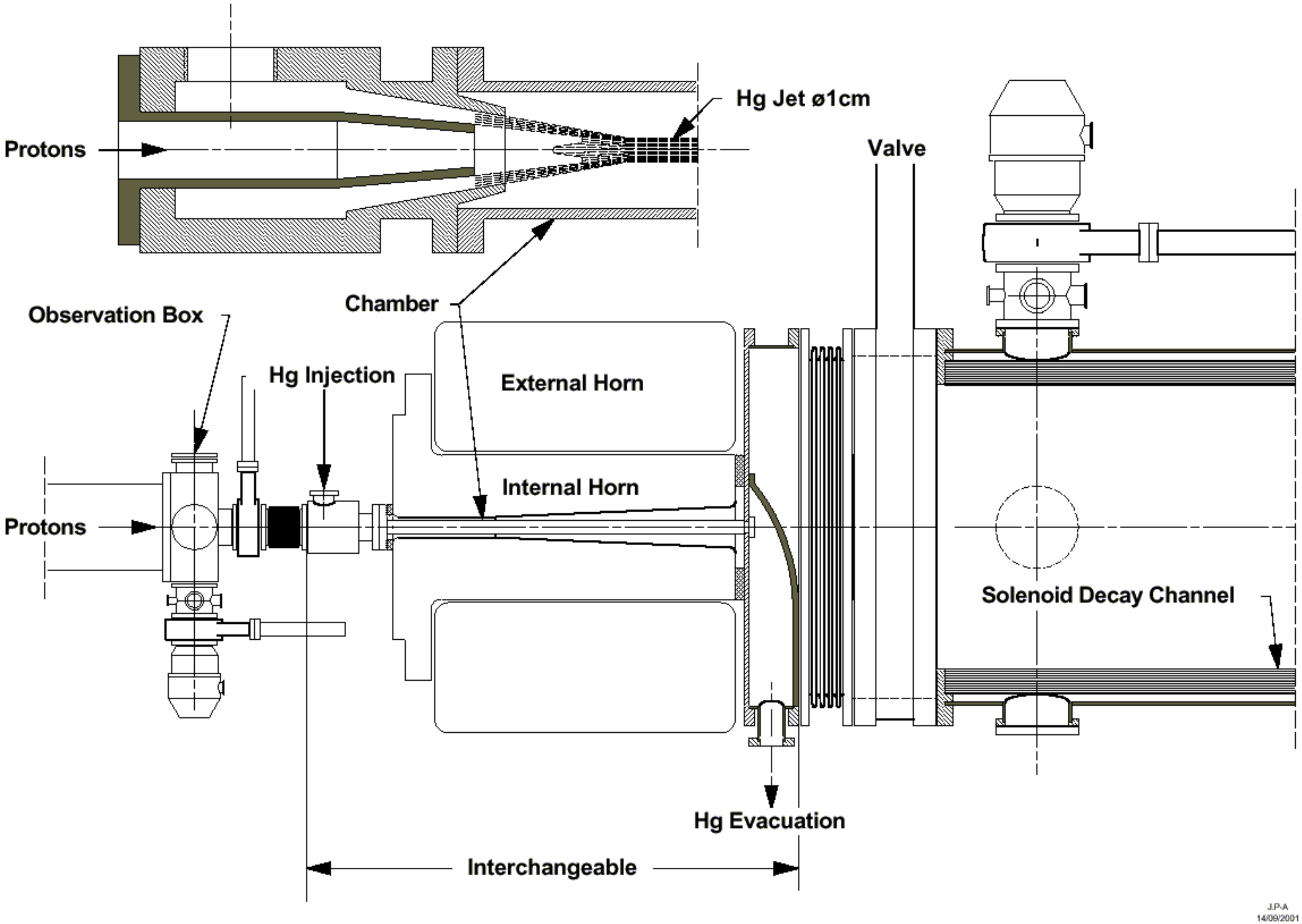
Picture timing [ms]
0.00
0.75
4.50
13.00

P-bunch: 2.7×10^{12} ppb
100 ns
t_o = ~ 0.45 ms

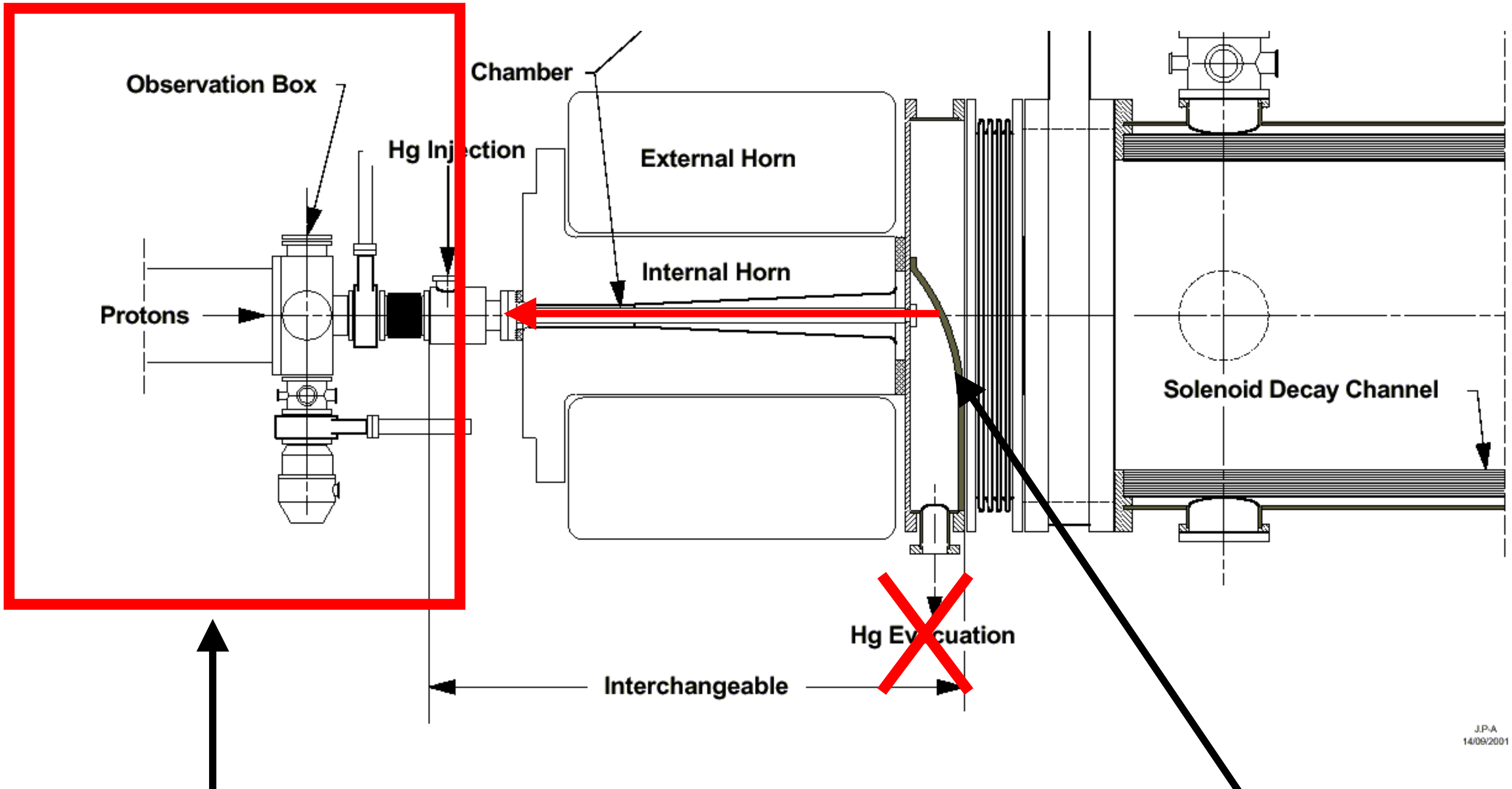
Hg- jet : diameter 1.2 cm
jet-velocity 2.5 m/s
perp. velocity ~ 5 m/s

K. Mc Donald, H. Kirk, A. Fabich

Target and Horn integration



Target and Horn integration



Chamber for Mercury Evacuation

New Nozzle position

Life-Time of Nozzle?

Any good ideas ?

Target inside or outside ?

Target INSIDE for low energy

- Max p_t more or less independent from the energy
  - p_t = 250 MeV/c

p_{tot}= 600 MeV/c

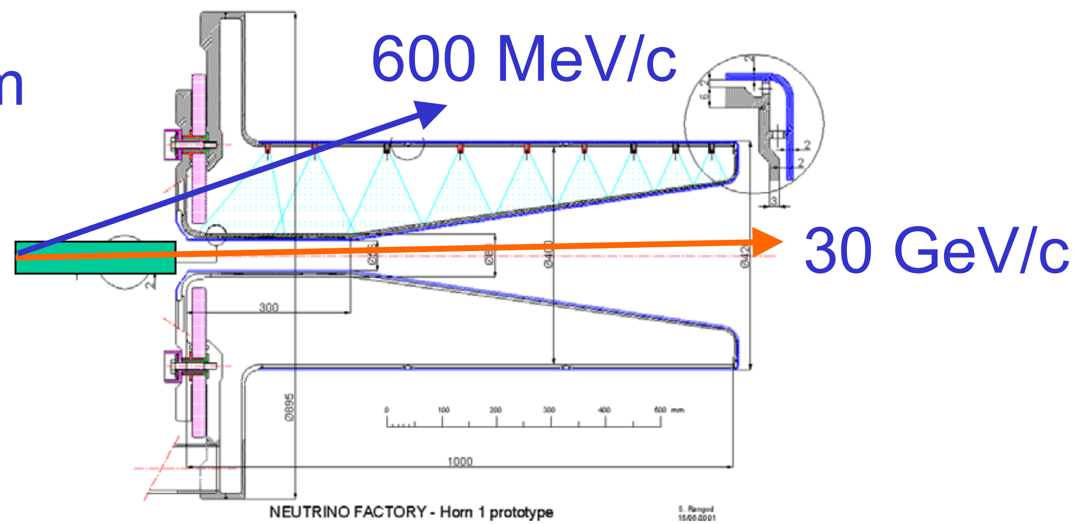
θ = 24º

R(z=30 cm)= 13 cm

p_{tot}= 30 GeV/c

θ = 0.47º

R(z=30 cm)= 0.25 cm



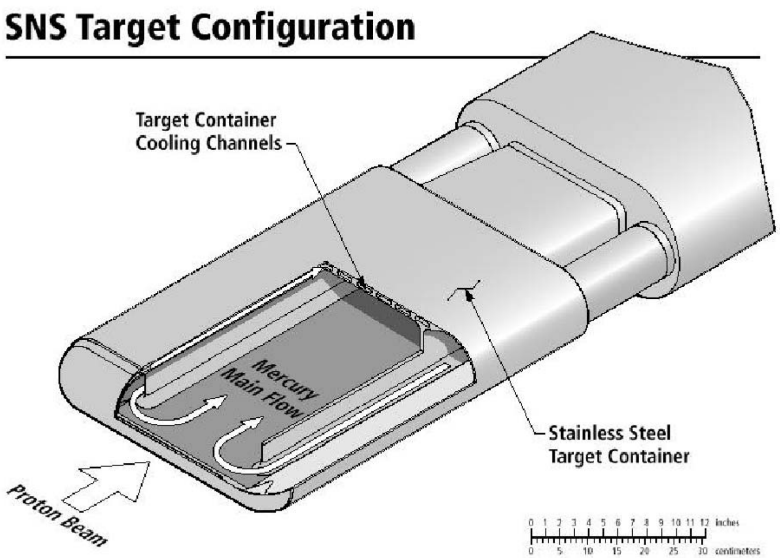
Target Inside

- Problem of integration between Al alloy and Hg
  - Hg compatible only with Ti
  - How to weld Ti with Al alloy?

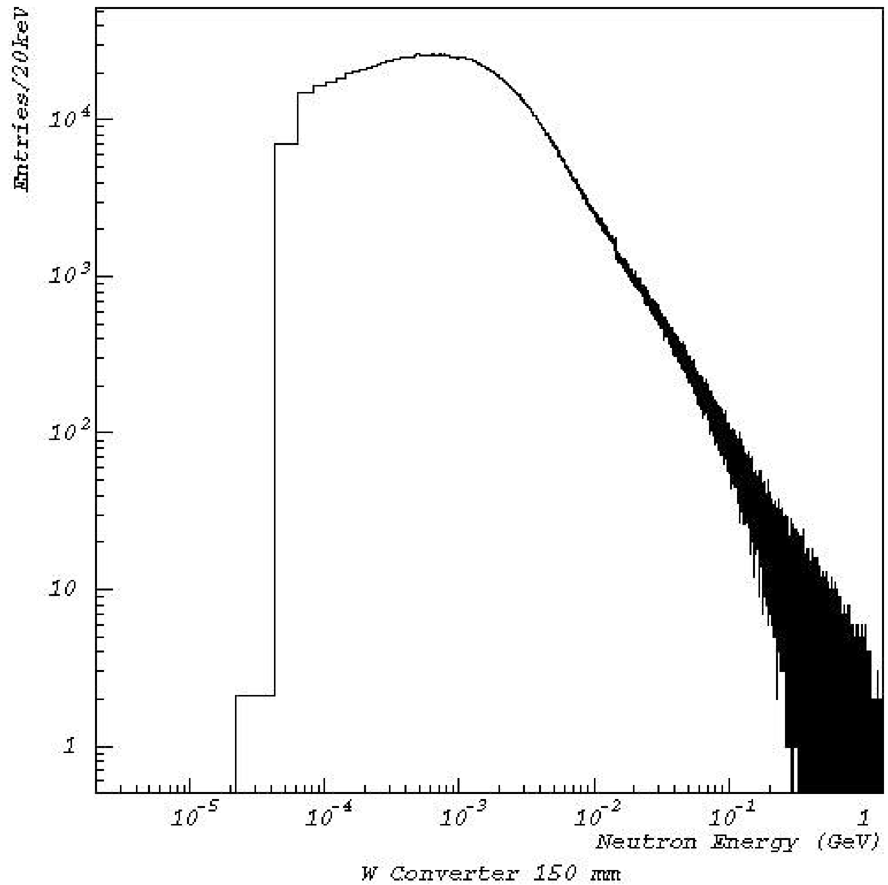
- Neutron irradiation damage
  - Neutron spectrum is isotropous
  - Most of neutrons stay in the neck

Neutron damage

Hg target as SNS target



Typical neutron spectrum



DPA: Displacements per atom

$$DPA = 0.4\frac{T_{dam}(MeV-barn)}{T_d^a(MeV)}\Phi\left(\frac{n}{cm^2 s}\right)t(s) = \sigma_{damage}\Phi t$$

T_{dam} : damage energy cross section

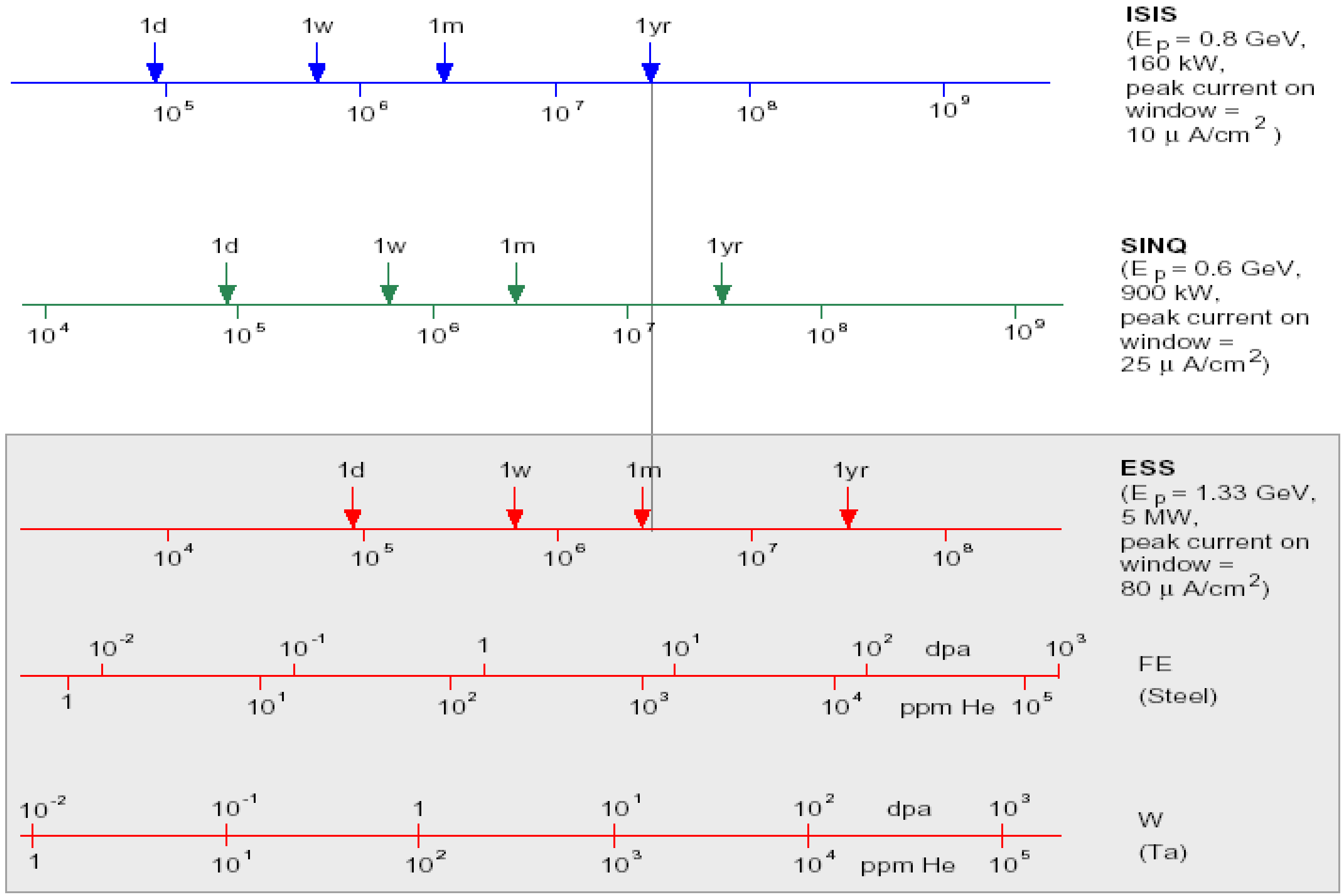
$\rightarrow$ Total available energy to cause displacement

$T^a{}_d$: effective threshold displacement energy

$\rightarrow$ Energy required to displace an atom (Al = 27 eV)

And the 0.4 ? Please don't ask …

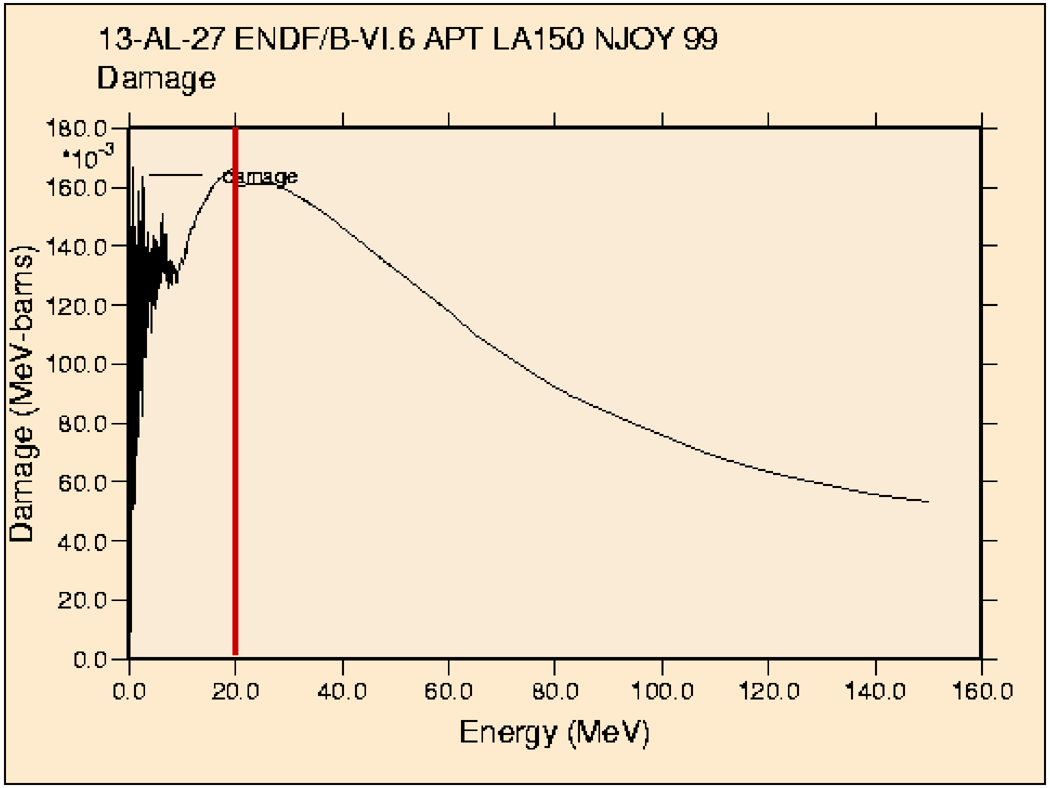
DPA for spallation sources

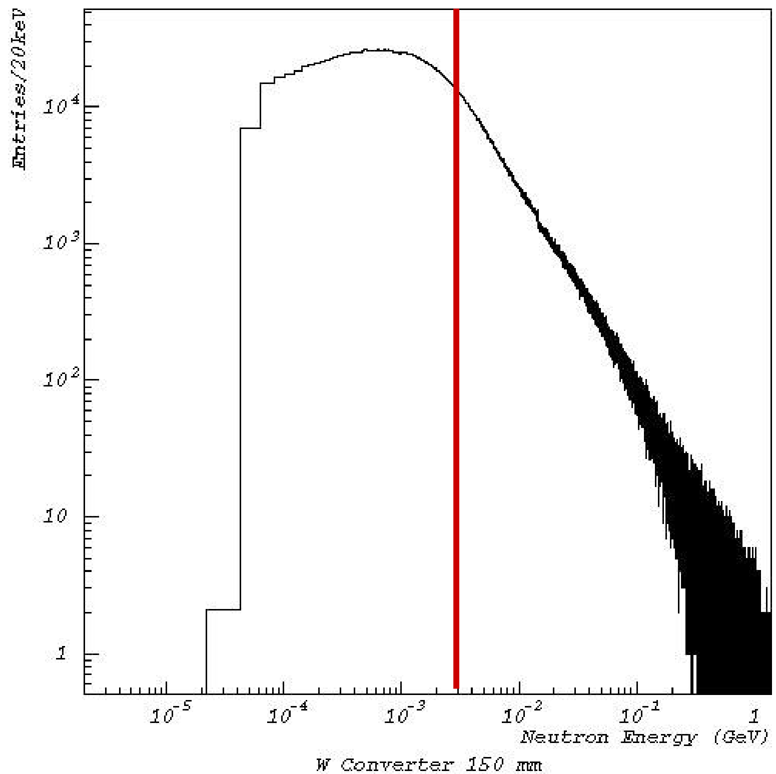


Neutron damage

Damage cross section

Neutron spectrum





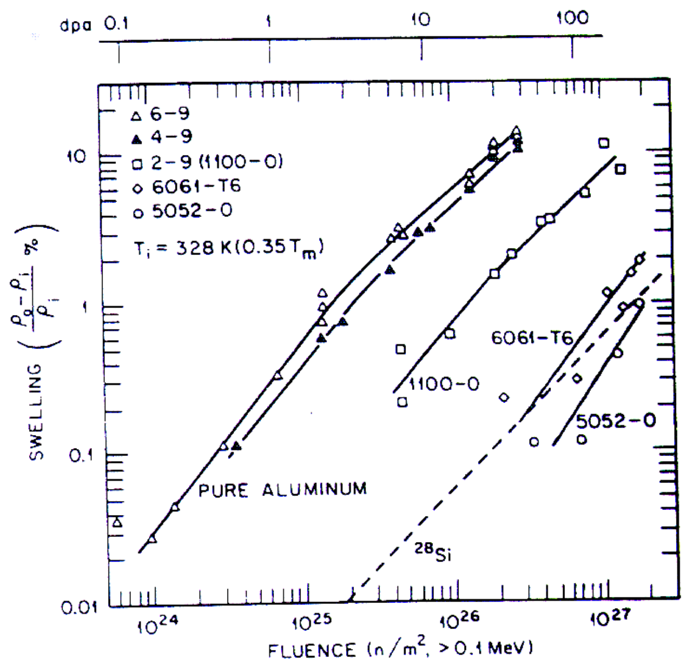
GeV

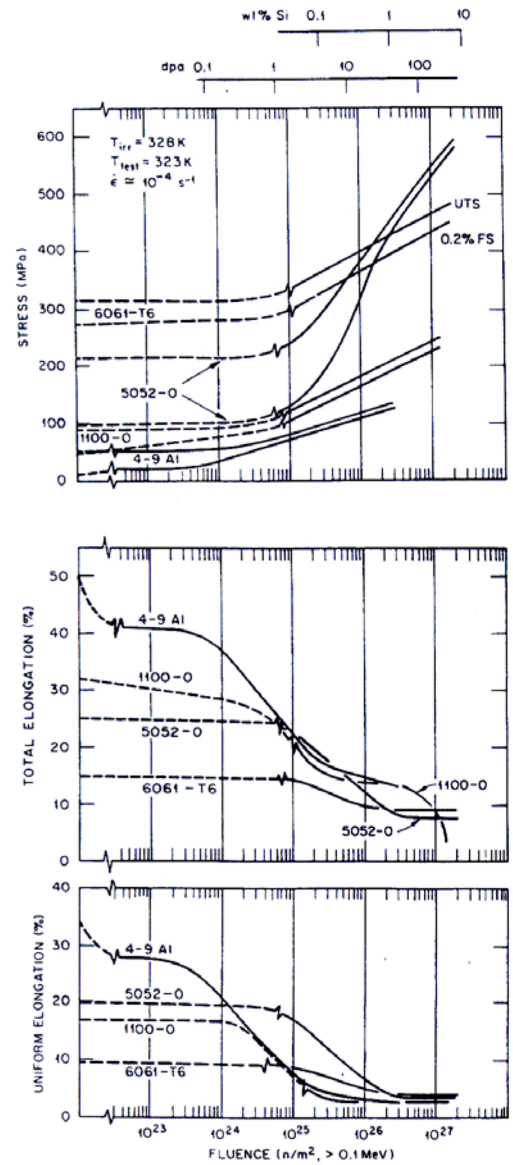
Large neutron fraction where damage cross section is high

Ductility variation and swelling

Neutron flux from Hg
typical of a
Neutron Spallation Source
(ESS, SNS)

Approx 10^{26} n/m²





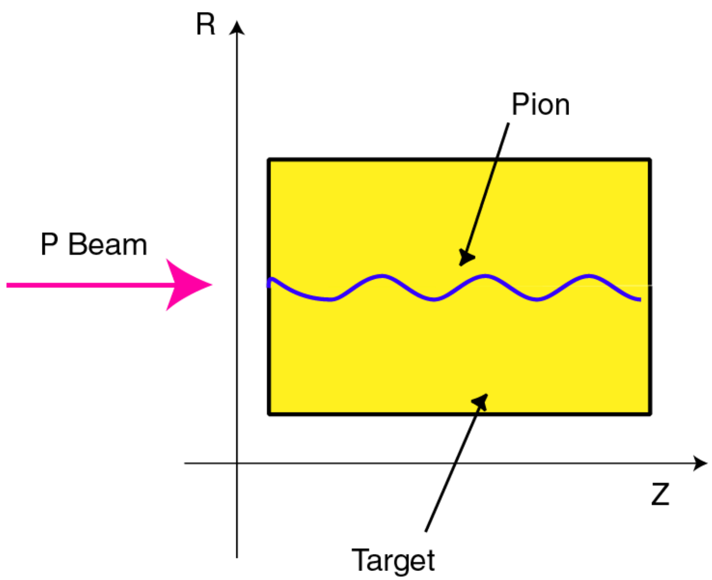
Material development

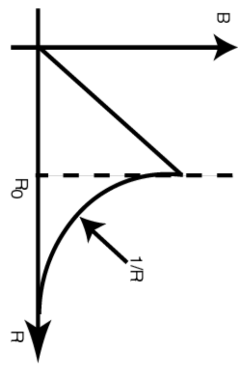
- Mechanical tests of Aluminum-Alloys before and after irradiation
  - Variation of the mechanical parameters
  - CERN is not equipped for such measurements
    - Isolde as irradiation facility but somewhere else for tests

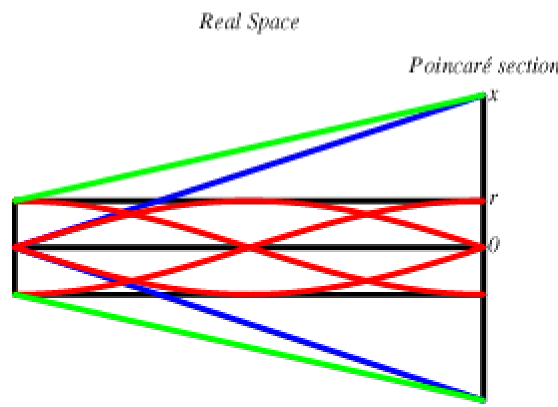
- Test for define material as a wall between Aluminum and Hg
  - Highly “active” environment:
    - Mercury splashing around
    - Minimum thickness but high mechanical resistance (Ti-Alloys? Stainless Steel? See ESS, SNS target)

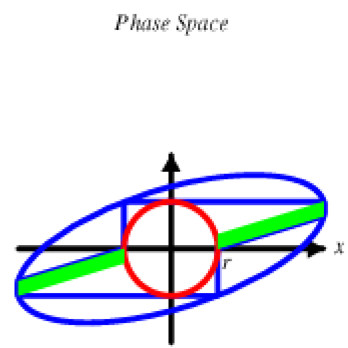
Principle: high current flowing axially in a conductor

➡ Magnetic field rise linearly inside the conductor

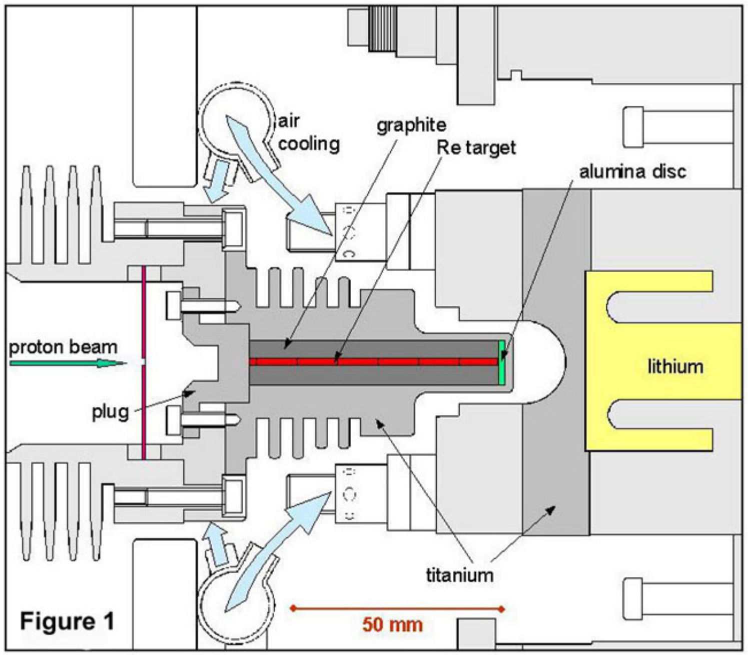


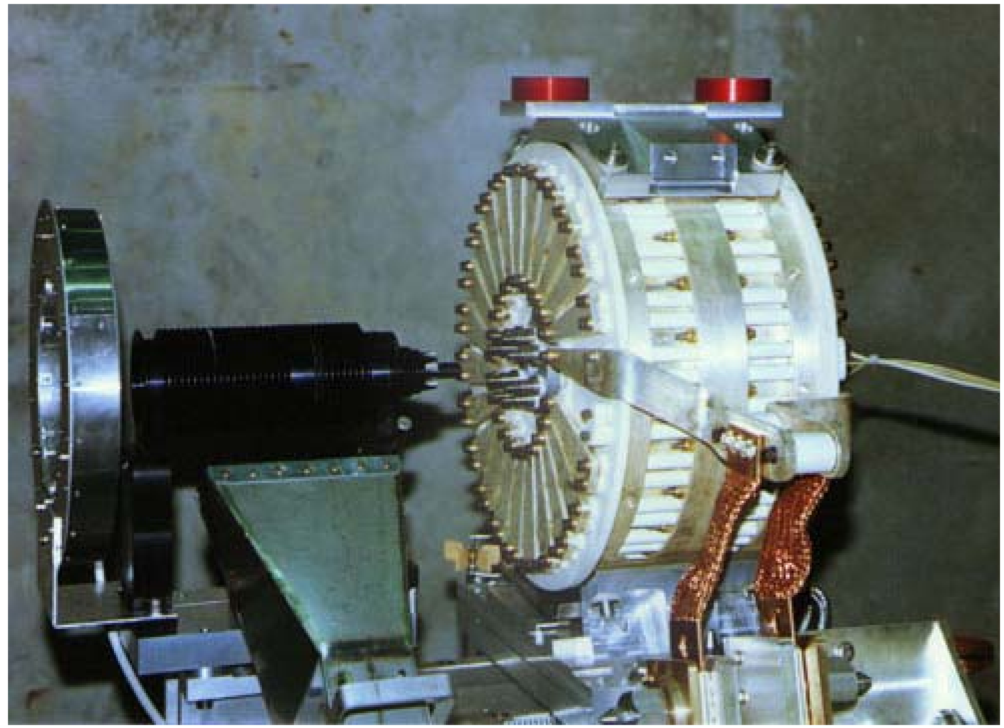






Li-Lens: how it looks like





From Nufact Note 10

Simulation results

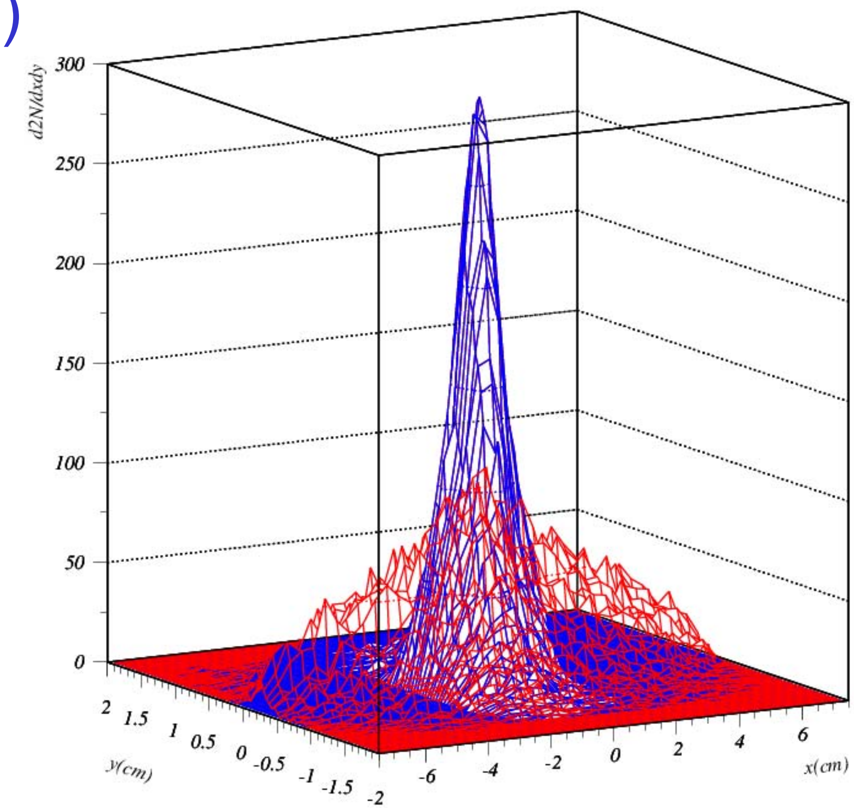
Simulation parameters

Conducting target

- Current: 2.49 MA (B=20 T at R_{max})
- Phase : π
- Target : L = 13 cm R = 2.26 cm

Tilted target in solenoidal field

- B field: 20 T
- Target : L = 30 cm R = 0.75 cm
- Solenoid : L = 30 cm R= 7.5 cm



Li-lens studies

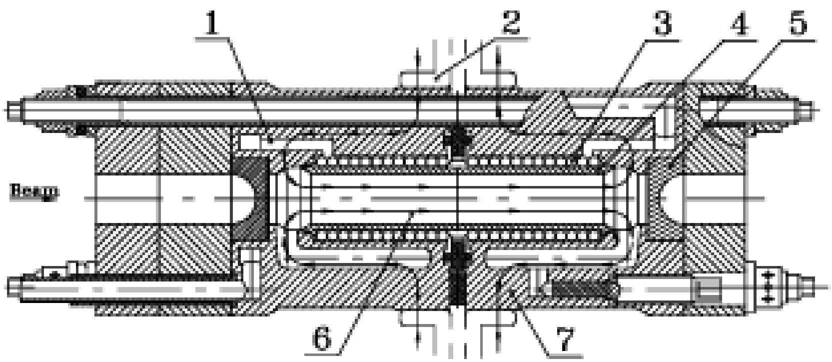


Fig. 2. CERN solid lithium lens with rigidly supported shell.

1– cooling inlet channels; 2 –current contacts; 3 – silicon nitride spheres; 4 –stainless steel container; 5 – titanium window; 6 –lithium rod, 7 –steel housing.

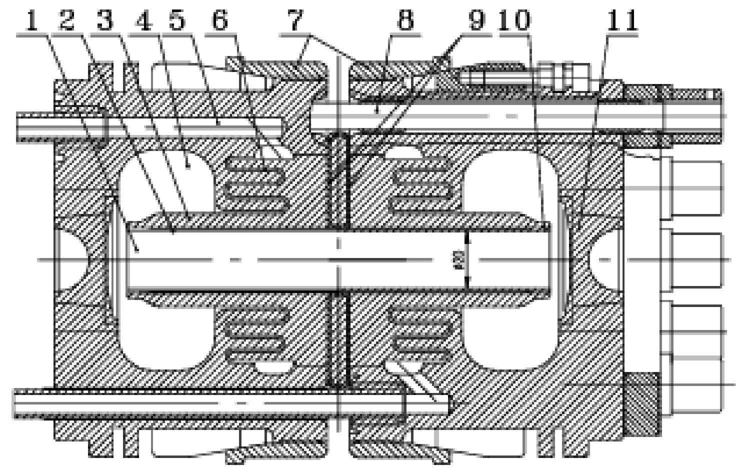


Fig. 3. Lens with liquid lithium.

1 – lithium rod; 2 – thin wall titanium shell; 3 – thick wall pipe; 4 – buffer volume; 5 – liquid lithium input; 6 – hydrodynamical dampers; 7 – current input; 8 – retaining bolts; 9 – insulation gap; 10 – weld; 11 – beryllium windows.

Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

LIQUID LITHIUM LENS WITH HIGH MAGNETIC FIELDS

B. Bayanov, V. Belov, A. Chernyakin, V. Eschenko, V. Karasuk, M. Petrichenkov, G. Silvestrov[#] ,
T. Vsevolozhskaya, BINP, Novosibirsk, Russia

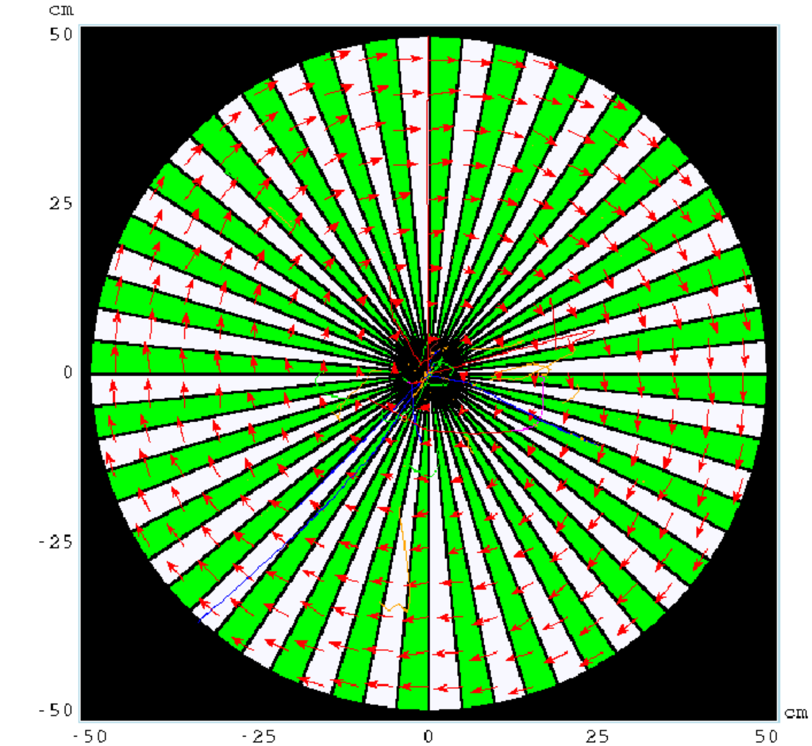
Limitation of conducting target

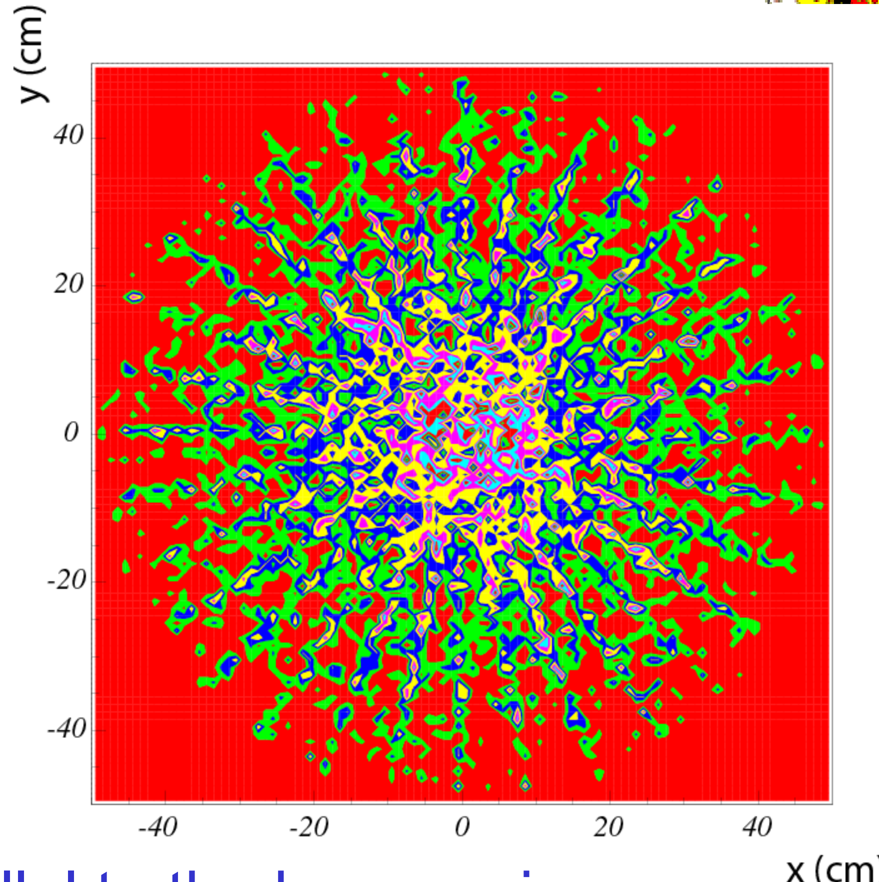
- High power dissipation ≈ 3.18 MW (Mercury)
- π^- production: protons defocused inside the target
- Windows for target/beam-line separation

Why not lithium ?

- Long target (1 λ = 1.37 m): large π time spread
- Proton focusing inside the target
- High power deposition: 33.6 MW (liquid Li needed)

Big lithium lens

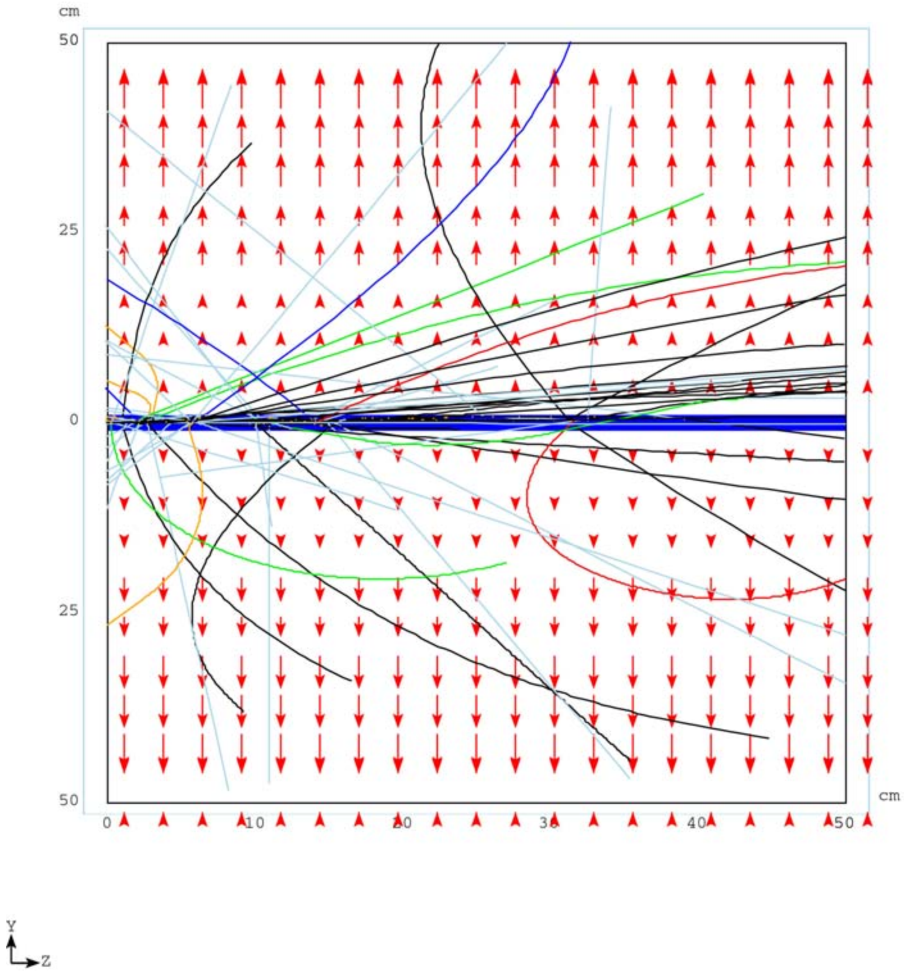


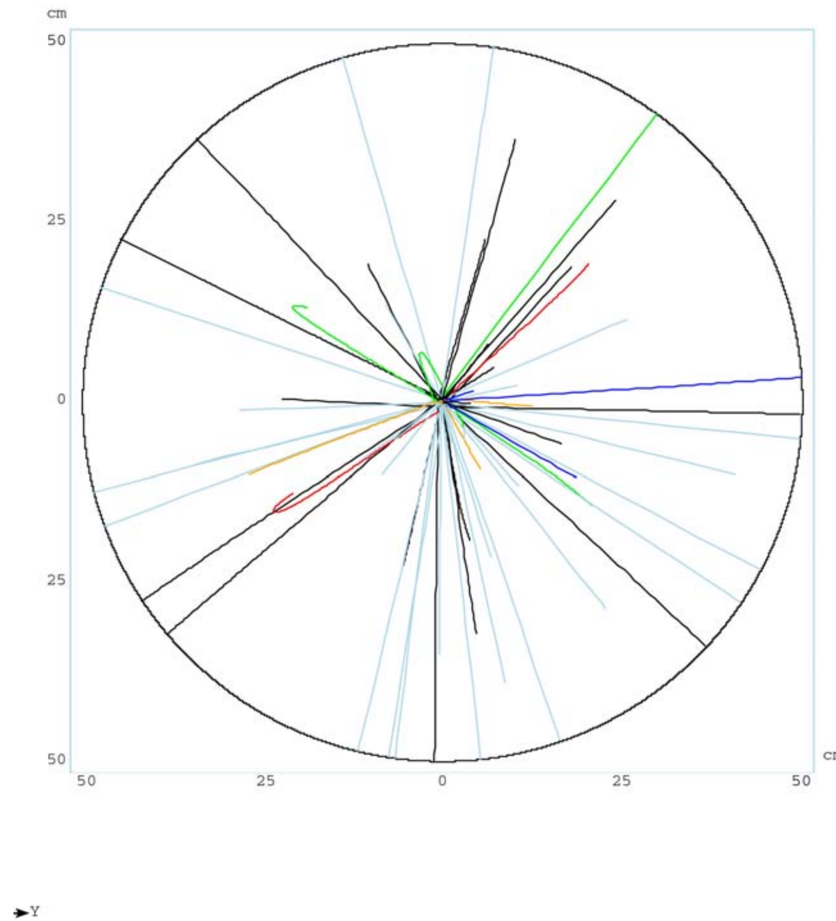


1 MA flowing in wedge parallel to the beam axis

- More focusing at large radius (x4 normal horn flux)
- Dead zone for material interaction

Few rays





Conclusions

- A lot of work has still to be done:
  - Horn development
    - Final power supply
    - Final horn design
    - Horn life time
  - Other ideas:
    - Still on paper (or on my hard-disk)

New ideas, friends and fresh air is WELCOME !!!