Technological challenges of future Super Beam projects

Marco Zito

Irfu/SPP CEA Saclay

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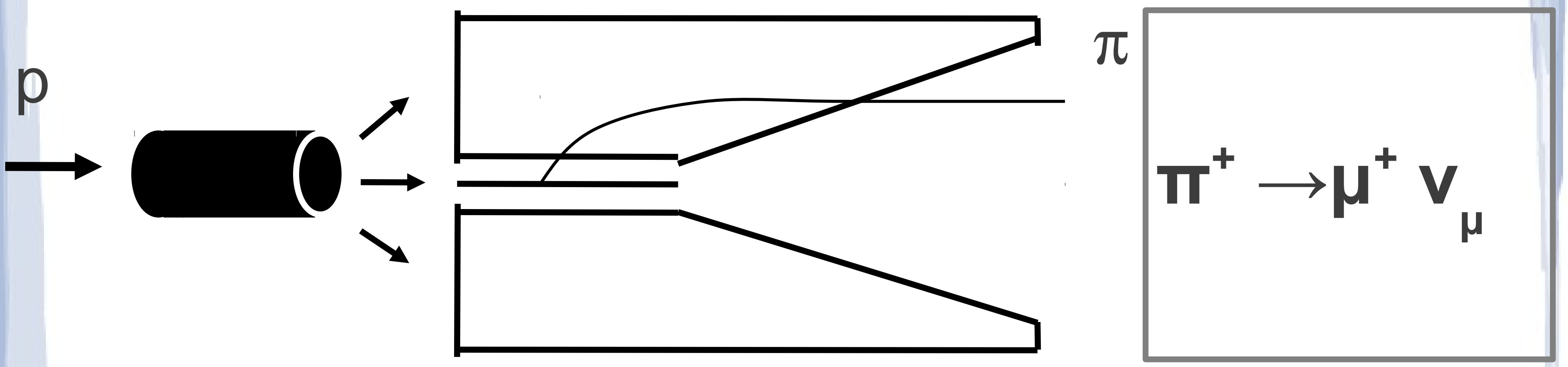
Outline

- Motivation
- The Super Beam concept
- Overview of challenges
- The target
- The focusing device
- Conclusion

Thanks to Mary Bishai, Marco Calviani, Takuya Hasegawa,Takeshi Nakadaira, Vaia Papadimitriou, and Yoshikazu Yamada for providing material

The neutrino (Super) beam



Primary proton beam on target

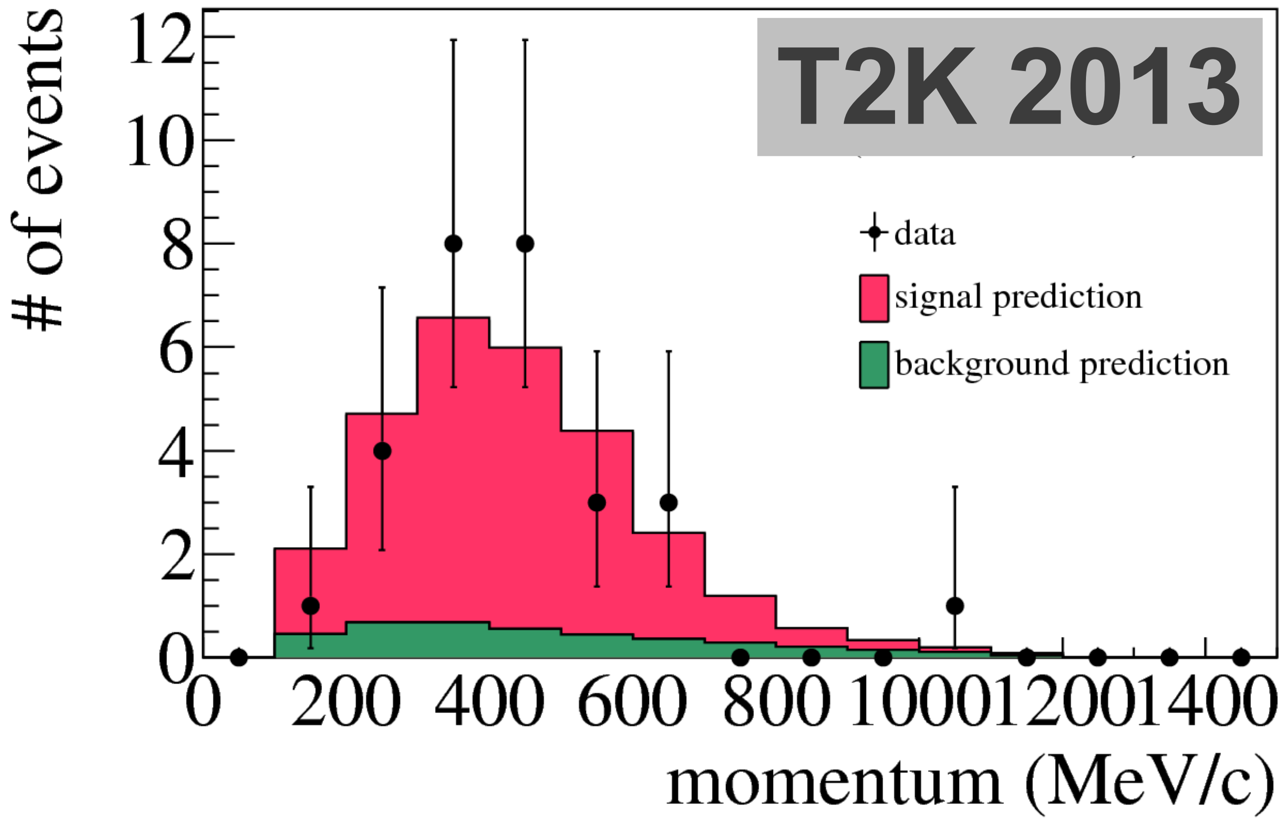
Focusing the pions with a magnetic device

Decay volume

Not a novel device !

Simon van der Meer, CERN-61-07 1961

A tool for discovery: $\nu_\mu \rightarrow \nu_e$



Discovery of $\nu_\mu \rightarrow \nu_e$: 28 events sel. (4.6 bckg) 7.5 sigma evidence

Need several hundred of events for CP phase space exploration

$\nu_\mu \to \nu_e$: beyond the leading term

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2} \sin^2((\hat{A}-1)\Delta)$$

"Atmospheric" term

$$+\alpha \frac{8 J_{CP}}{\hat{A}(1-\hat{A})} \sin(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$

CP violating term

$$+\alpha \frac{8 I_{CP}}{\hat{A}(1-\hat{A})} \cos(\Delta) \sin(\hat{A}\Delta) \sin((1-\hat{A})\Delta)$$

$$+\alpha^2 \frac{\cos^2\theta_{23} \sin^2\theta_{12}}{\hat{A}^2} \sin^2(\hat{A}\Delta)$$

"Solar" term

$$J_{CP} = 1/8 \sin\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

Jarlskog invariant

$$I_{CP} = 1/8 \cos\delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

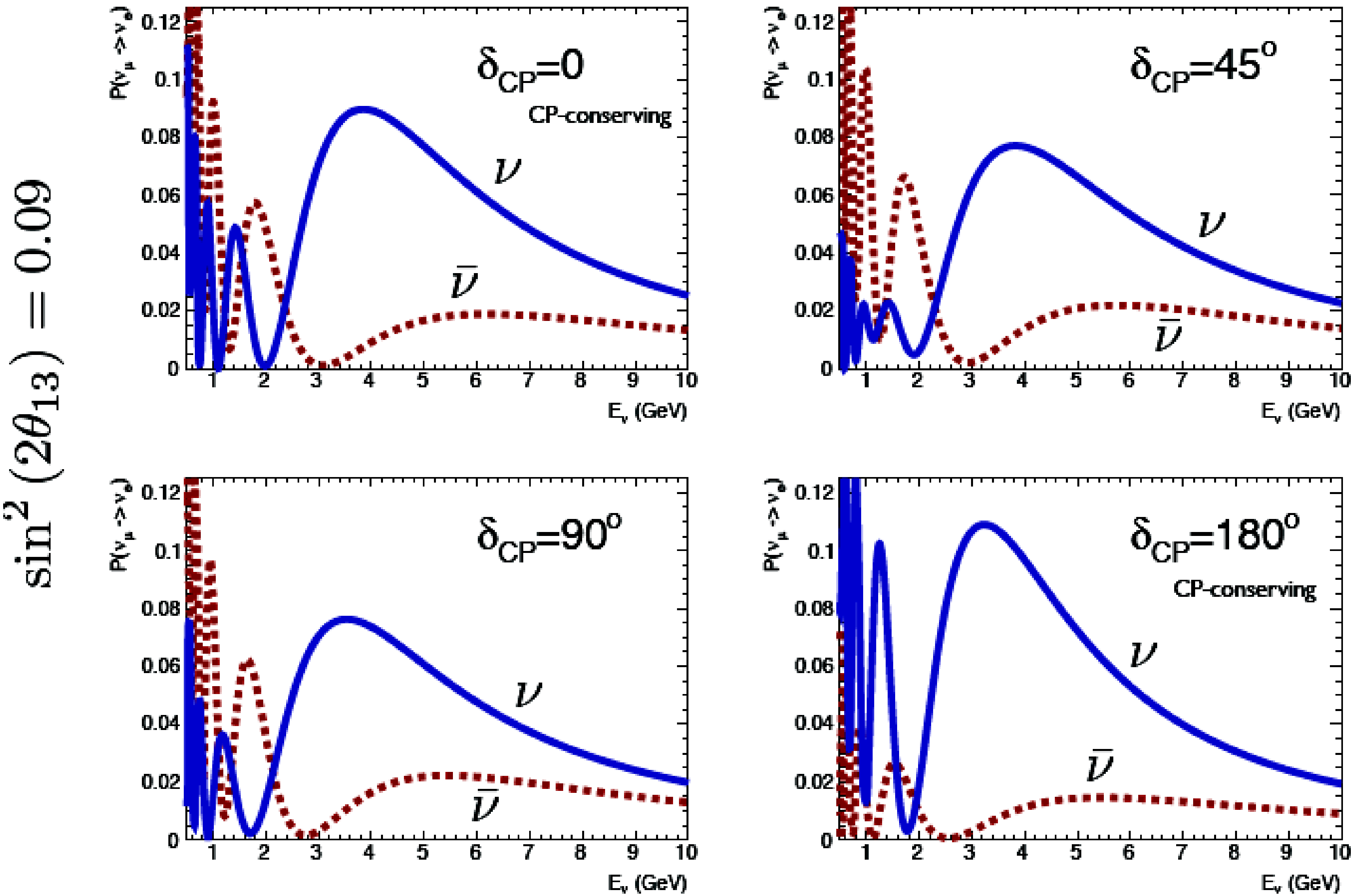
$$\alpha = \Delta m^2_{21} / \Delta m^2_{31}, \Delta = \Delta m^2_{31} L / 4E$$

$$\hat{A} = 2VE / \Delta m^2_{31} \approx (E_\nu / GeV)/11$$

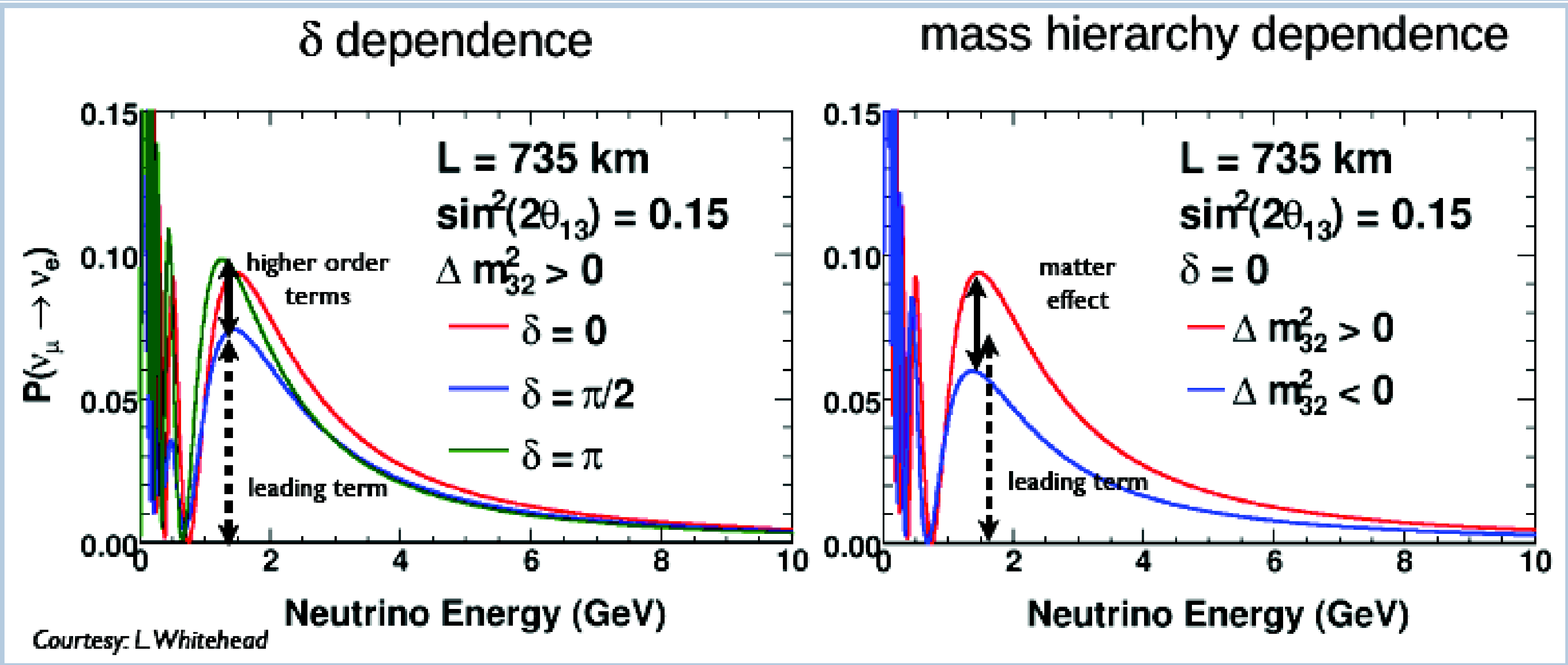
Approximate formula with matter effect:
M. Freund hep-ph/0103300

CERN-Pyhäsalmi: oscillations

★ Normal mass hierarchy L=2300 km

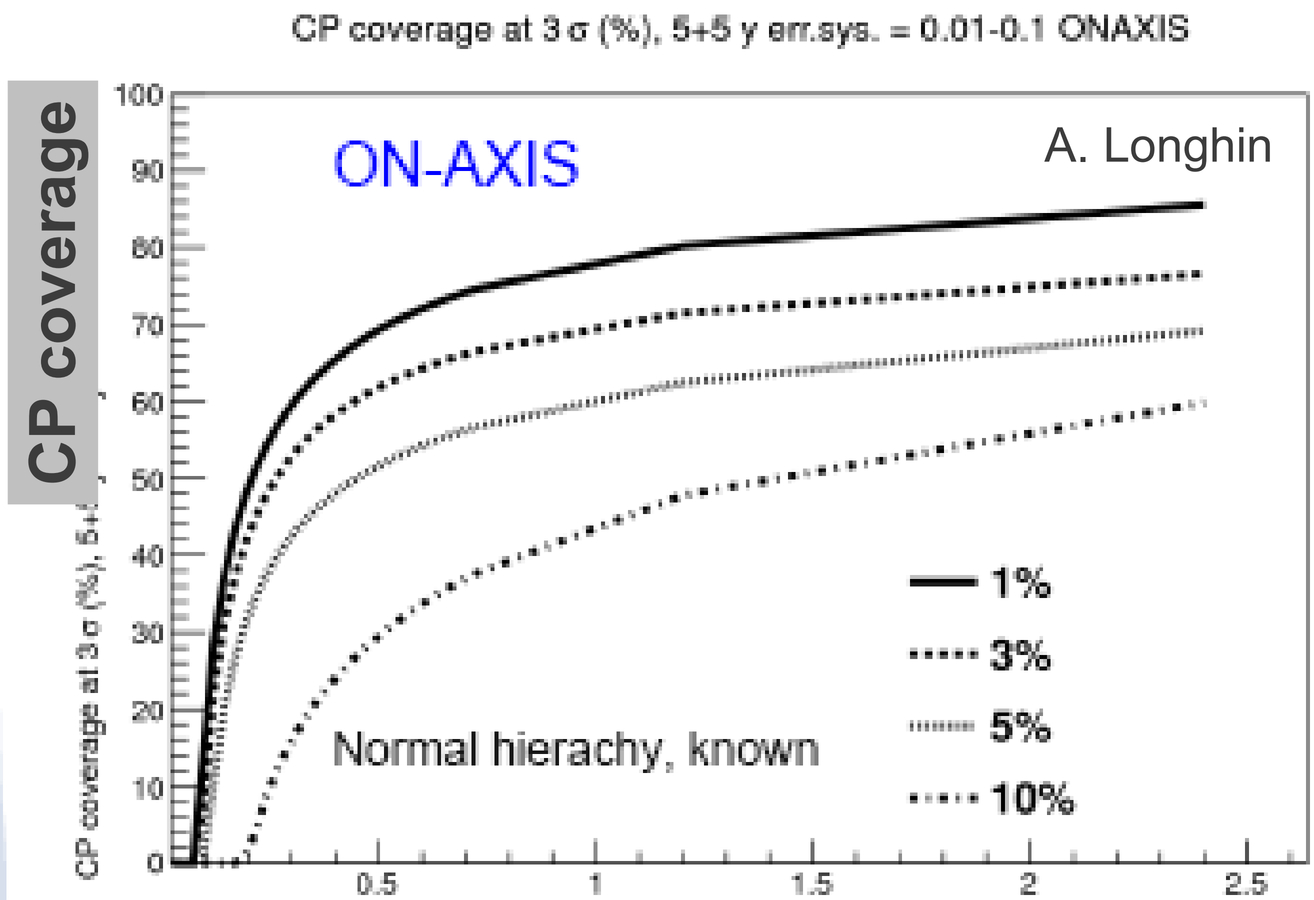


Beyond the leading term



- Sensitivity to the next-to-leading terms requires precise absolute measurement at the first oscillation maximum
- Or a wide flux covering also the second oscillation maximum

Towards CP violation and mass hierarchy



MW 10^7 s Mton

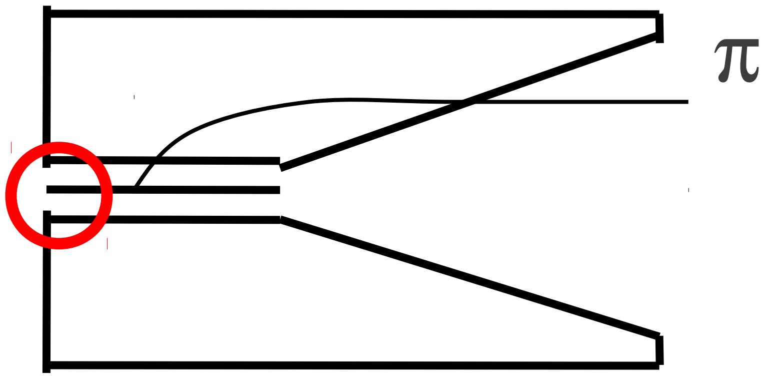
Notice the scale

Neutrino beams and future Super Beams projects

Project	Power (MW)	Baseline (km)	Pr. energy (GeV)
NUMI	0.4	735	120
CNGS	0.5	730	450
T2K-HK	0.75	295	30
LBNE	0.7-2	1290	60-120
LBNO	0.7-2.3	2300	50-400
CERN-Fréjus	4	130	4.5
ESS	5	365	2.5

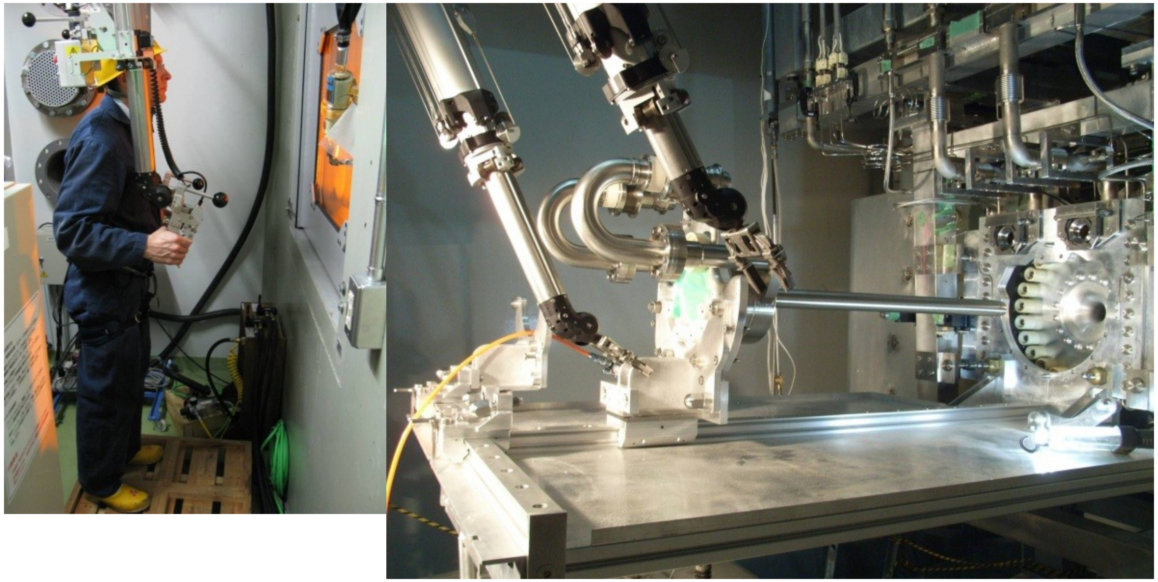
The source of neutrinos

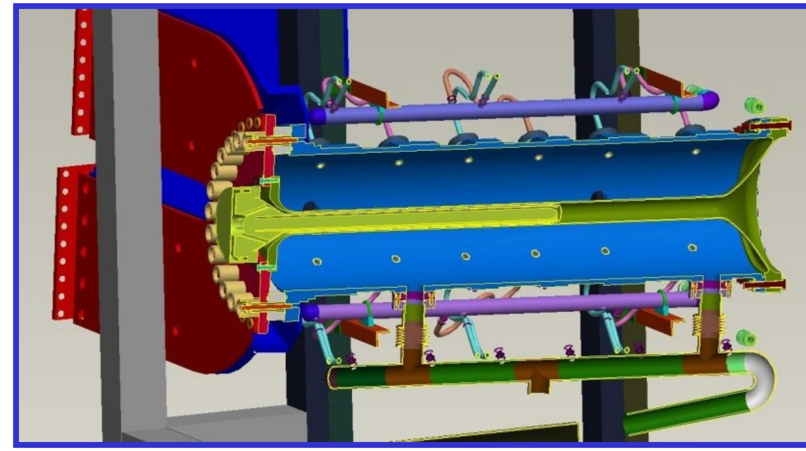
- Point to parallel focusing : need the beam-target interaction spot to be quasi point-like



- As soon as you scale up the beam power this leads to very high energy density
- Problem made worse by: low energy proton beam, target inside the horn, integration of cooling, 1/r field in the horn

T2K : Target and first horn

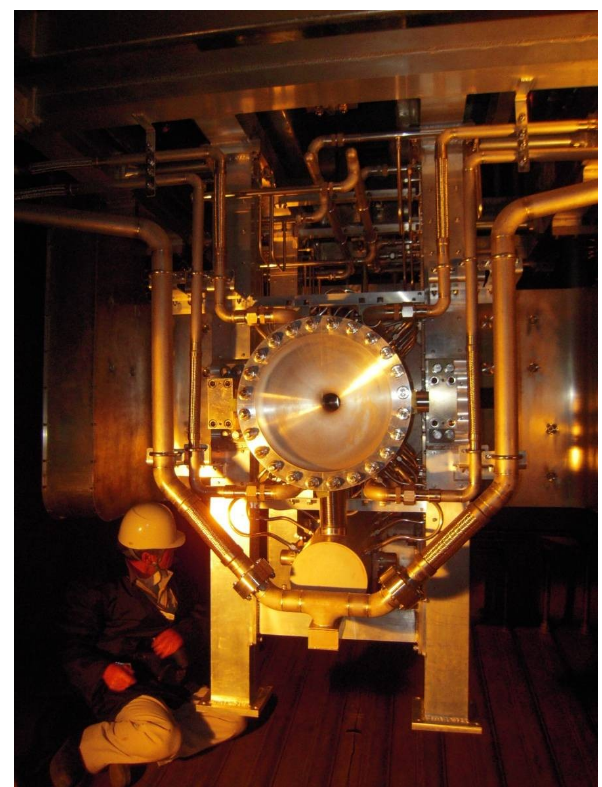




Target: 26mm-ϕ x 900mm-L graphite

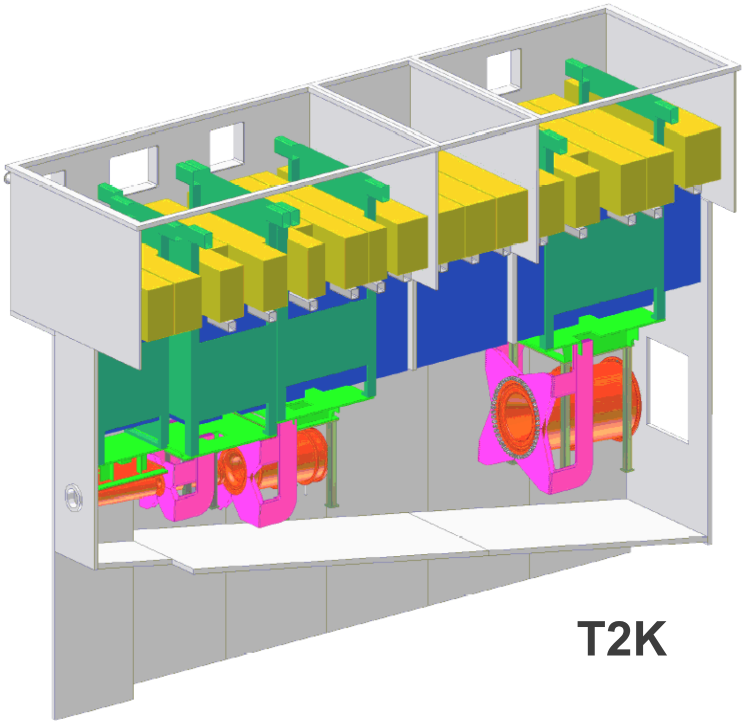
Target extracted from horn

Down-stream side of 1st horn



Super Beam technology

- The current neutrino beam technology (solid static target, aluminum horns) works for proton beams in the ~100 kW range
- Can we extrapolate to it to the MW range or will we find a hard limit ?

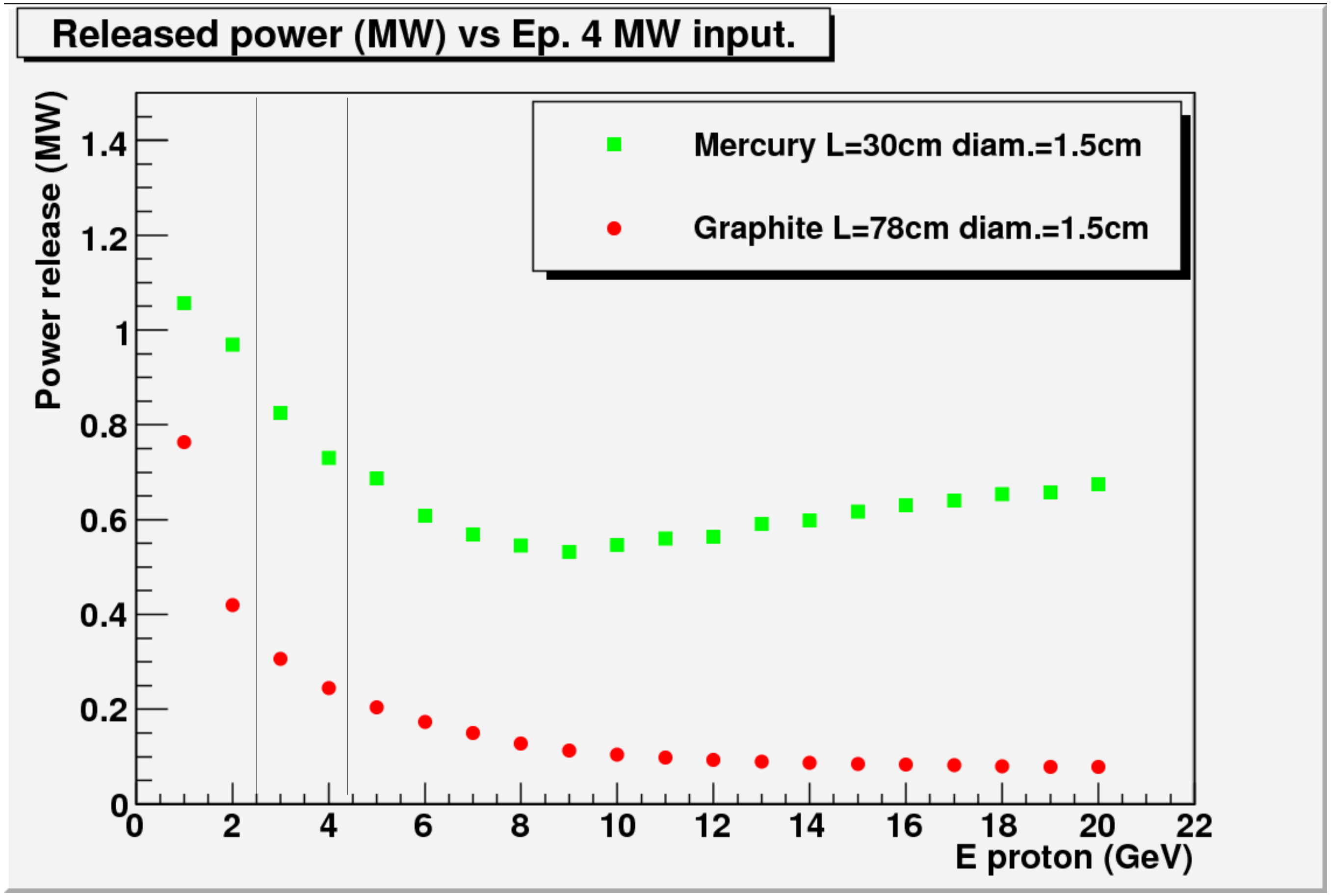


T2K

Technological challenge N1 : the target

- Sustain the proton flux
- Maintain physical properties (integrity, thermal and mechanical properties)
- Withstand the dynamical stress
- and the static stress

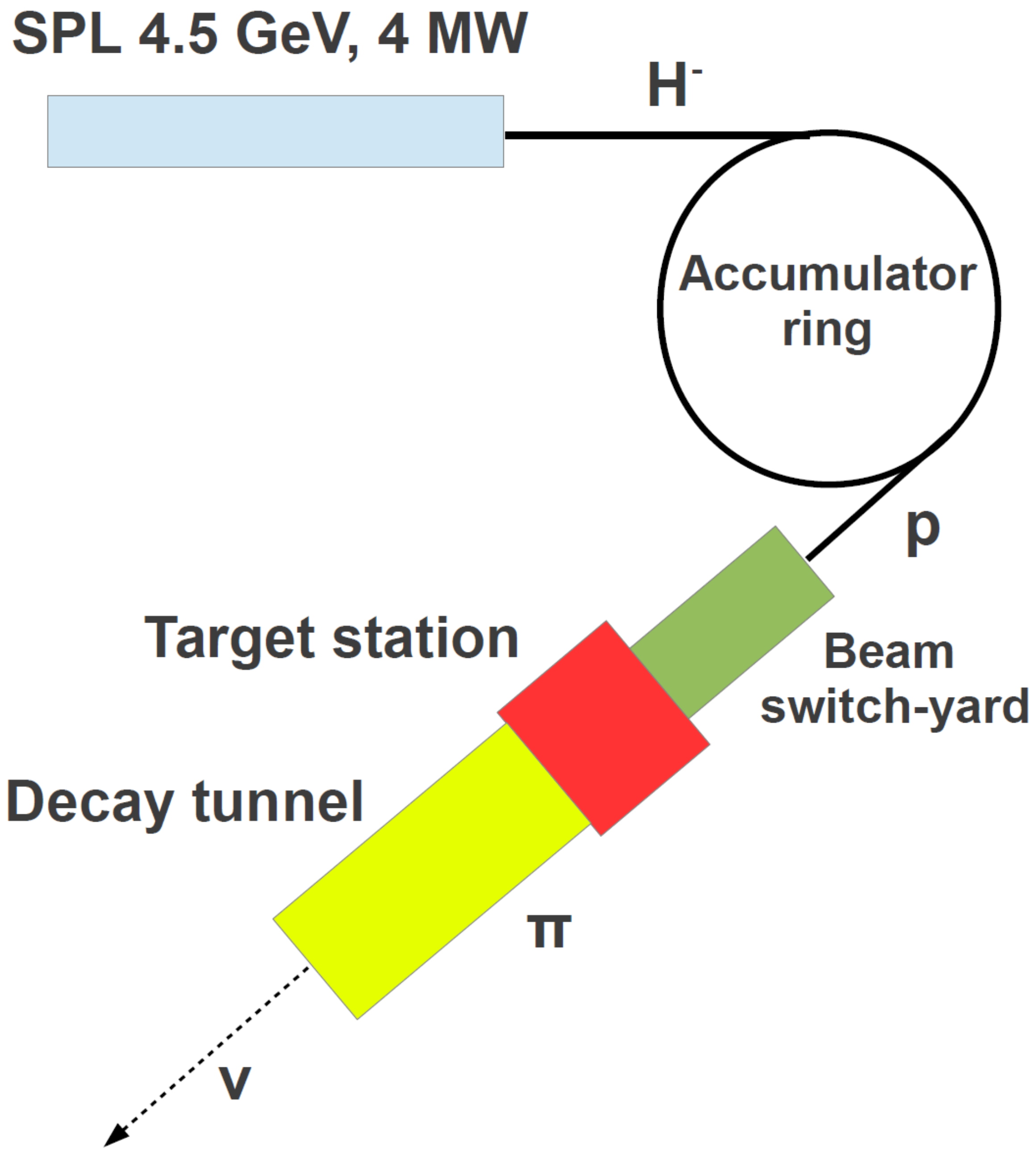
Power released in the target



For comparison: T2K target ~20 kW at 750 kW beam power
Low energy Super Beams face an even more challenging task

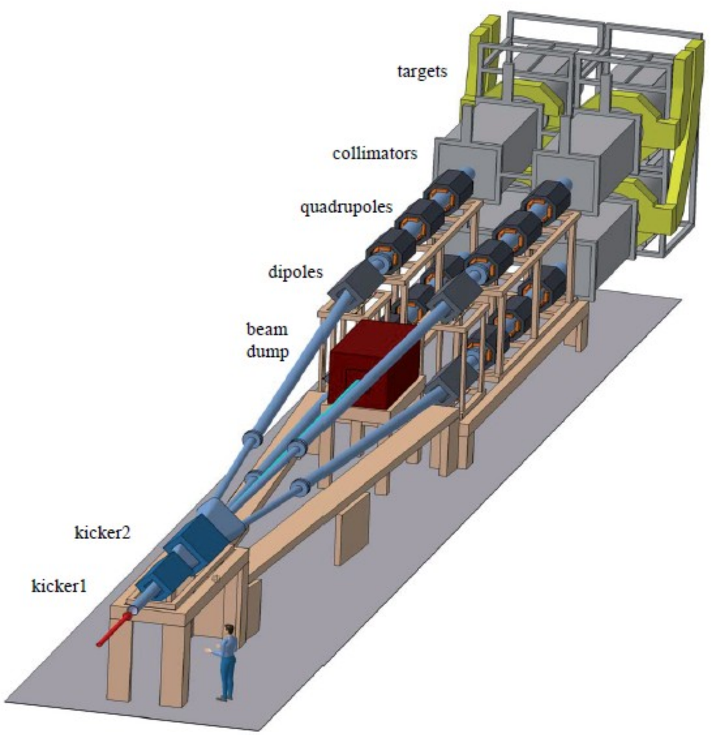
arXiv:1212.0732

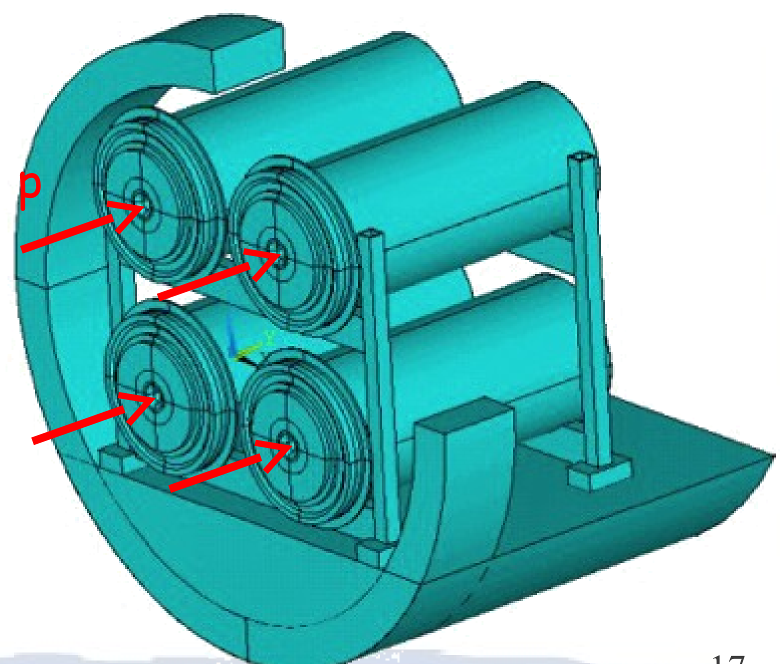
The EUROnu Super Beam facility



A first step towards reducing the power density

- The 4 MW 50 Hz beam is split in 4 beam lines, each pulsed at 12.5 Hz
- Overall dimensions 4x4 m**2
- Pions decaying in the same 25m decay tunnel

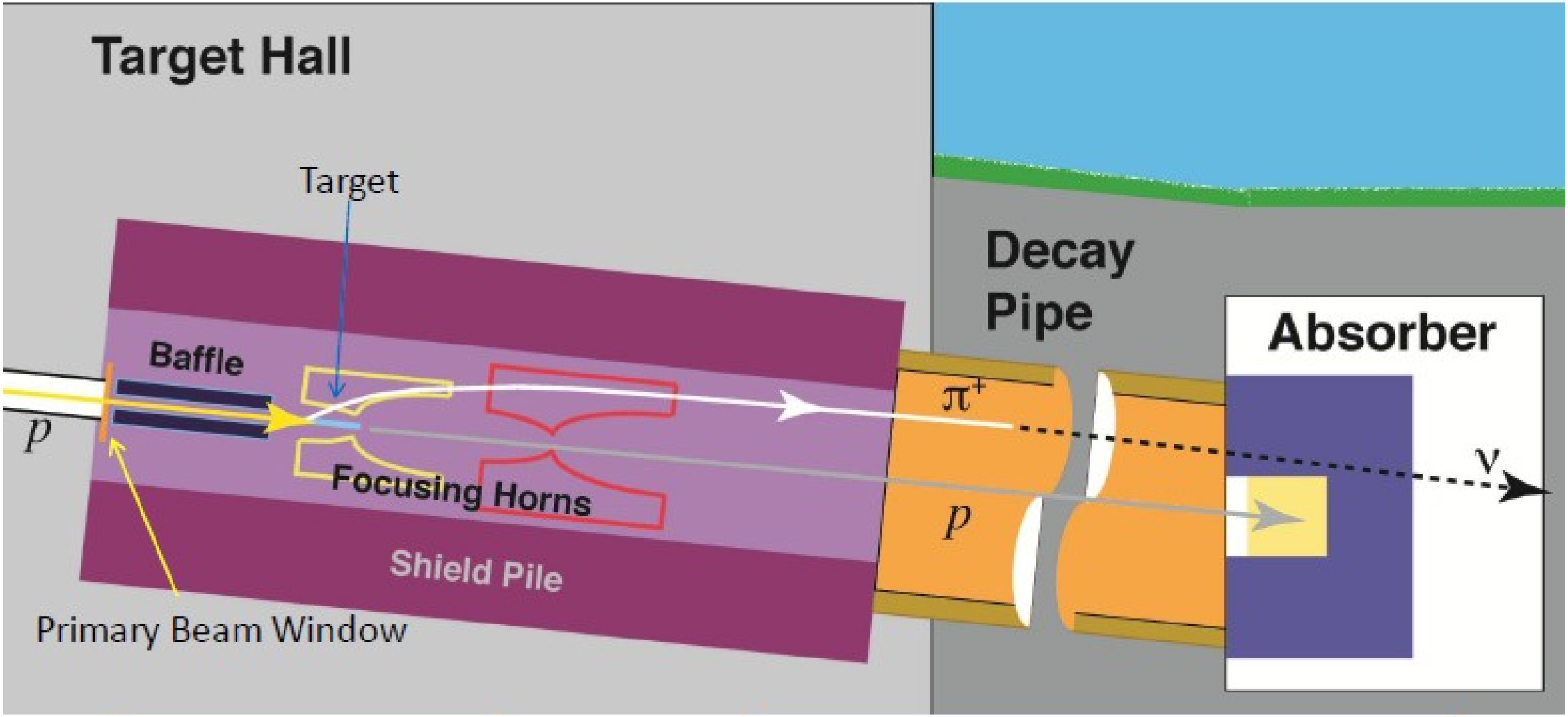




The EUROnu target

- Even splitting the beam, the power density exceeds the limit of a solid target
- Use of a pebble-bed envisaged (see C.Densham talk)
- This solution can be proposed also for other projects like a neutrino beam at ESS or for a Neutrino Factory

The LBNE target/horn configuration



NuMI design Horns.

NuMI-like low energy target for 708 kW operation.

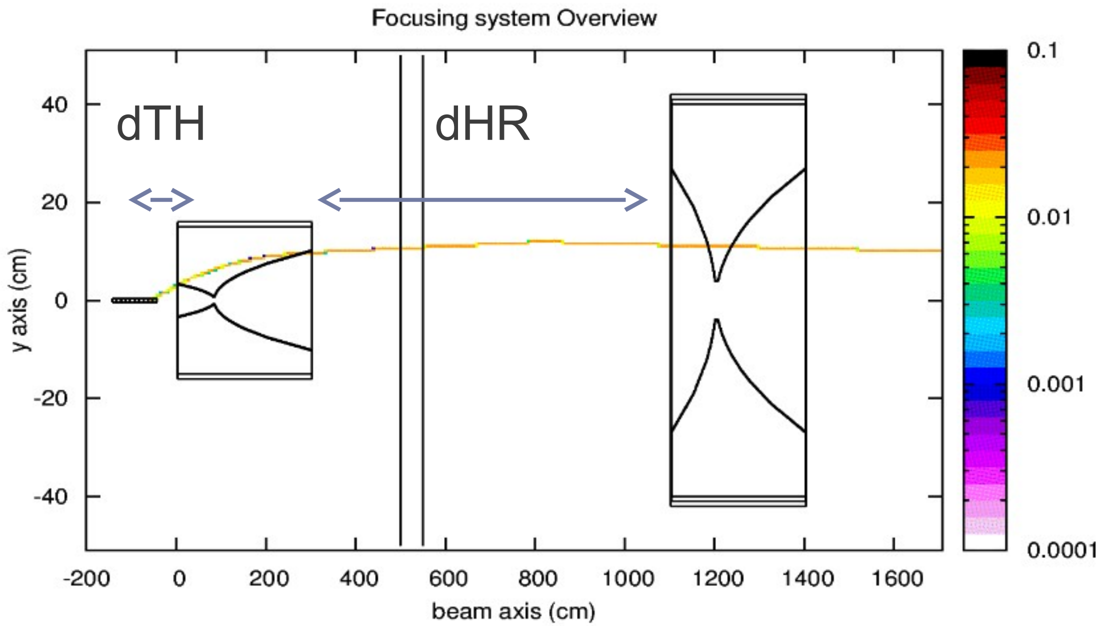
Target inserted into Horn 1.
Upstream end of target at -35 cm relative to the upstream face of Horn 1.
Tunable neutrino energy spectrum.

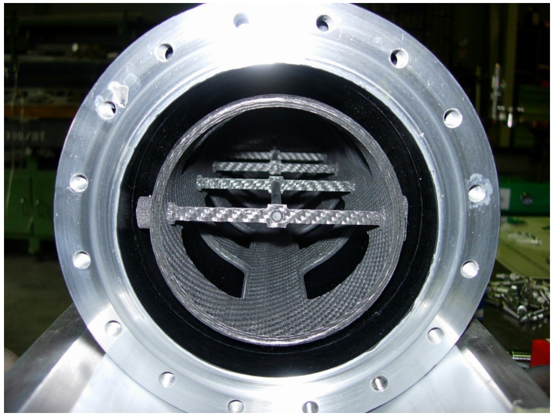
LBNE target studies

- LBNE reference target : upgraded version of the NUMI target. 47 segments 2 cm each of graphite
- Test of target materials completed at the BLIP facility (BNL)
- The chosen graphite grade is the best choice in term of strength and thermal expansion coefficient
- Further tests on beryllium at the CERN HiRadMat facility

M. Calviani

LBNO beam configuration

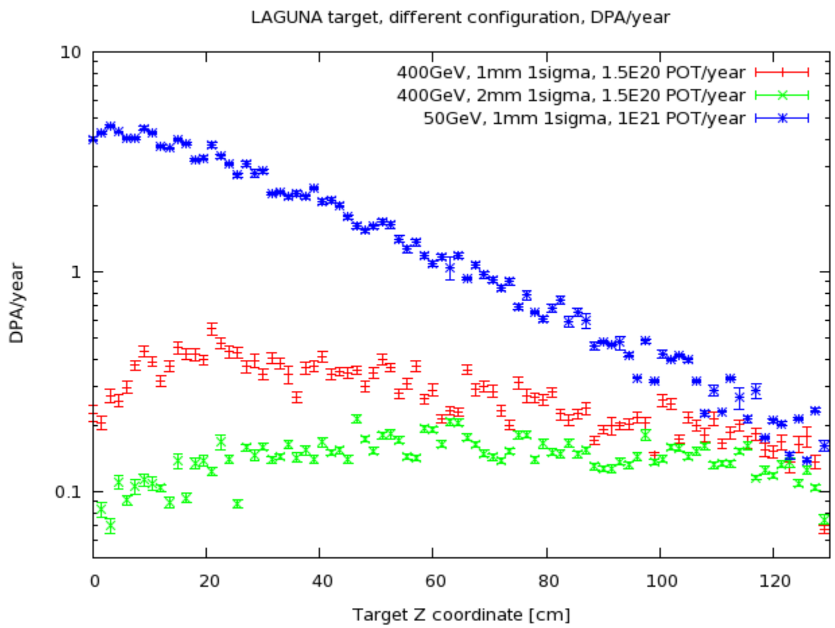




Target : 130 cm, 4-6 mm radius, carbon, outside horn
Cooling : either by radiation (like CNGS) or with forced Helium flow
Target operating at 700/900 C

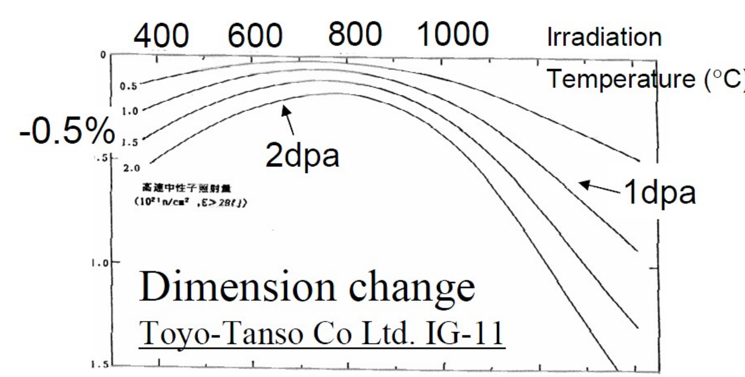
M. Calviani

LBNO target study



- DPA evaluation with FLUKA:
  - **0.2-0.5 DPA/y** for 1st phase
  - **~5 DPA/y** for 2nd phase
- CNGS target ~3 DPA at end of 2012 (after 5 years)

- Radiation damage of graphite
  - At 600-1000 °C: dimension change and thermal conductivity are **minimized**
  - Reduction of H embrittlement
- High operational temperature: favours annealing and reduction of imperfection

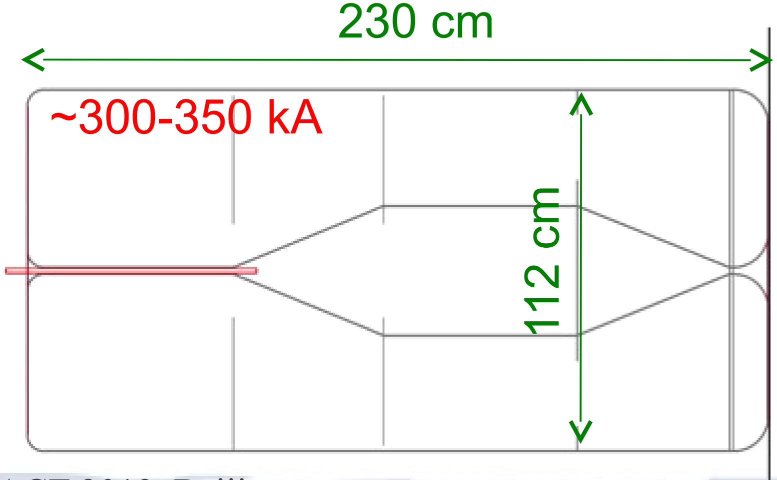


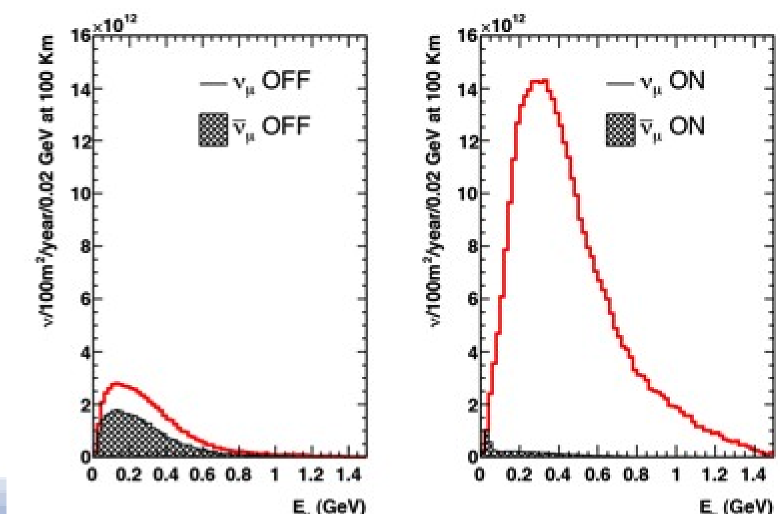
Technological challenge N2 : the horn

- Efficiently focus the pions
- Sign selection
- Joule and beam heating
- Under severe stress (static, B field stresses)
- Under radiation
- Sustain 10**7-10**9 pulses: fatigue

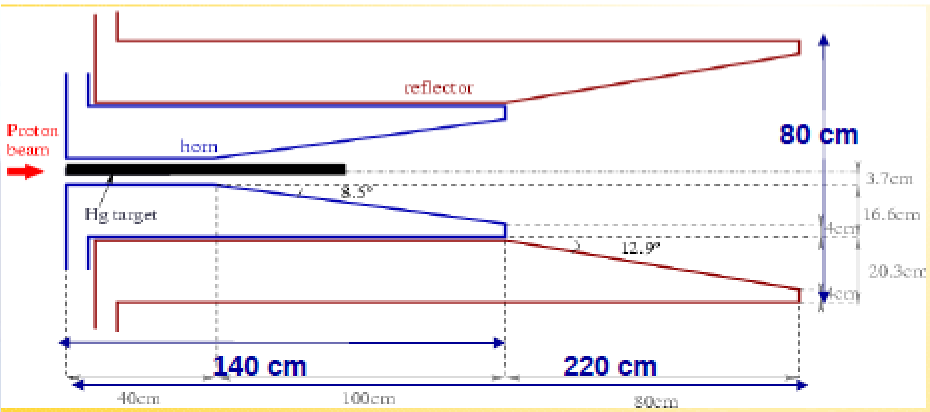
EUROnu SB : the horn

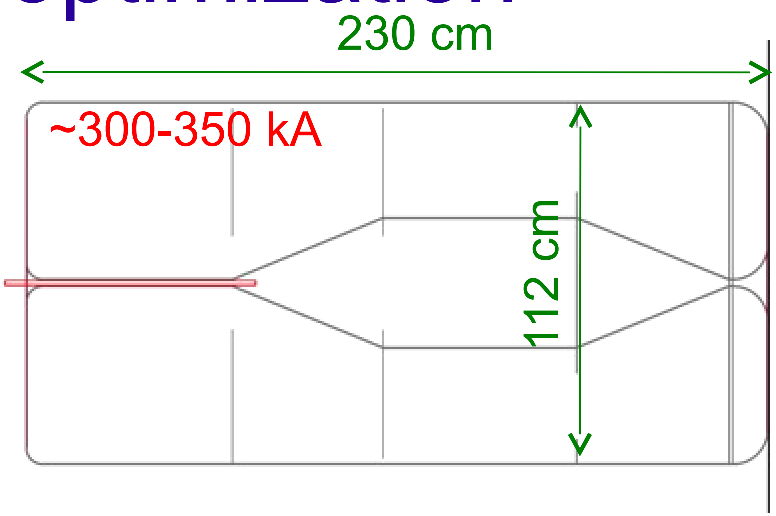
- Shape optimization using physics performance as a guideline
- Important role of downstream “neck” : defocusing of wrong charge pions
- 350 kA excitation current at 12.5 Hz
- Need to withstand 10^9 pulses !





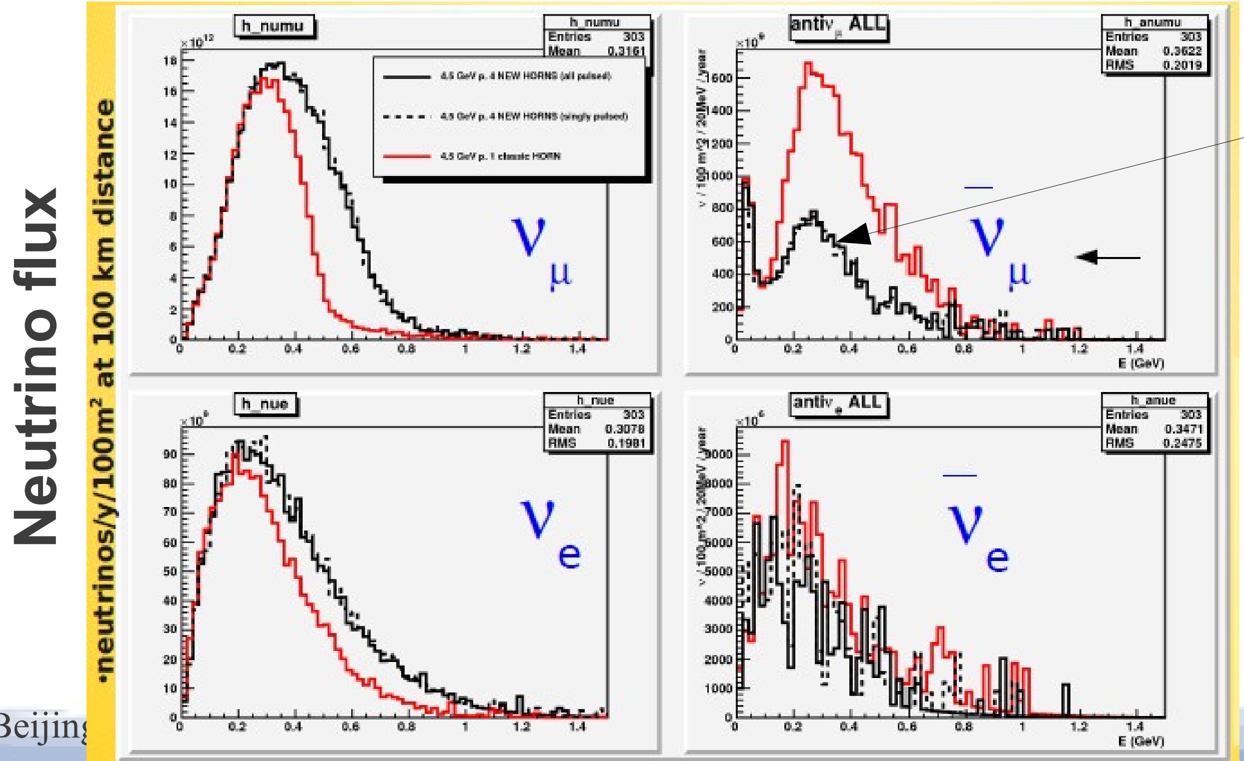
EUROnu SB:
impact of horn shape optimization





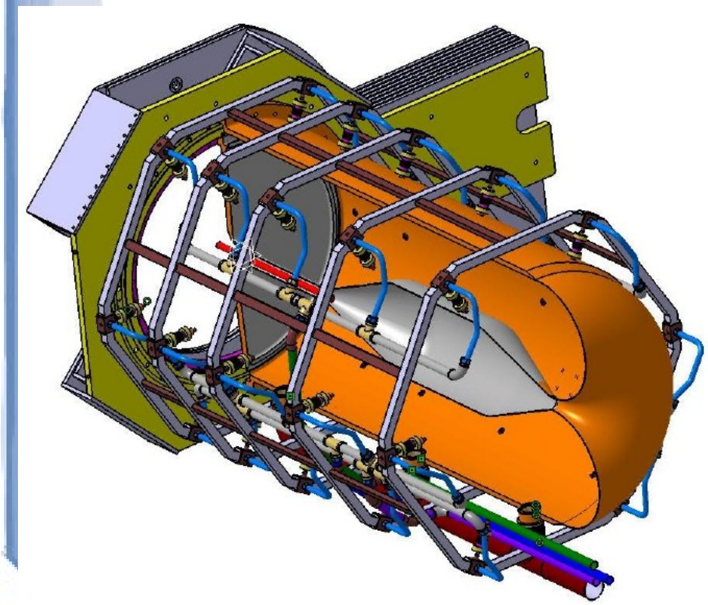
OLD

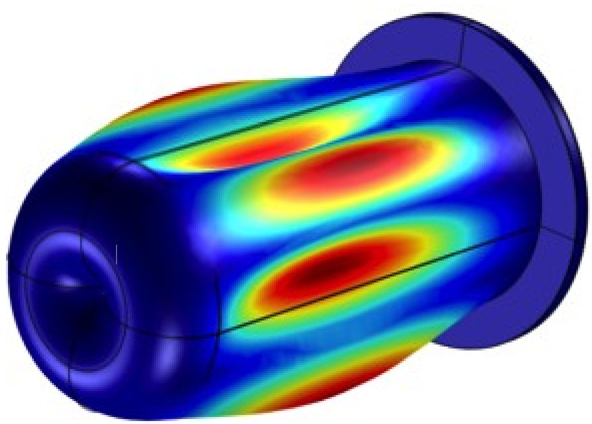
NEW



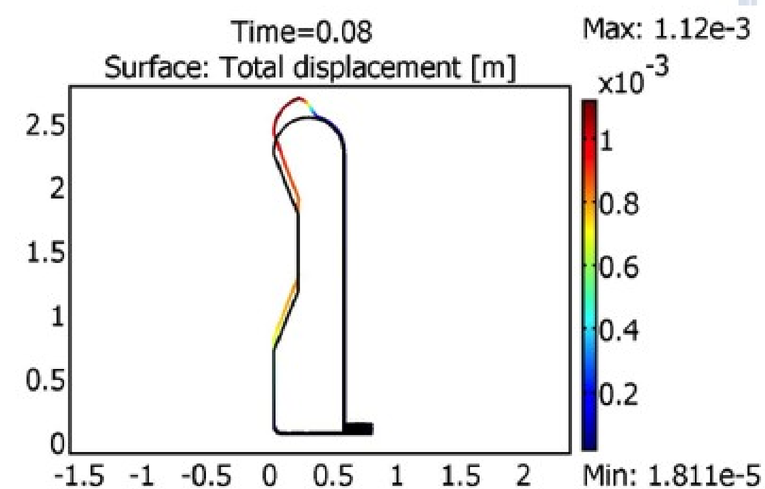
EUROnu SB horn study

- Maximum temperature 340-370 K
- Maximum stress: 38 Mpa
- Challenging requirements on the heat transfer ratio for the water cooling





f) $f = 144.2$ Hz



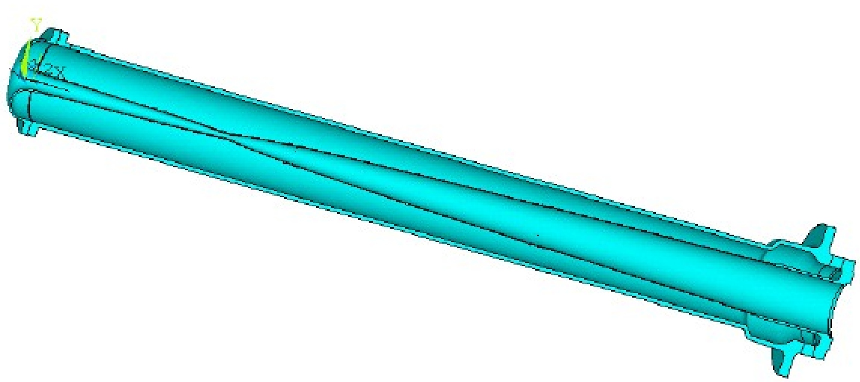
V. Papadimitriou

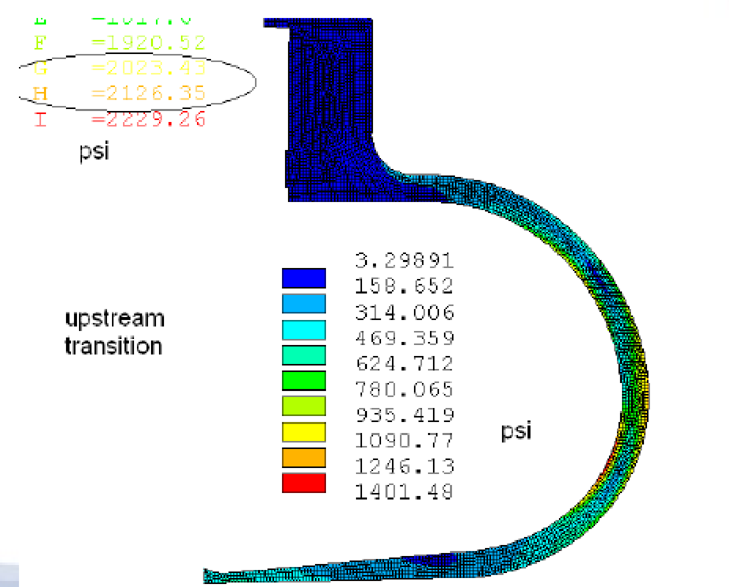
LBNE horn study

Result of a detailed Finite Element Analysis for the NUMI horn: safety factor 3.19 for running the horn at an increased current of 230 kA with a temperature of 61 C

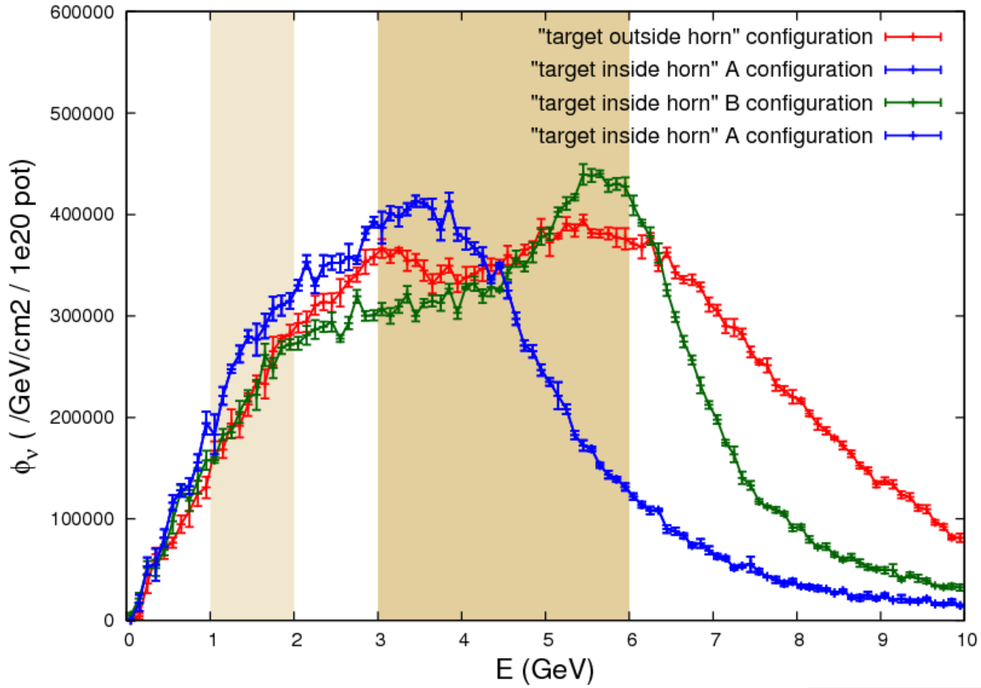
This current will result in 12 % more neutrinos at the first oscillation maximum

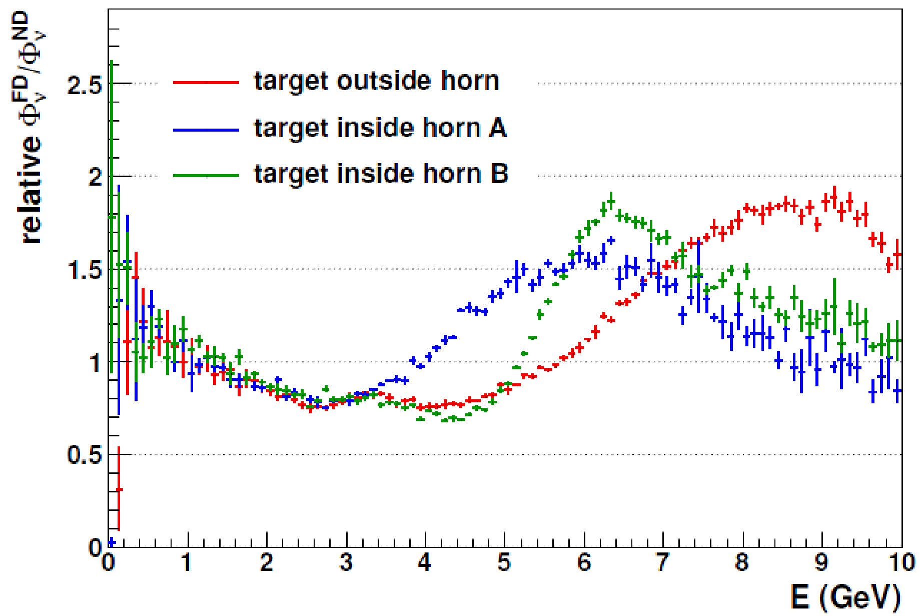
Further improvement possible with a new horn and higher current (300 KA)





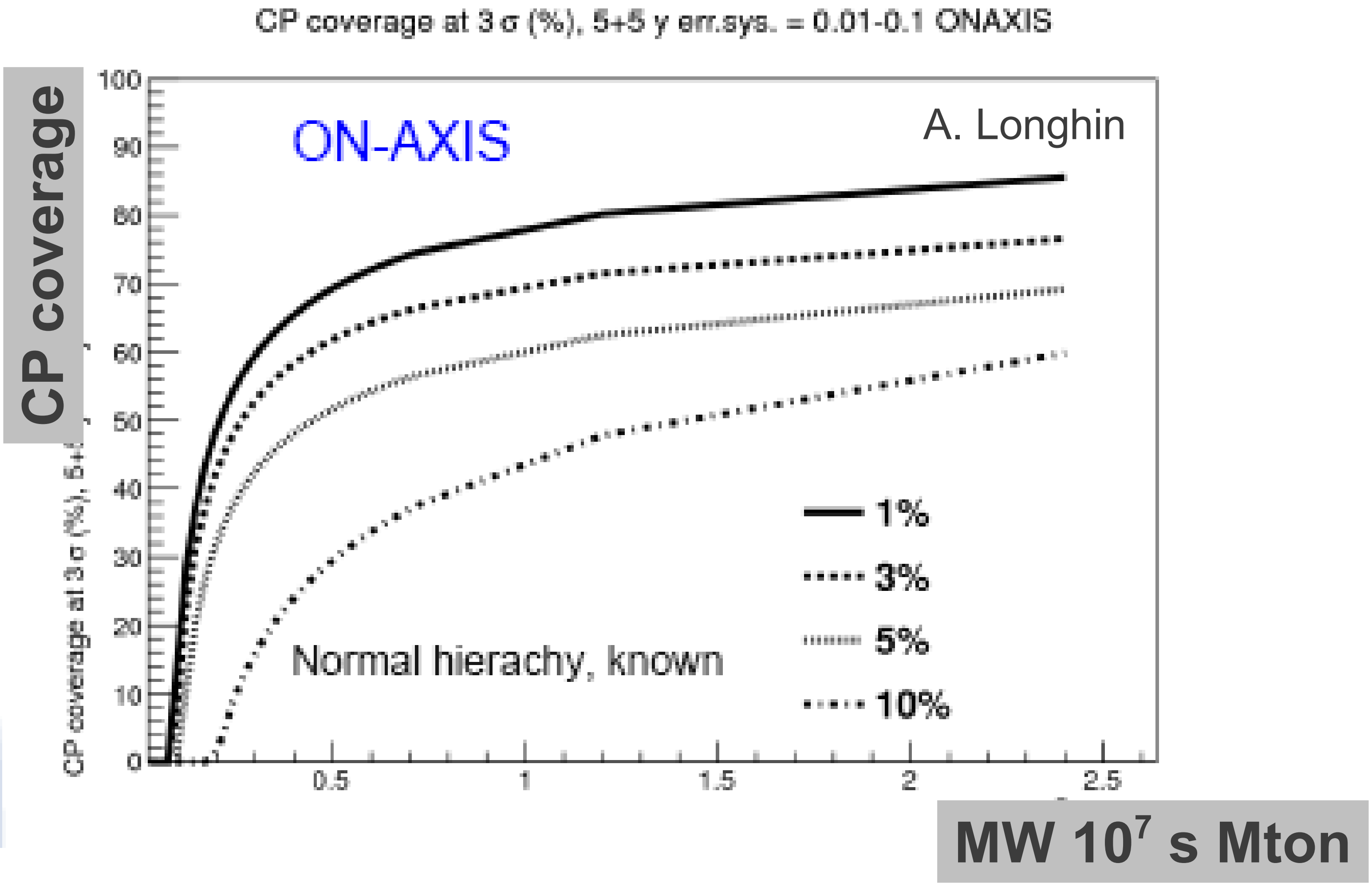
LBNO : study of the horn configuration





- Outside config:
  - Best compromise between the two osc. max
- Inside config. A:
  - Favor 2nd max
  - Limited by angular acceptance of horn

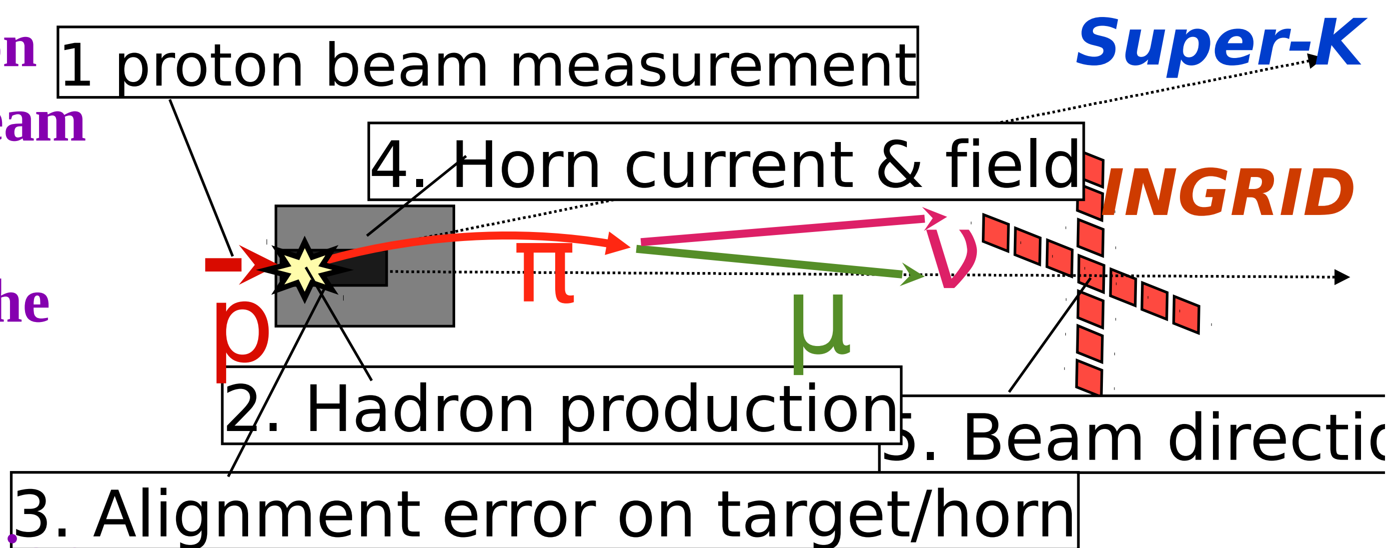
Towards CP violation and mass hierarchy

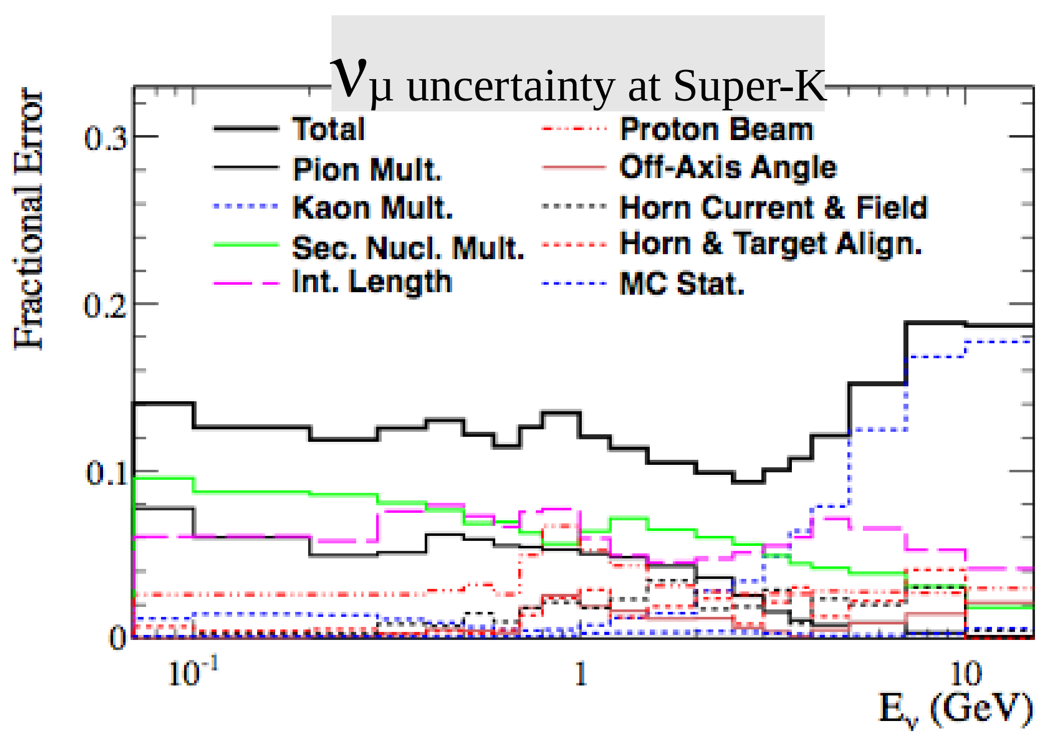


Courtesy: T2K Collaboration

T2K :Systematic error sources for neutrino flux

1. Measurement error on monitoring proton beam
2. Hadron production
3. Alignment error on the target and the horn
4. Horn current & field
5. Neutrino beam direction (Off-axis angle)





Challenge N3 : keep these contributions within the 5% error budget

Conclusions-1

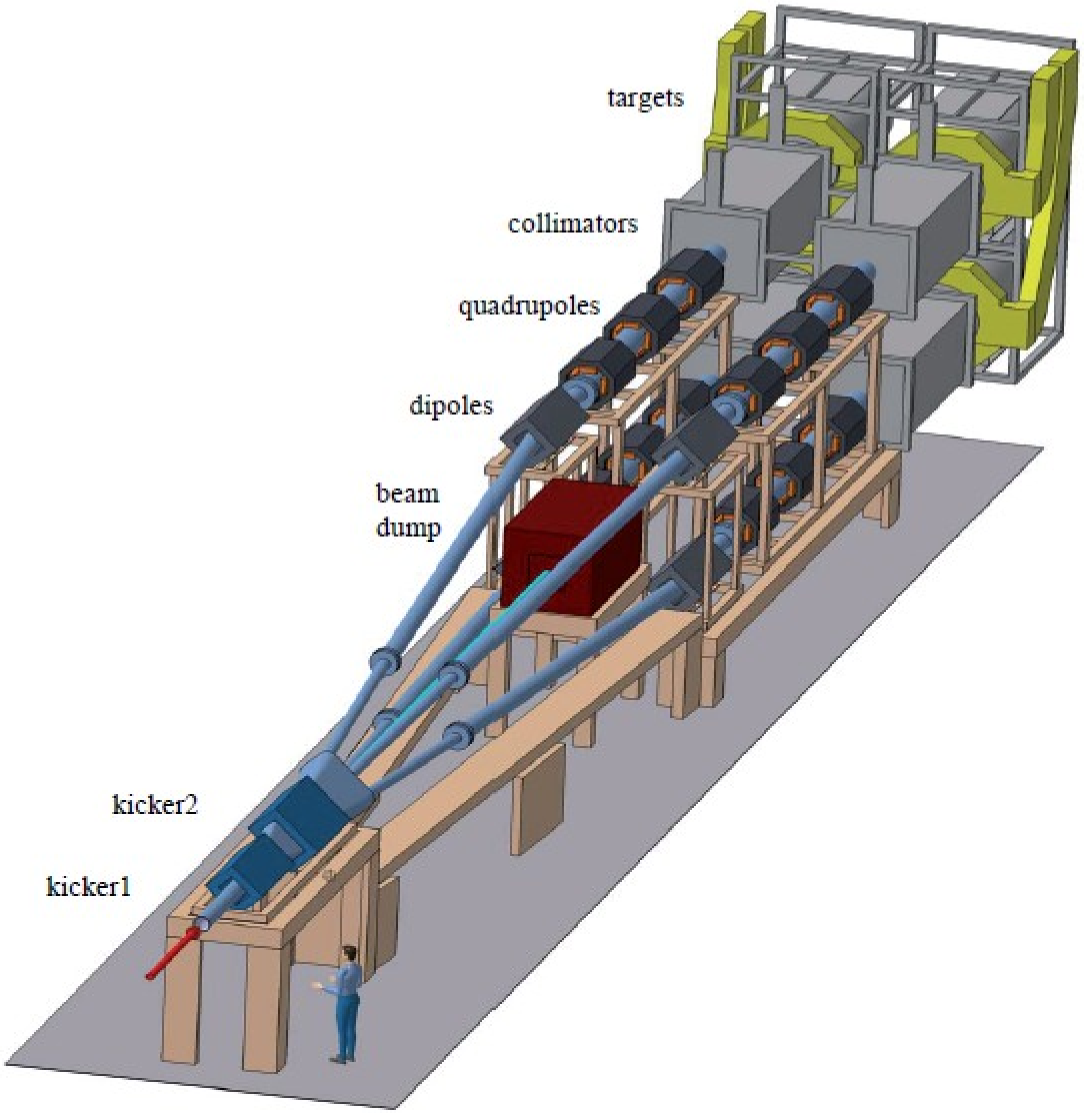
- A conventional neutrino beam with an increasing beam power towards the multi-MW range remains the primary tool for the further study of neutrino oscillations
- The EUROnu design study concluded that practical solutions exists for the target and horn
- Several aspects (target, horn cooling) require further prototyping to validate these solutions
- The devil is in the details: strips, cooling system, piping, remote replacement system

Conclusions-2

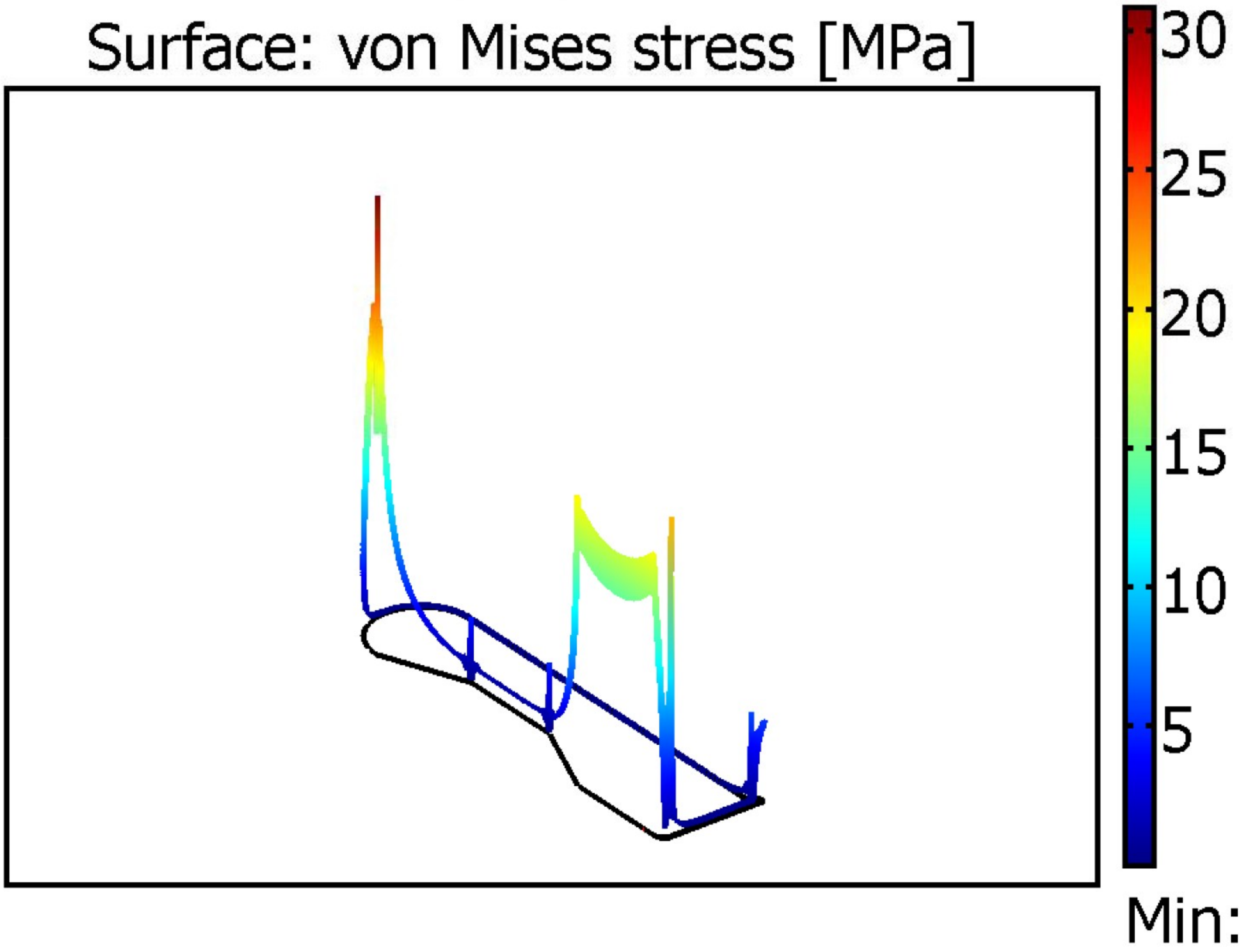
- The target system remain the primary area for further investigations towards feasibility
- The horn system has the potential for boosted performances
- The precision frontier needs to be thoroughly studied for the ultimate systematical uncertainty

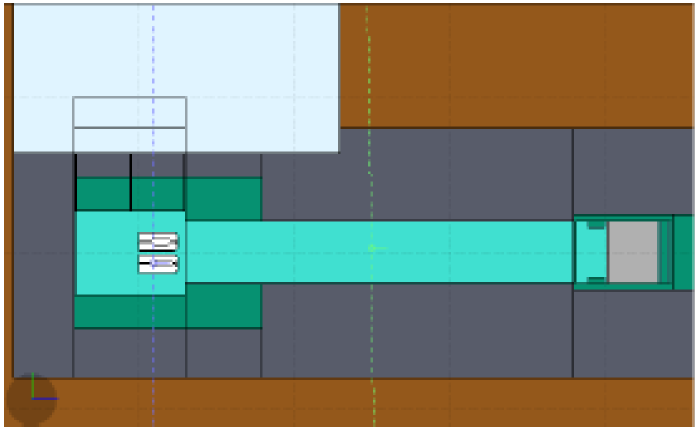
Backup slides

EUROnu switch yard



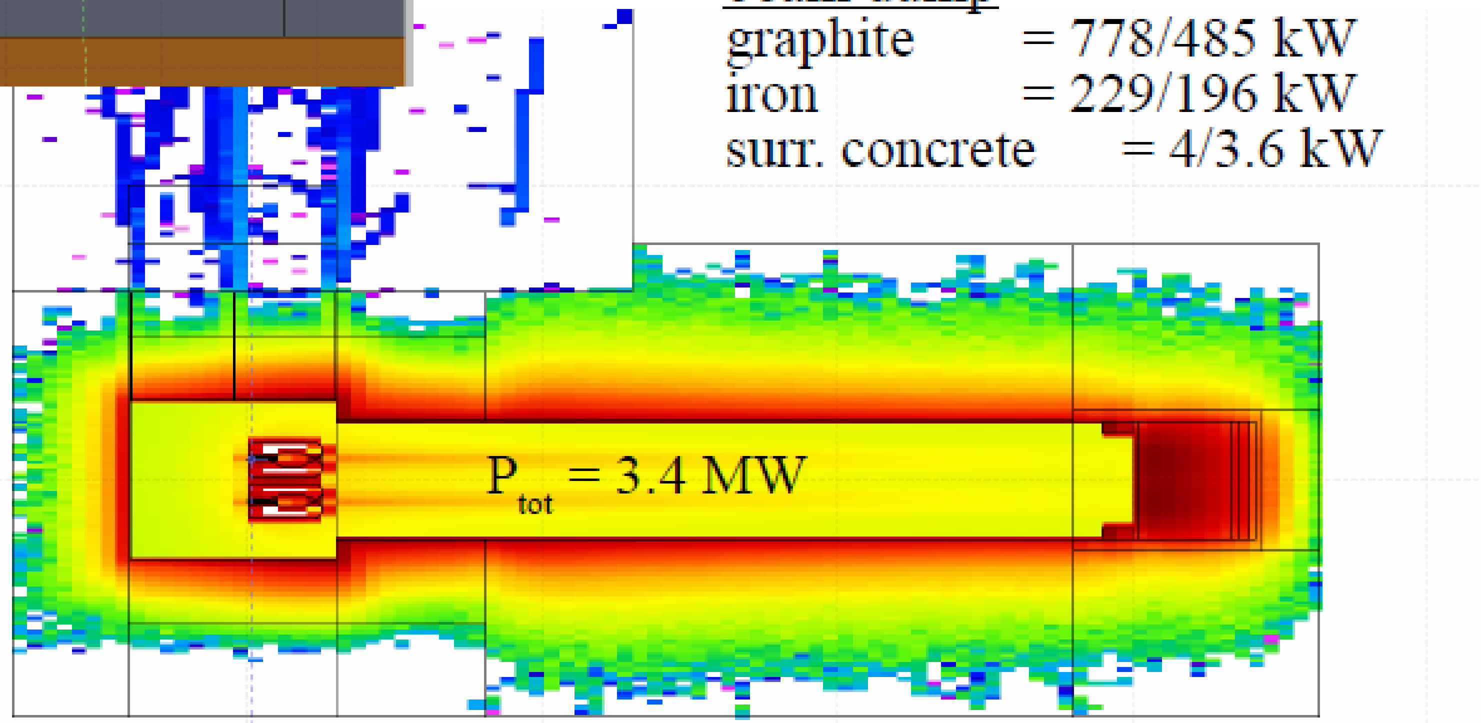
EUROnu horn study





ν/anti-ν power distribution

iron, concrete, molasse, He



beam dump

graphite	= 778/485 kW
iron	= 229/196 kW
surr. concrete	= 4/3.6 kW

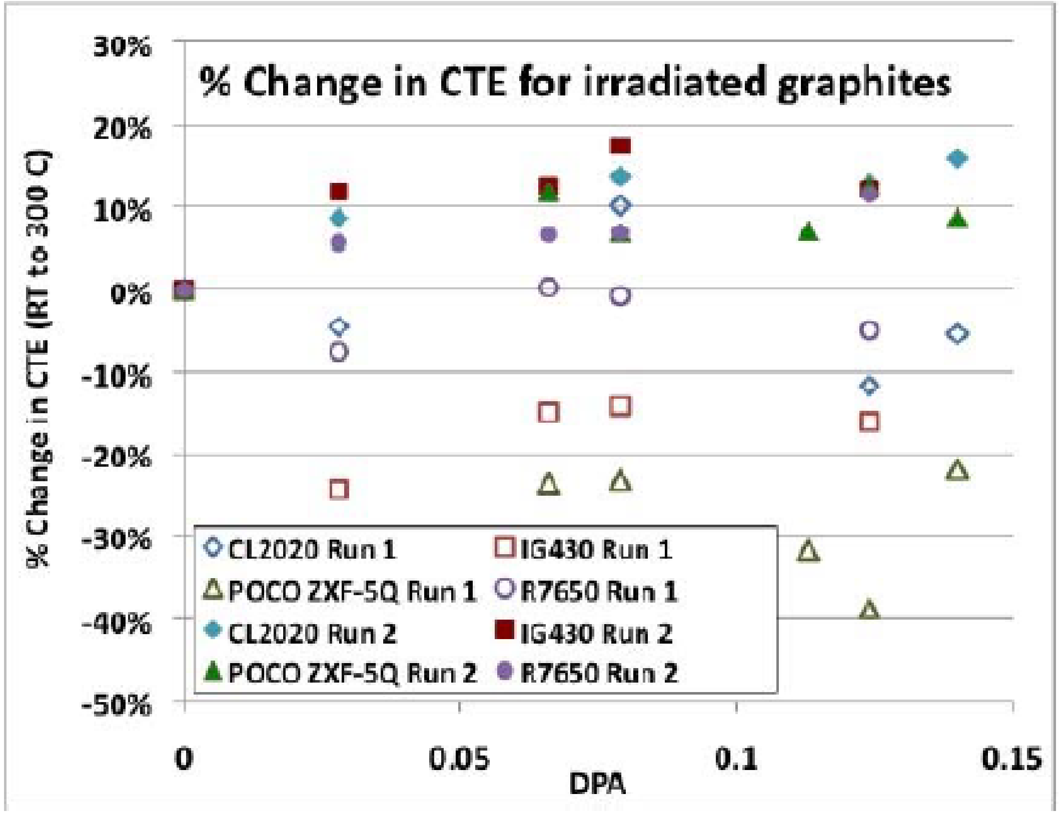
horns/target gallery

iron	= 437/496 kW
horn	= 32 kW
target	= 85 kW

decay tunnel

iron vessel	= 437/496 kW
upstream iron	= 32 kW
surr. concrete	= 85 kW

BLIP test results and recommendations



Comparison of change in coefficient of thermal expansion (20-300ºC) for graphite samples during two consecutive thermal cycles after irradiation. Open symbols: first cycle; Filled symbols: second cycle

Recommended candidate materials for LBNE out of the ones studied are 3D C/C, POCO and R7650 graphites and they should be exposed to higher fluences.

Expect to do single pulse beam tests of prototype Be fins and other target materials at CERN's High-Rad-Mat Facility as well.