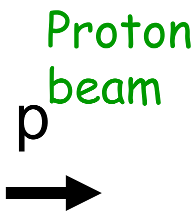
Overview and Status of the Target/ Horn Studies for Neutrino Production (EUROnu/ESSnuSB) (WP2)

E. Bouquerel on behalf of the ESSnuSB project

Sofia, Bulgaria
October,15 2016

- Targetry
- Horn/Collector
- Power Supply
- Shielding
- Layout

How to produce neutrino beams?



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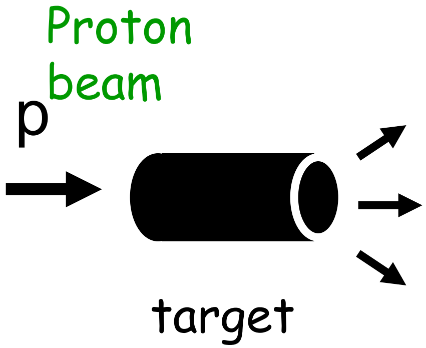
How to produce neutrino beams?



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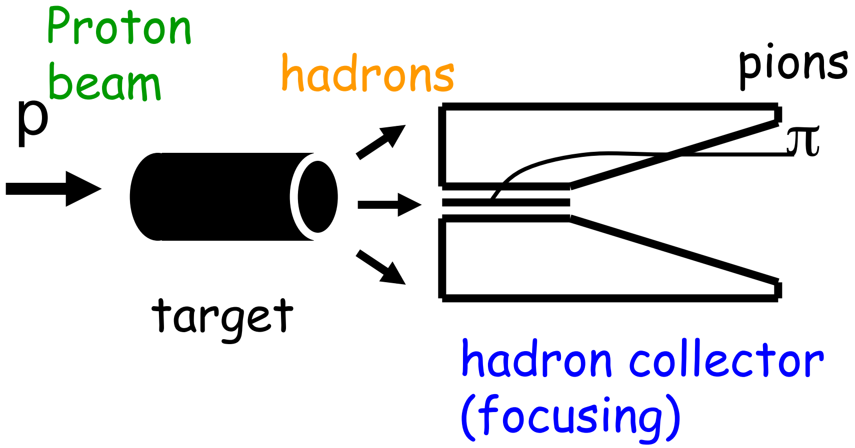
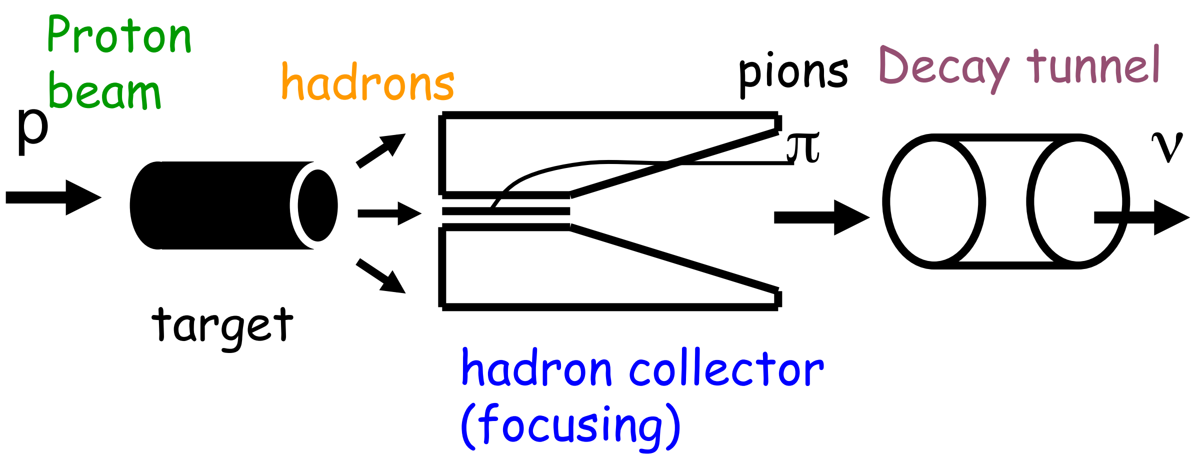


How to produce neutrino beams?

NEUTRINOS



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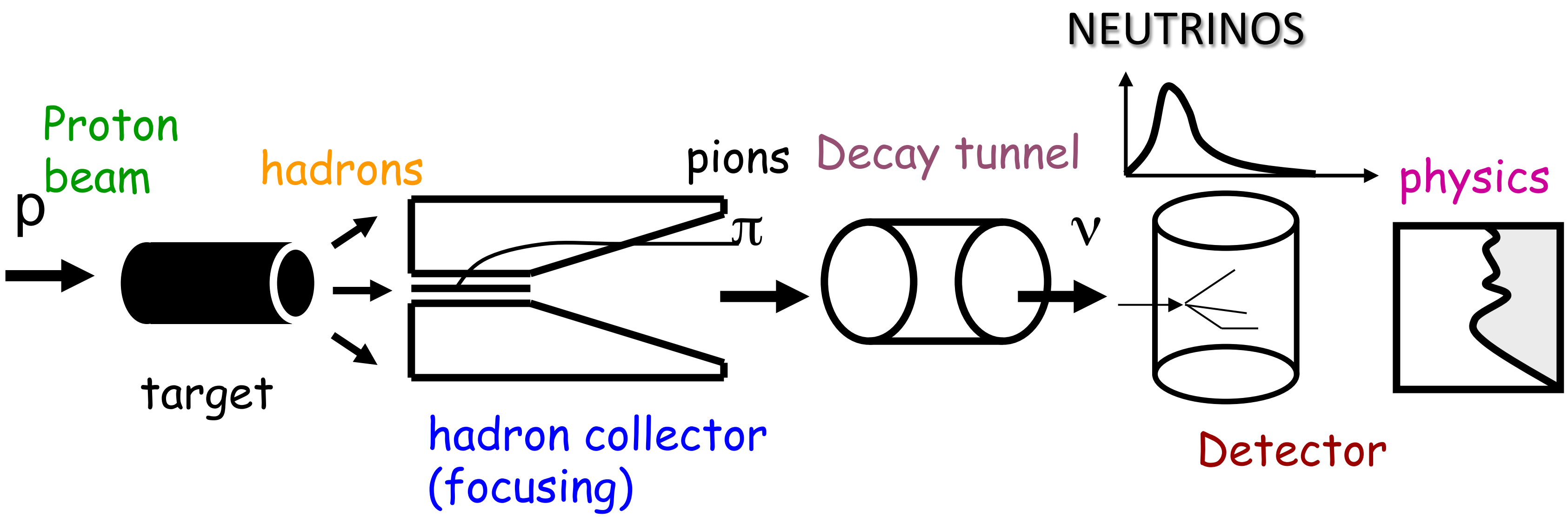

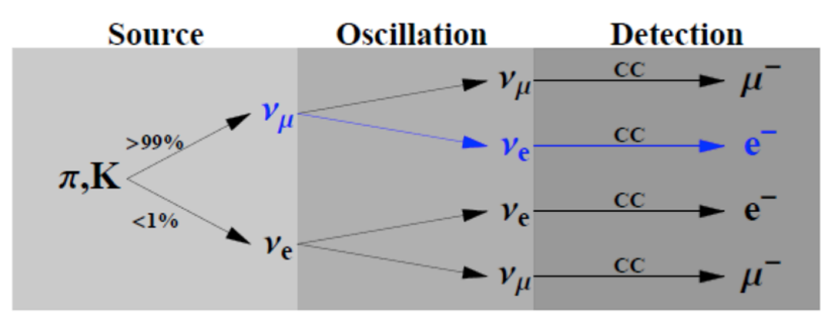

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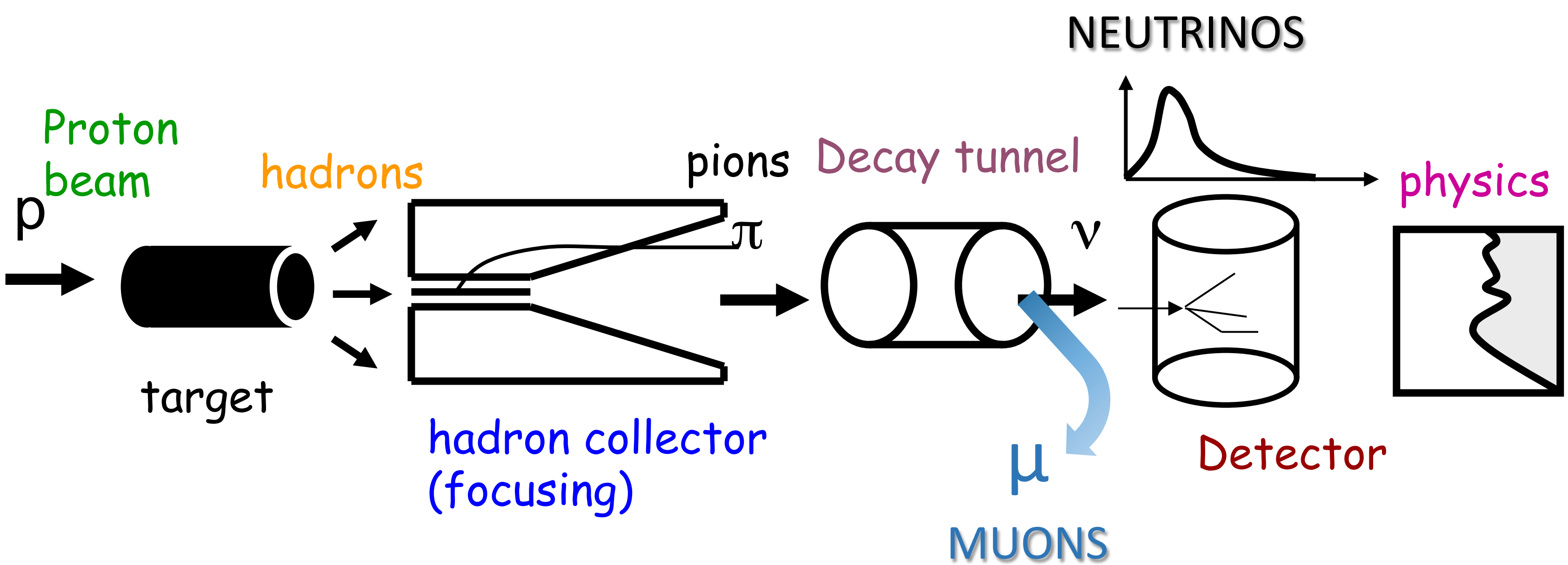

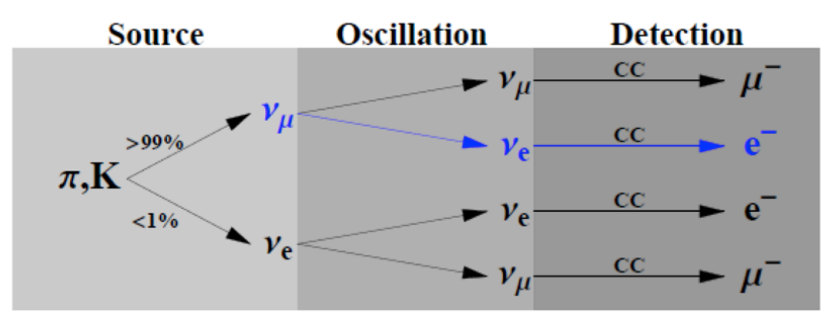

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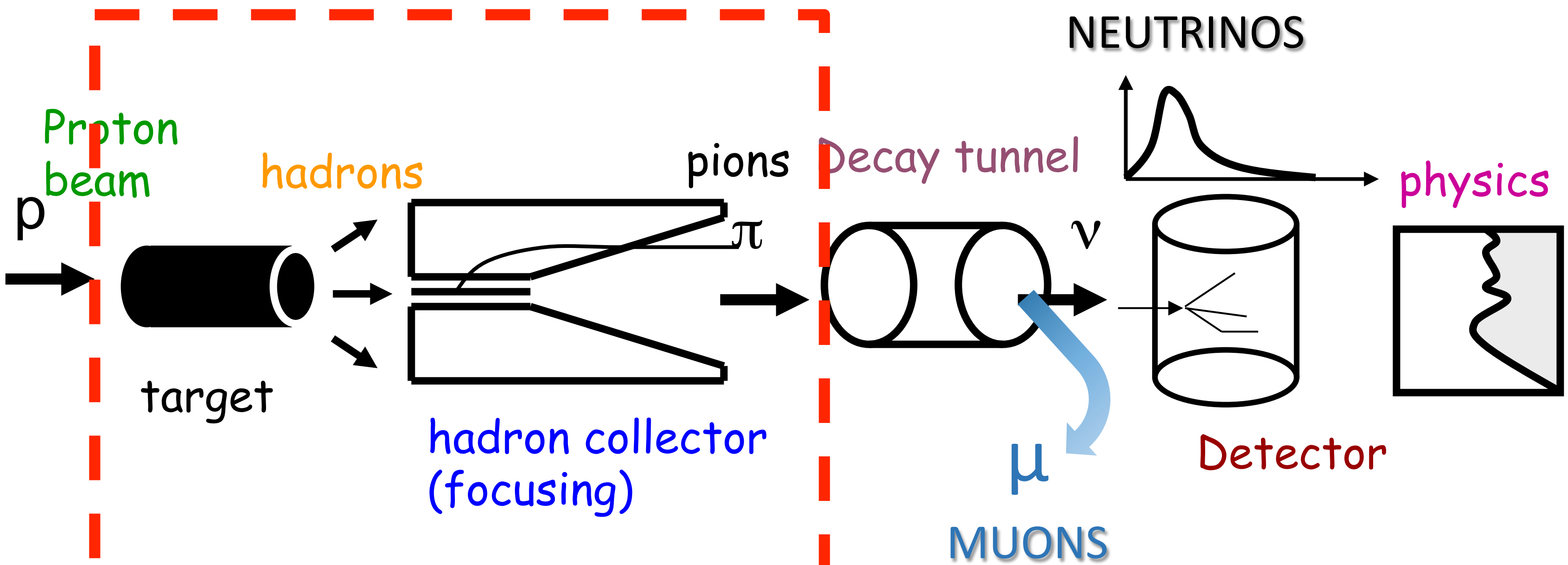
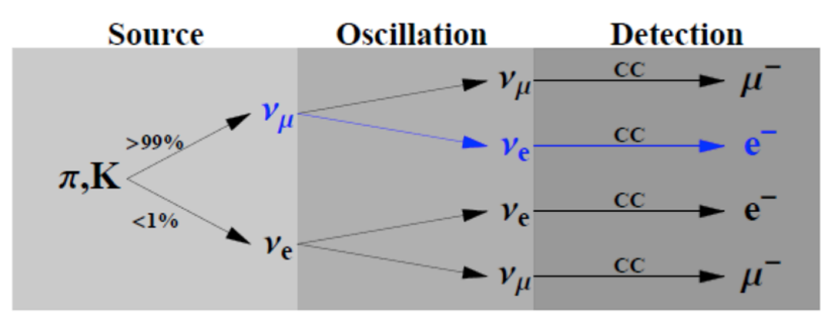


CONCERNED BY THIS PRESENTATION



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- **Targetry**
- Horn/Collector
- Power Supply
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Targetry

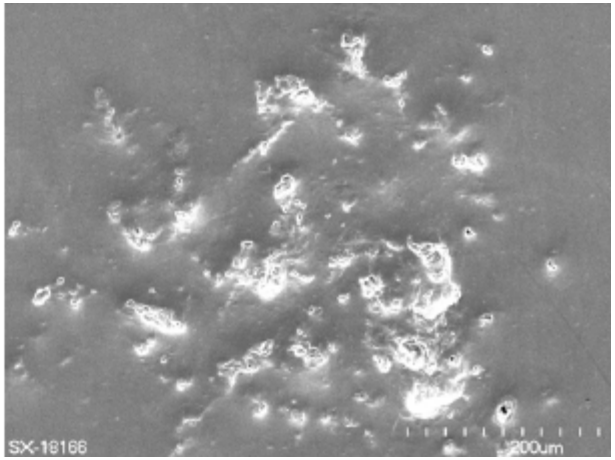
Technological Challenges

- Afford 5 MW (1.25 MW/target)
- Severe problems from : sudden heating, stress, activation
- Safety issues (profit of installations to exist by then like T2K, ESS, SNS)
- Solid versus liquid targets:
  - Extremely difficult problem :
    - Liquid metal target (mercury, Merit experiment), better cooling
    - Solid target, better handling

Liquid Target?

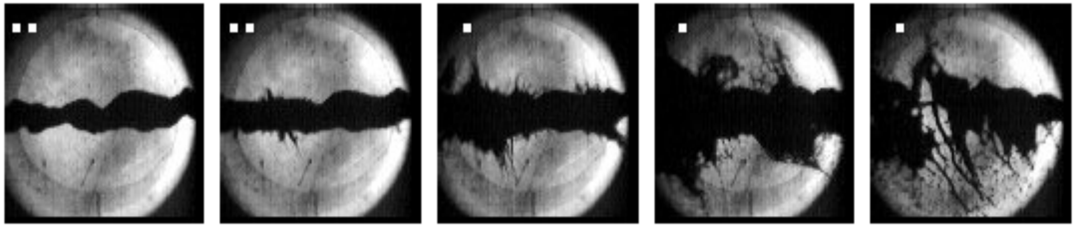
Studies made on Hg targets

Contained mercury



Cavitation damage in wall of Hg target container after 100 pulses of 19 J/cc proton beam (WNR facility at LANL)

Free mercury jet



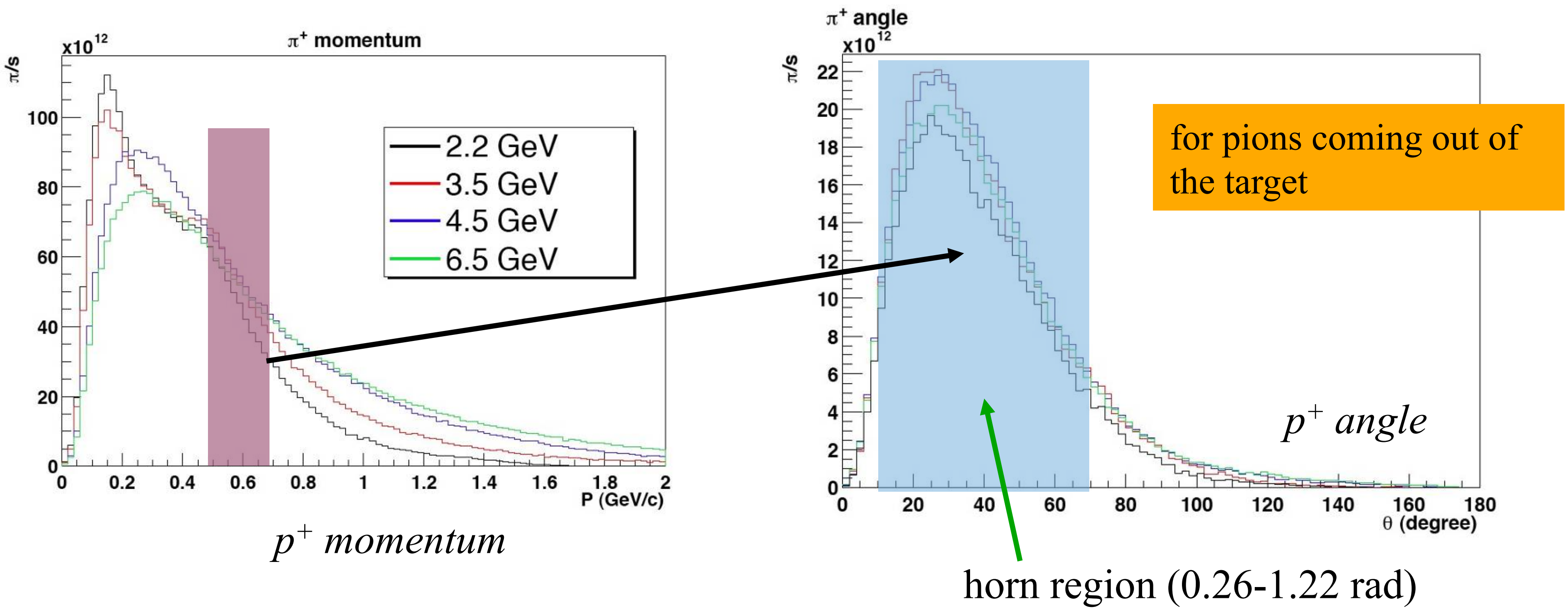
MERIT experiment: Beam-induced splashing of mercury jet (c.200 J/cc)

- Damping of splashes due to magnetic field observed as predicted
- More studies ongoing

no problem with target cooling but…

- Magnetic horns are typically manufactured from aluminium alloy not compatible with Hg (severe and rapid erosion in addition to the shock wave problem)
- Is it possible to protect a horn with a material compatible with liquid Hg?
- B=0 inside horn, ie no magnetic damping of mercury jet as in MERIT experiment
- Combination of a mercury jet with a magnetic horn would appear to be extremely difficult.

Proposed design for SPL



for a Hg target, 30 cm length, ∅15 mm ($N_{particles}$x10^{16}/sec, FLUKA)

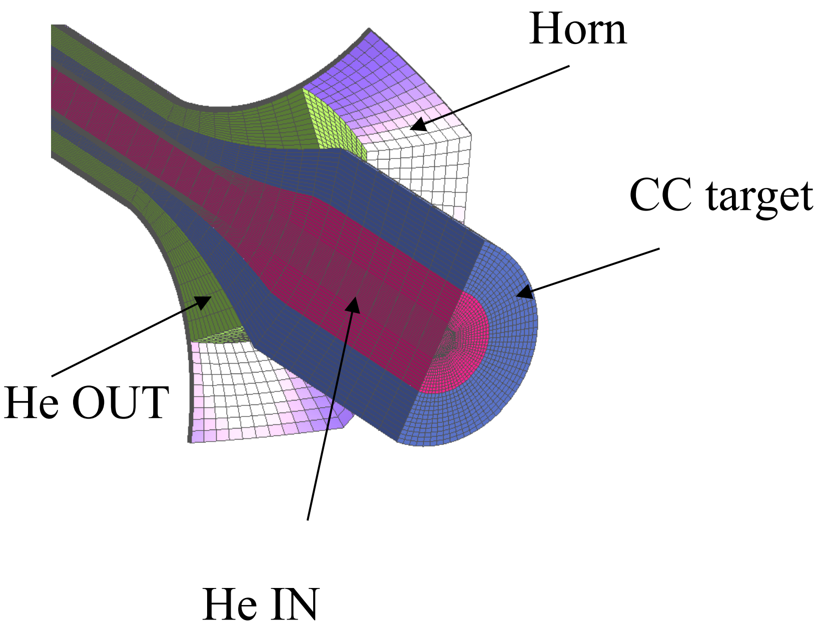
E_k (GeV)	p	n	γ	e^+	e^-	π^+	π^-	μ^+	μ^-	K^+	K^0
2.2	1.4	17	5.0	0.08	0.17	0.24	0.18	4	1	7	6
3.5	1.8	23	7.0	0.15	0.28	0.41	0.37	10	3	35	30
4.5	2.3	25	7.7	0.21	0.35	0.57	0.39	11	3.3	93	68
8	3.1	33	11.0	0.41	0.63	1.00	0.85	30	9.5	413	340

→ relatively better collection when p_{proton} ↗

→ the target must be inside the horn

Solid Target?

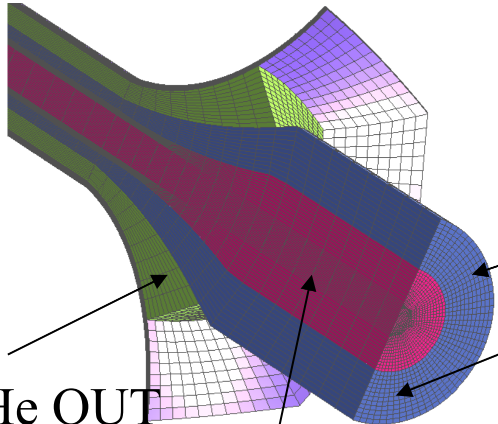
- Graphite is conventional and already used for neutrino beams
- Easier to combine with a magnetic horn (e.g. T2K target)
- Questions include:
  - How does particle production for C compare with Hg?
  - Can a static graphite target dissipate heat from a 4 MW beam?
  - What is the expected lifetime for a graphite target in a 4 MW beam?
  - According to studies done at BNL, no problem with 1MW proton beam.

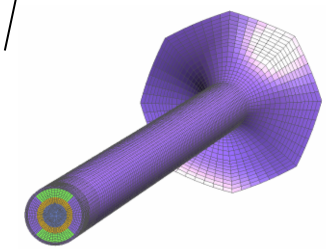


Cooling is a main issue…

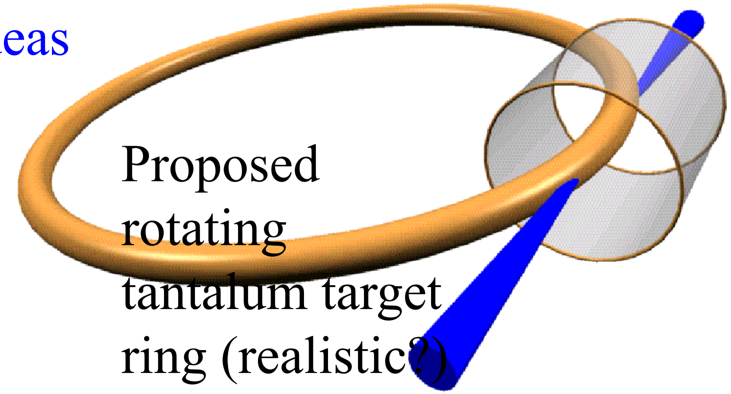
Proton Target

some ideas

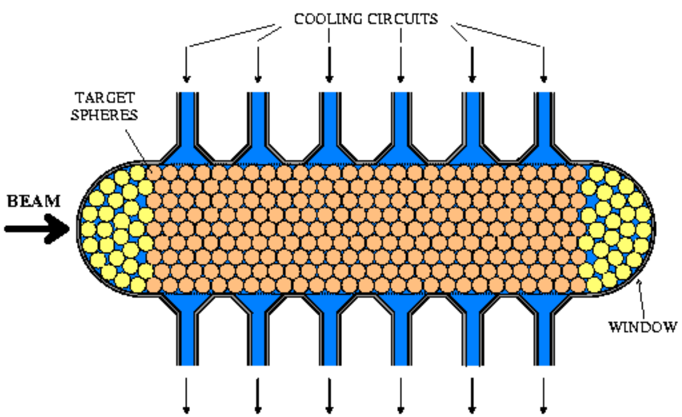




Helium cooling of target



Proposed rotating tantalum target ring (realistic?)



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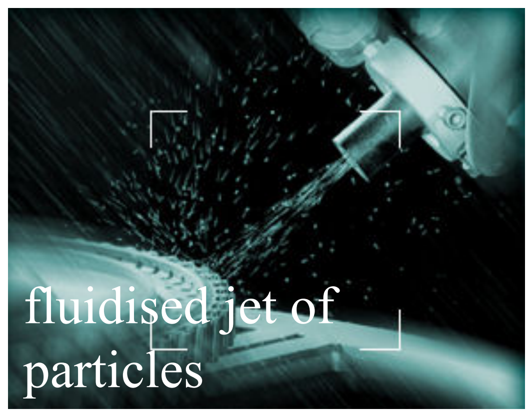
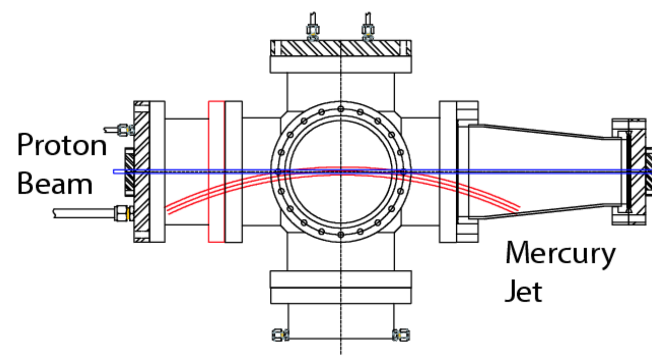


fluidised jet of particles

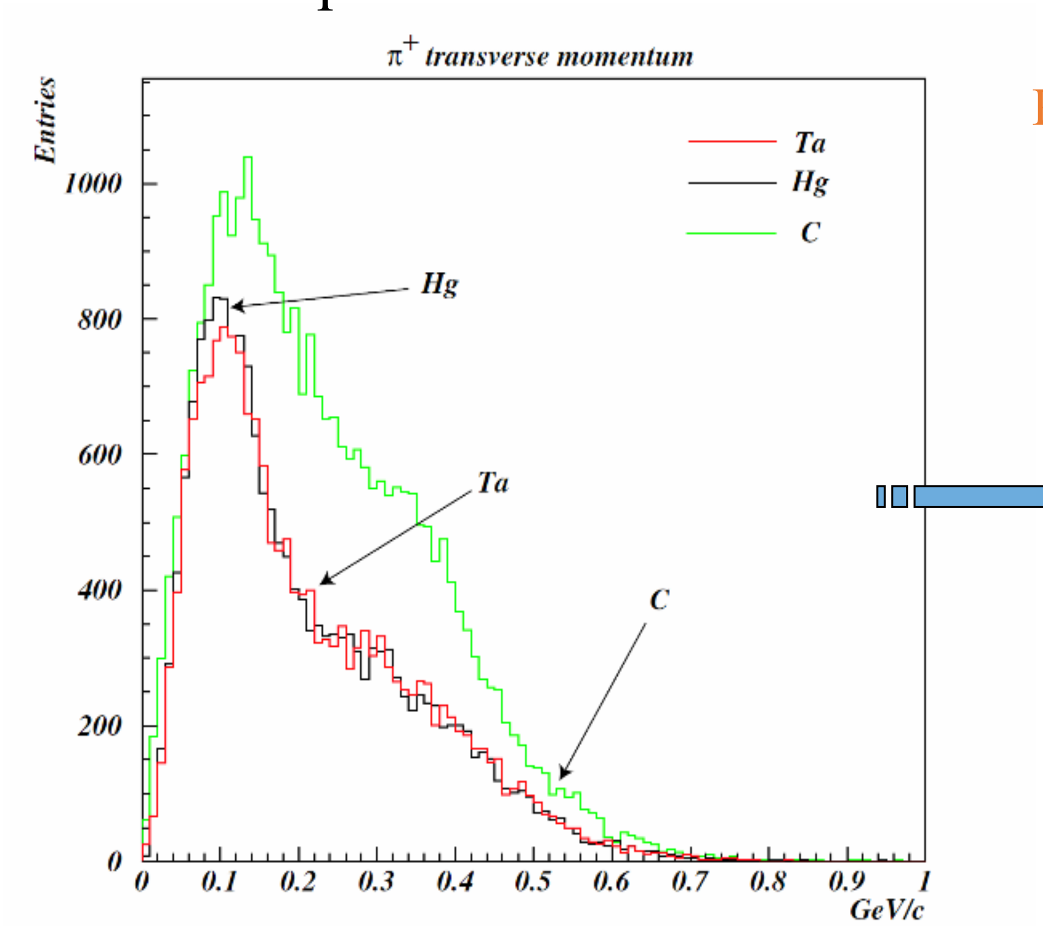


Liquid Mercury (MERIT)

Work at BNL and RAL
Experience on T2K target (750 kW) very useful

Hadron production from different target materials

2.2 GeV protons



p_T

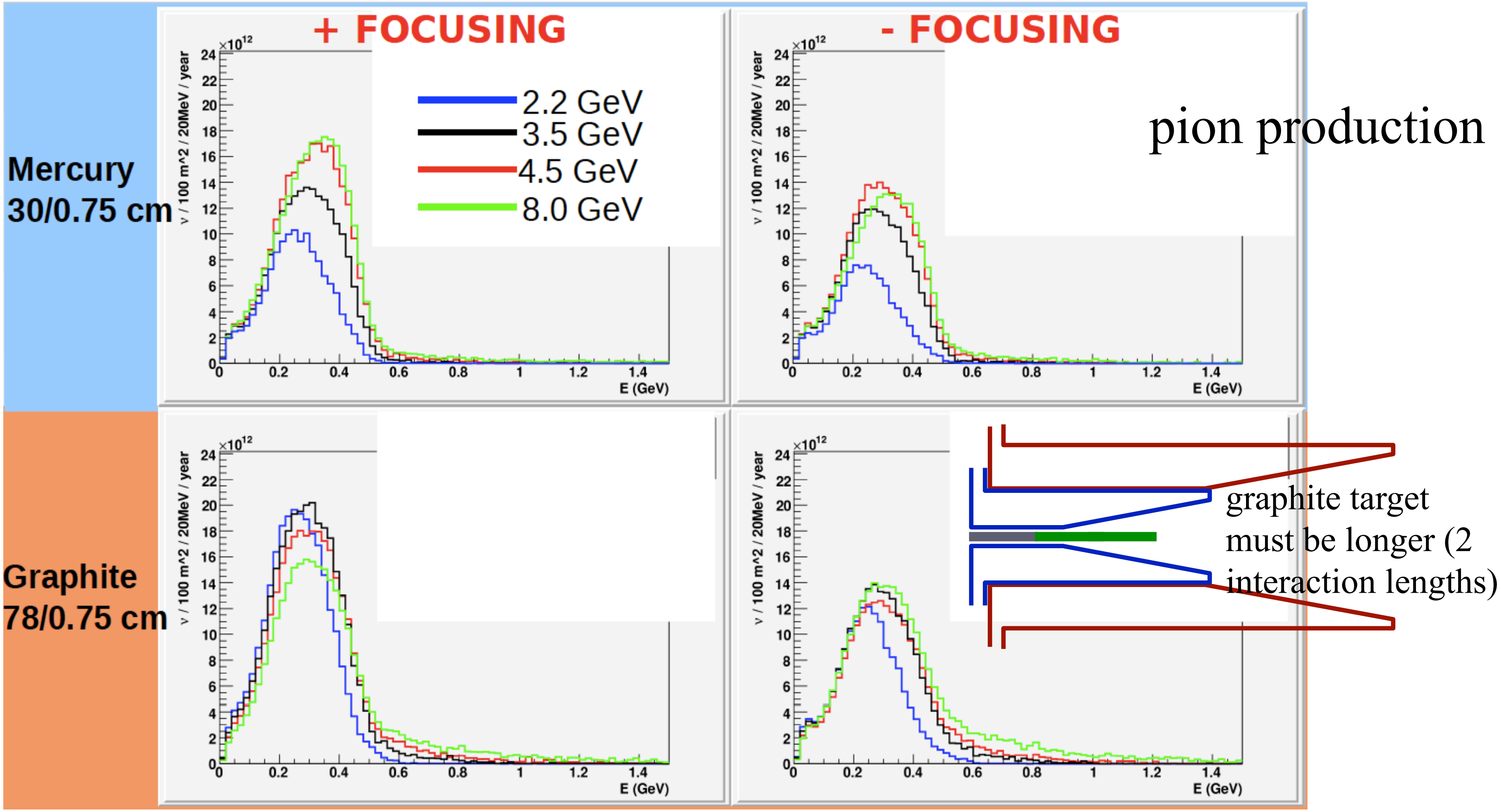
Particles coming out of the target

p_T distribution not the same for all targets

$\Rightarrow$

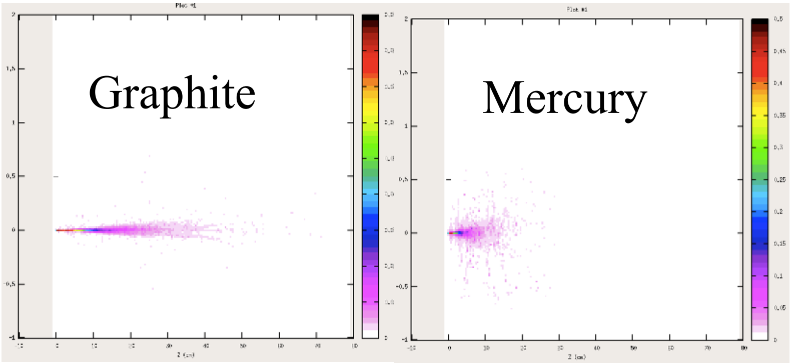
The choice of the target could influence the hadron collection system (horn shape)

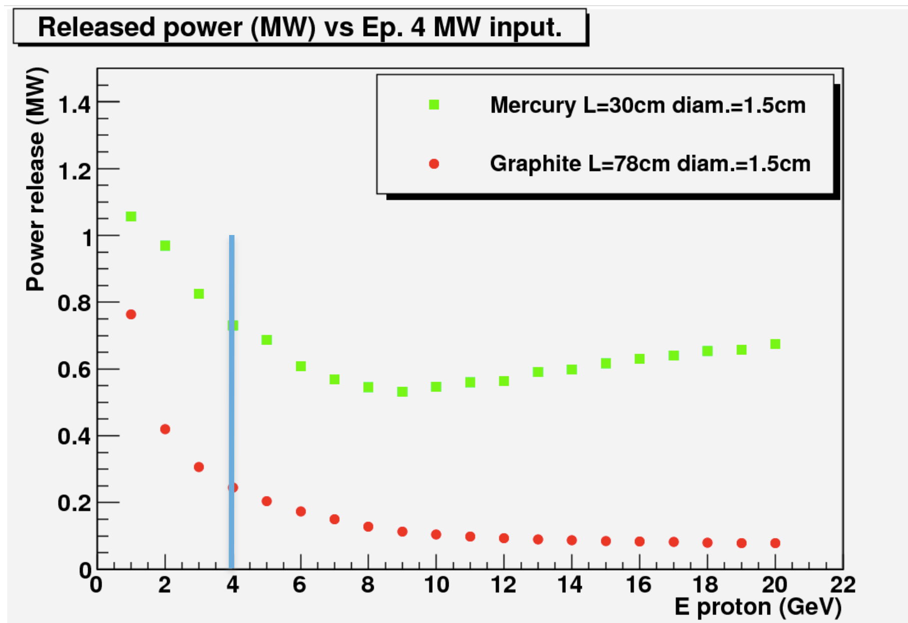
Comparison Mercury/Carbon



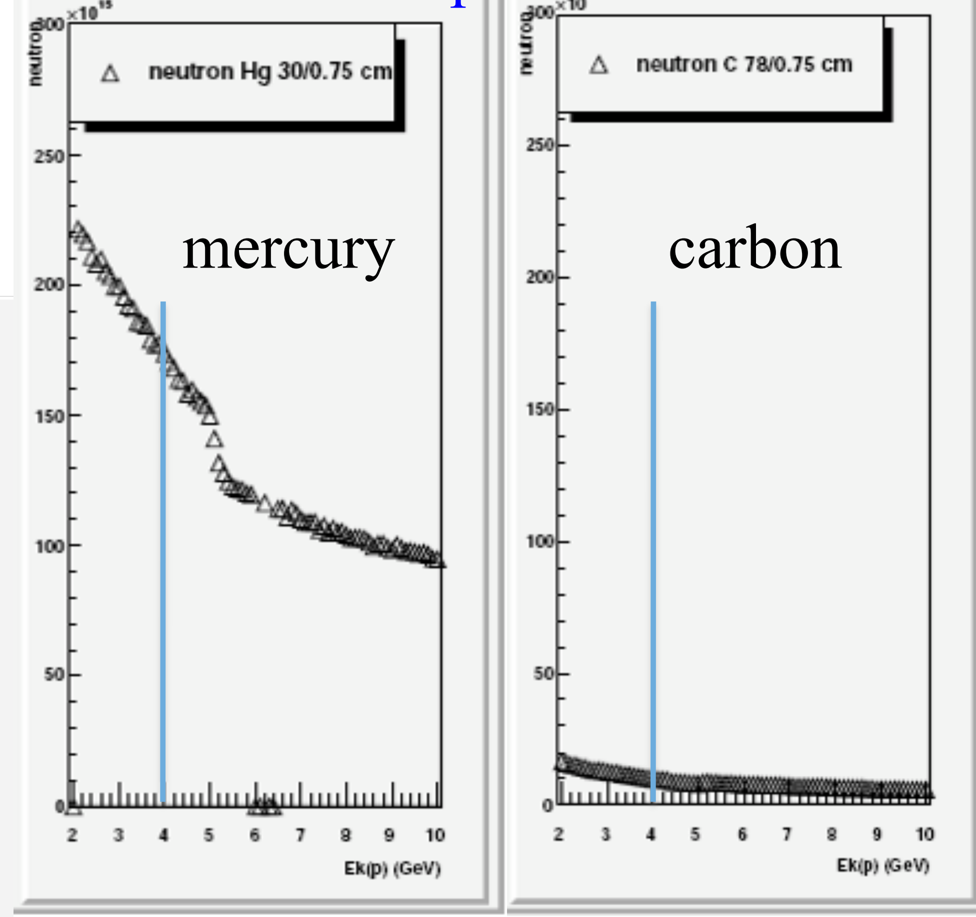
- Neutrino intensities are comparable despite non optimized focusing for long Graphite target
- Higher energy tail for Graphite (not optimized focusing)

Comparison Mercury/Carbon





neutron production



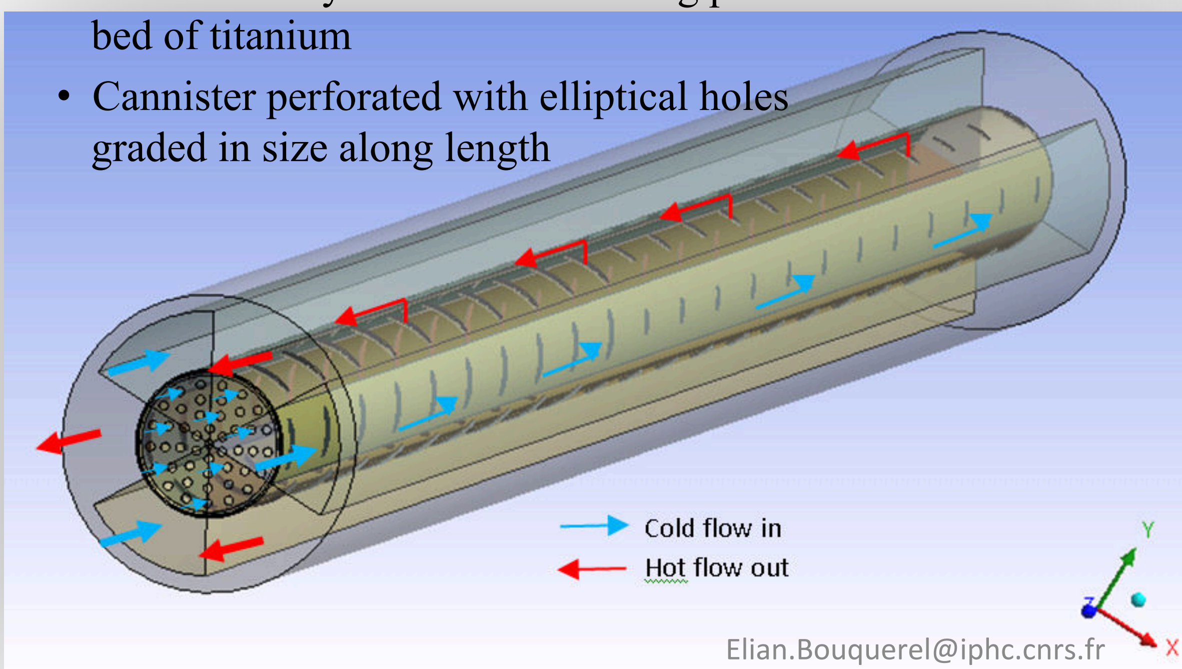
Hg: ~ 1 - 0.6 MW
C : ~ 0.8 - 0.1 MW
considerably lower for Carbon !

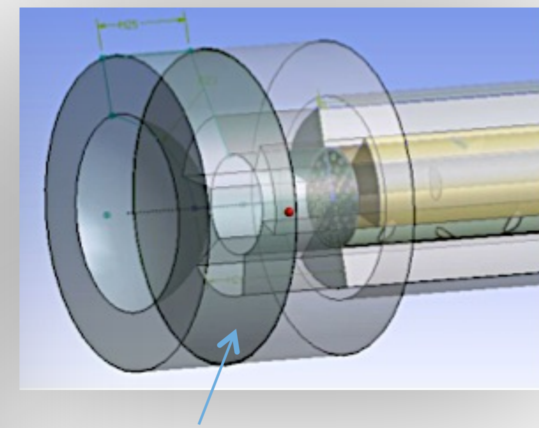
n flux dramatically reduced wrt Hg! (~ 15 x)

Solution Retained: Packed Bed

- Large surface area for heat transfer
- Coolant able to access areas with highest energy deposition
- Potential heat removal rates at the hundreds of kW level
- Pressurised cooling gas required at high power levels
- Minimal stresses
- Full study in EUROnu.org, arXiv:1212.0732 (SPL super beam)

- Titanium alloy cannister containing packed bed of titanium
- Cannister perforated with elliptical holes graded in size along length





- Beam window, Be is a candidate
- Pressure stresses can be dealt by having a hemispherical window design
- Separation from target station coolant

Are the adopted SPL Super Beam parameters fit well the ESS case ?

Parameter	SPL	ESS
Power (MW)	4	5
E_{p+} (GeV)	4.5	2, 2.5
Baseline (km)	130	365, 540
Target	Packed-bed	Packed-bed
Target length (cm)	78	53-78
Target radii (cm)	1.5	1.5
Horn	Forward closed	Forward closed
Horn current (kA)	350 @ 12.5 Hz	350 @ 14 Hz
# of horns/targets	4	4
Tunnel length (m)	25	15-25
Tunnel radii (m)	2	2
Exposure (years)	2 ν + 8 anti-ν	2 ν + 8 anti-ν

The Target for ESSnuSB

- One of the most challenging parts of this project
- To be hit by the 5 MW proton beam to produce the pions needed for the neutrino beam production
- Classical monolithic solid targets are almost impossible for this application because of the absence of efficient cooling.
- One design that will be investigated is a packed bed of titanium spheres cooled with cold helium gas.
- Questions:
  May the pulsed beam generate vibrations in the spheres which could be transmitted to the packed bed container and beam windows and cause degradation of the spheres where they are in contact with each other?

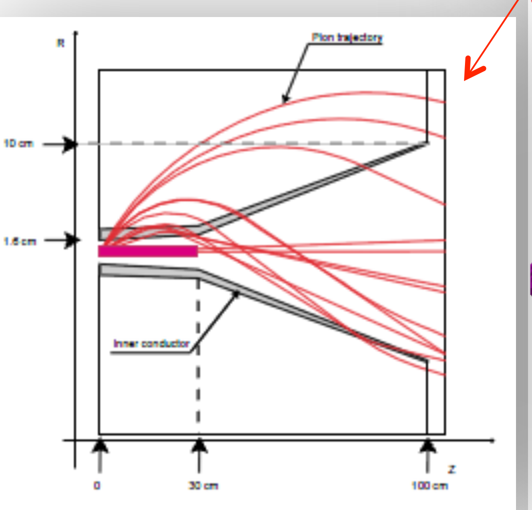
- *Targetry*
- **Horn/Collector**
- Power Supply
- Shielding
- Layout

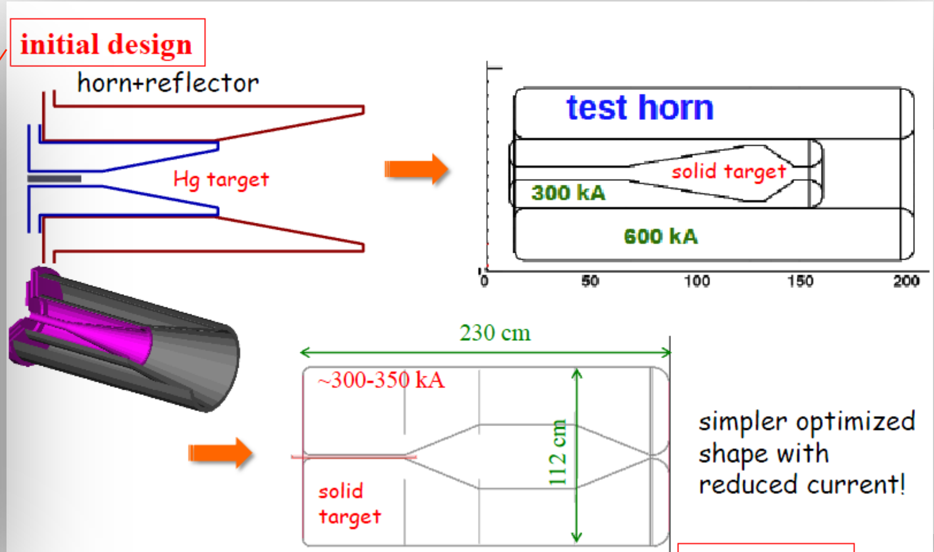
Horn Evolution

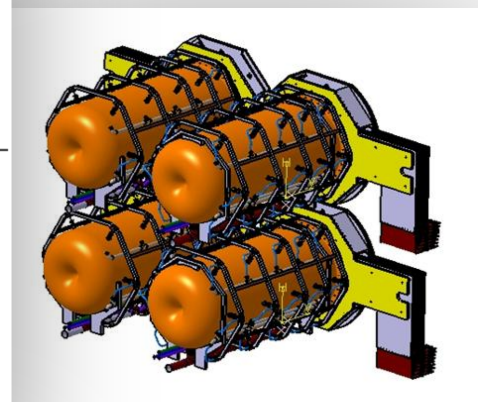
Full study in EUROnu, arXiv:1212.0732

Evolution of the horn shape after many studies:

- Triangle shape (van der Meer) with target inside the horn : in general best configuration for low energy beam
- Triangle with target integrated to the inner conductor : very good physics results but high energy deposition and stresses on the conductors
- Forward-closed shape with target integrated to the inner conductor : best physics results, best rejection of wrong sign mesons but high energy deposition and stresses
- Forward-closed shape with no-integrated target: best compromise between physics and reliability
- 4-horn/target system to accommodate the MW power scale



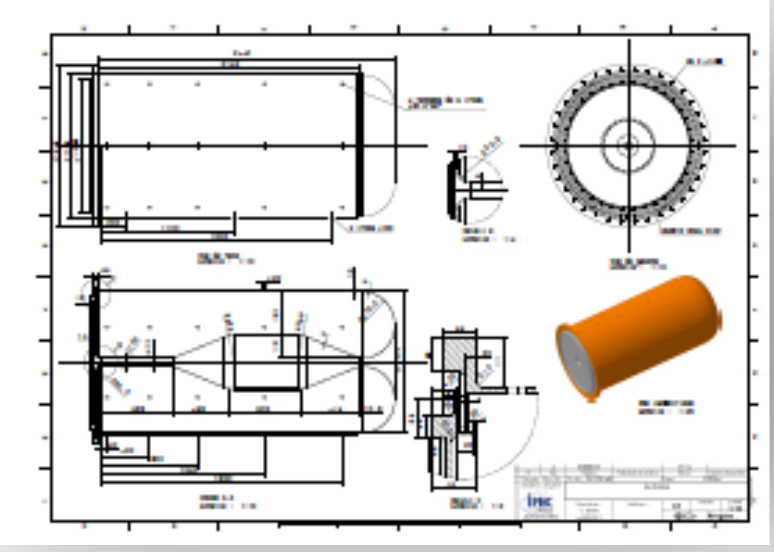


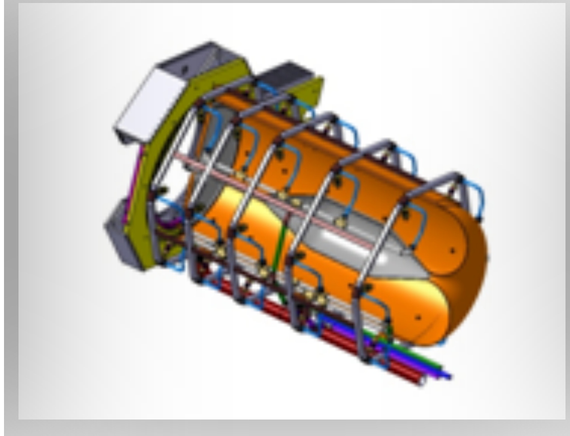


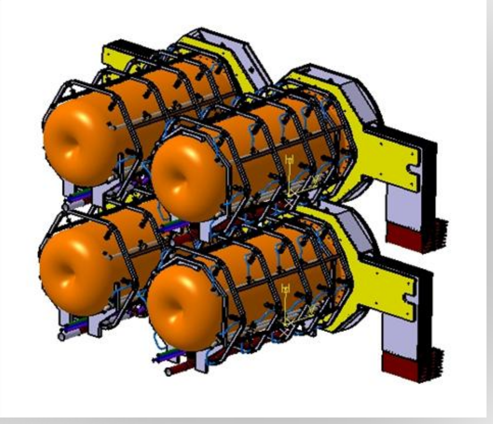
Horn Studies

- Horn Structure
  - ➢ Al 6061 T6 alloy good trade off between mechanical strength, resistance to corrosion, electrical conductivity and cost
  - ➢ horn thickness as small as possible: best physics, limit energy deposition from secondary particles but thick enough to sustain dynamic stress
- Horn Stress and Deformation ➡ Piotr's presentation
  - ➢ static mechanical model, thermal dilatation
  - ➢ magnetic pressure pulse, dynamic displacement
  - ➢ Horn lifetime at least 1 year from fatigue analysis (30 – 60 MPa max stress depending on HTCs)
  - ➢ 60 water jets for cooling

Full study in EUROnu, arXiv:1212.0732



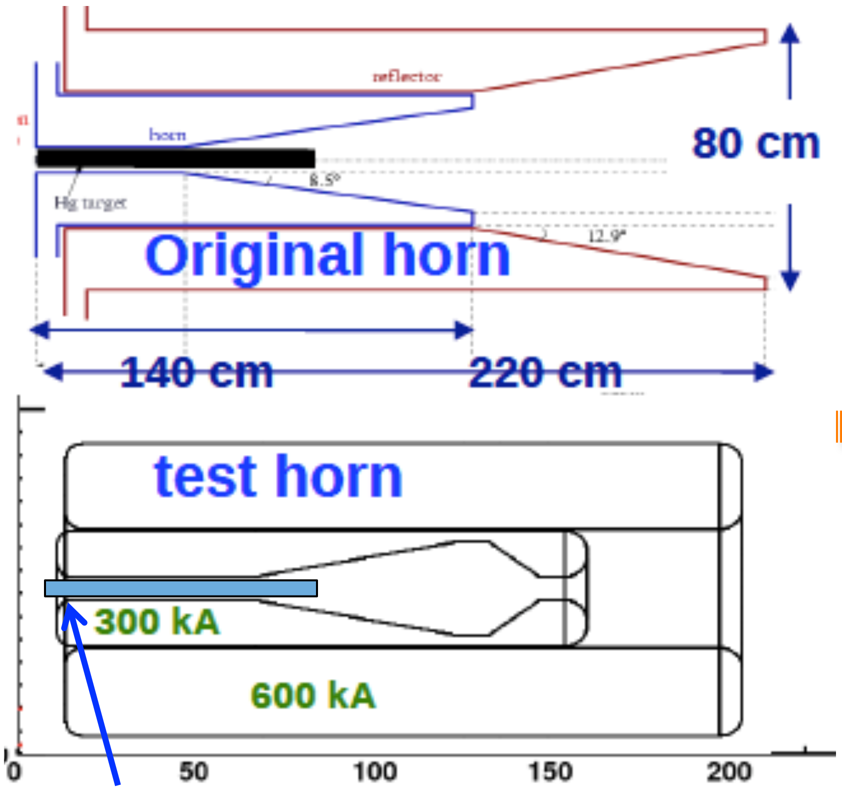




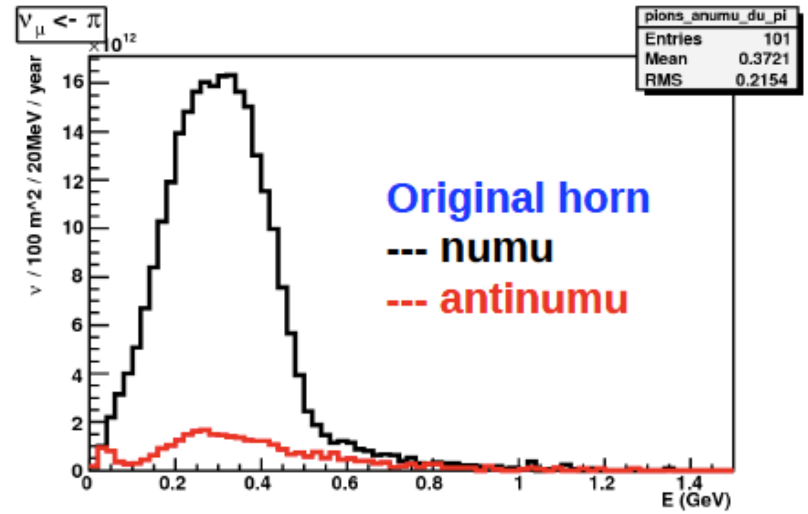
Horn: Main Challenges

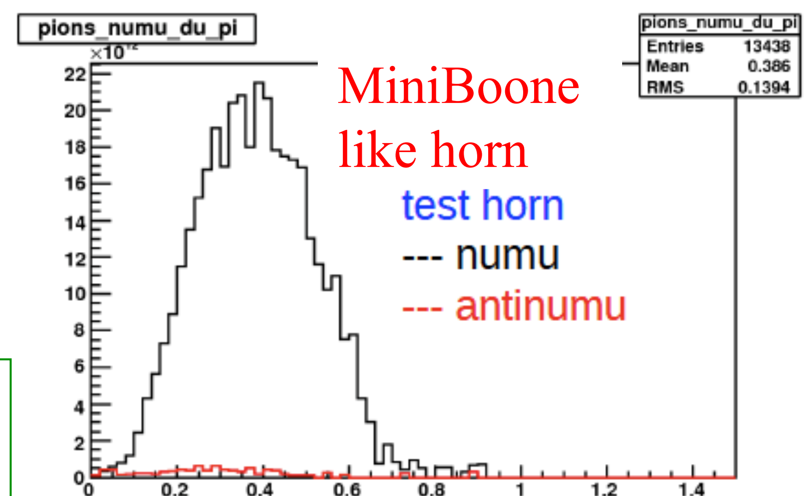
- Horn : as thin as possible (3 mm, EUROnu) to minimize energy deposition (5 MW beam power),
- Longevity in a high power beam,
- 14 Hz,
- Large electromagnetic wave, thermo-mechanical stress, vibrations, fatigue, radiation damage,
- Currents: 350 kA (horn) and 600kA (reflector)
  - From the design of a high current pulsed power supply done for Euronu (300 kA/100 μs/50 Hz),
- cooling system in order to maintain the integrity of the horn despite of the heat amount generated by the energy deposition of the secondary particles provided by the impact of the primary proton beam onto the target,
- definition of the radiation tolerance,
- integration of the target.

Can we optimize the horn shape for the solid target?



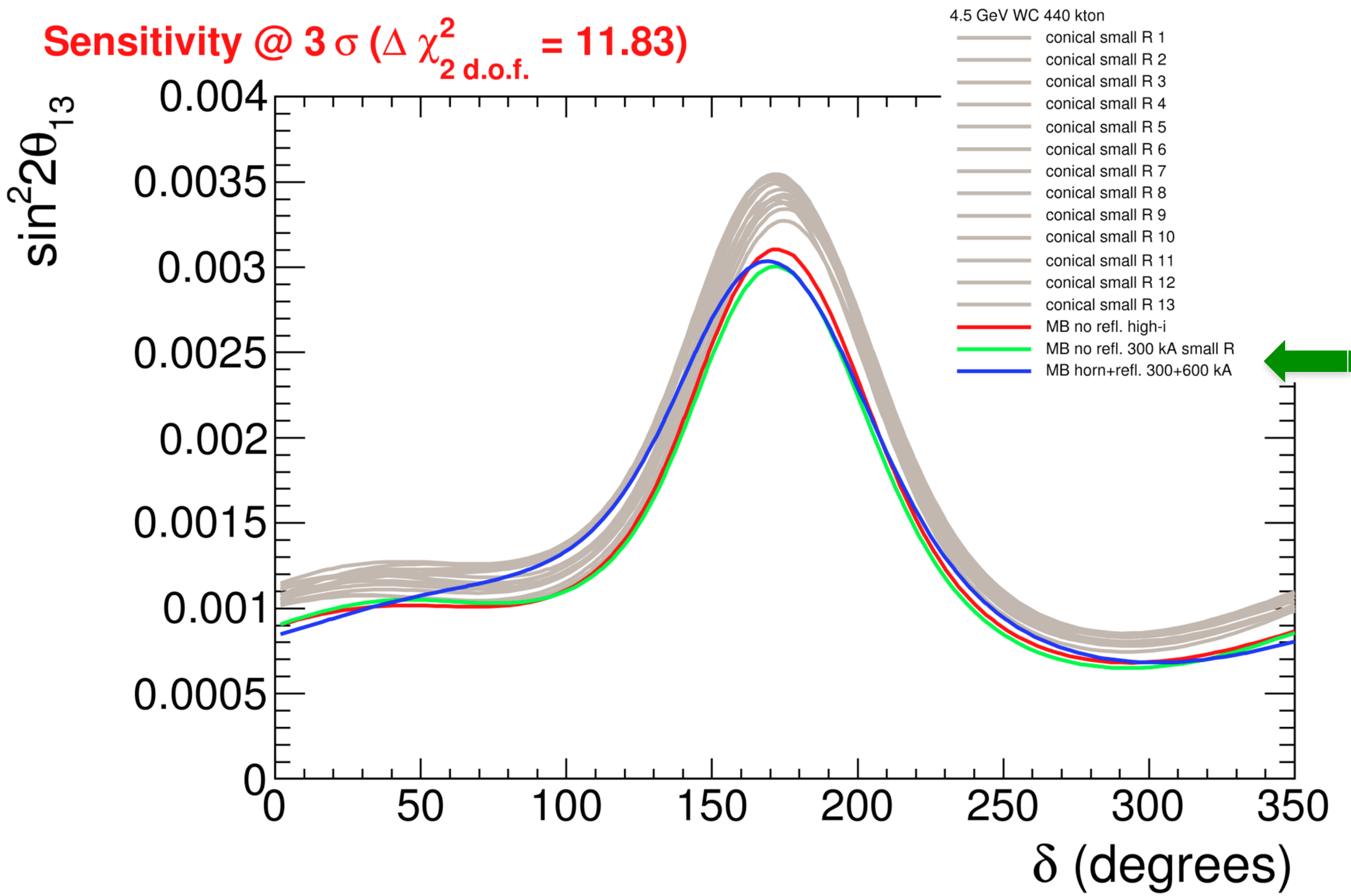
solid target (2 X0)





~simpler focalisation system without compromising with the physics performance (with even less contamination)

Comparison between horns



better results with the new horn geometry

Horn Studies

Electrical Model, B field

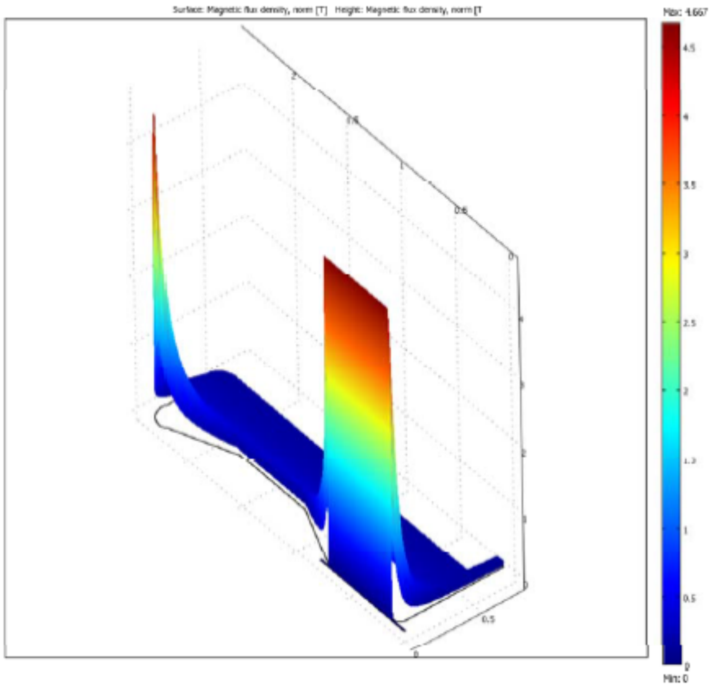
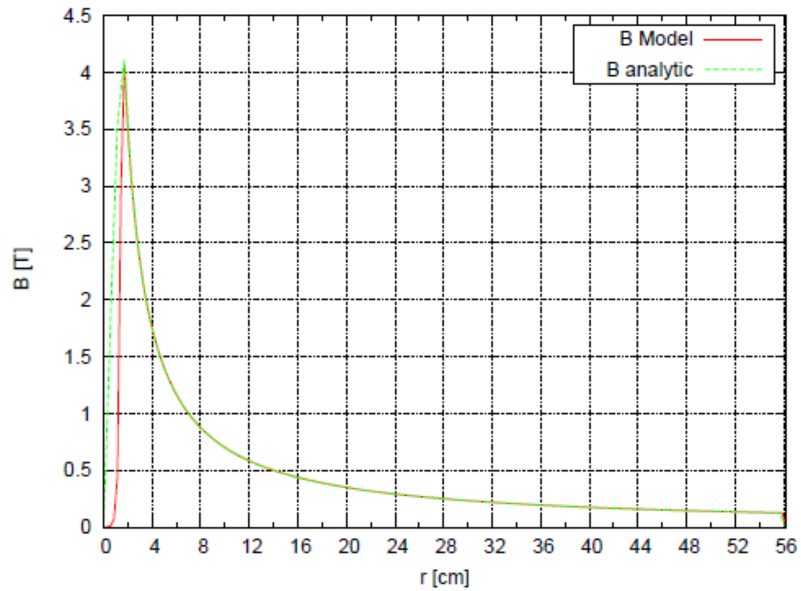
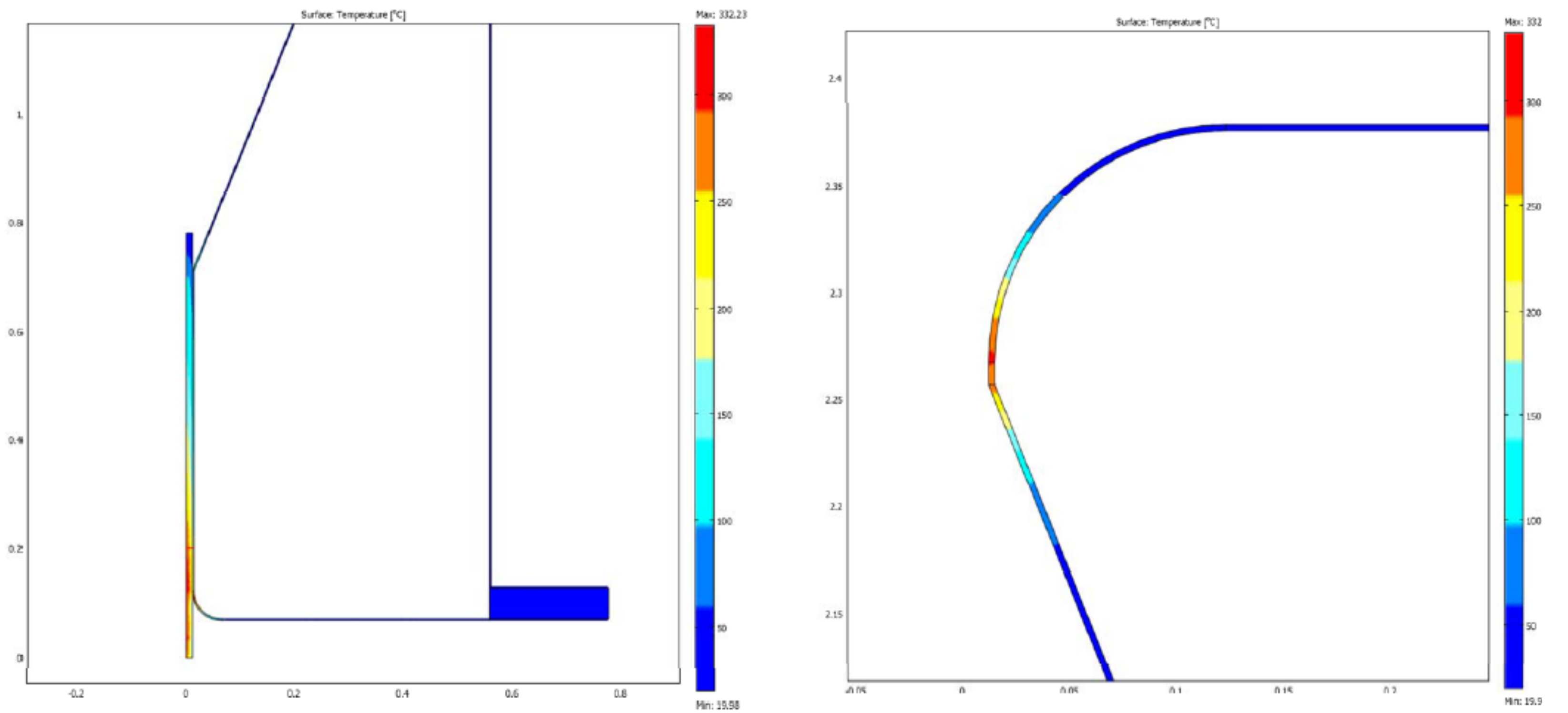


FIGURE: Magnetic flux distribution



Horn Studies

Temperature Field, Cooling

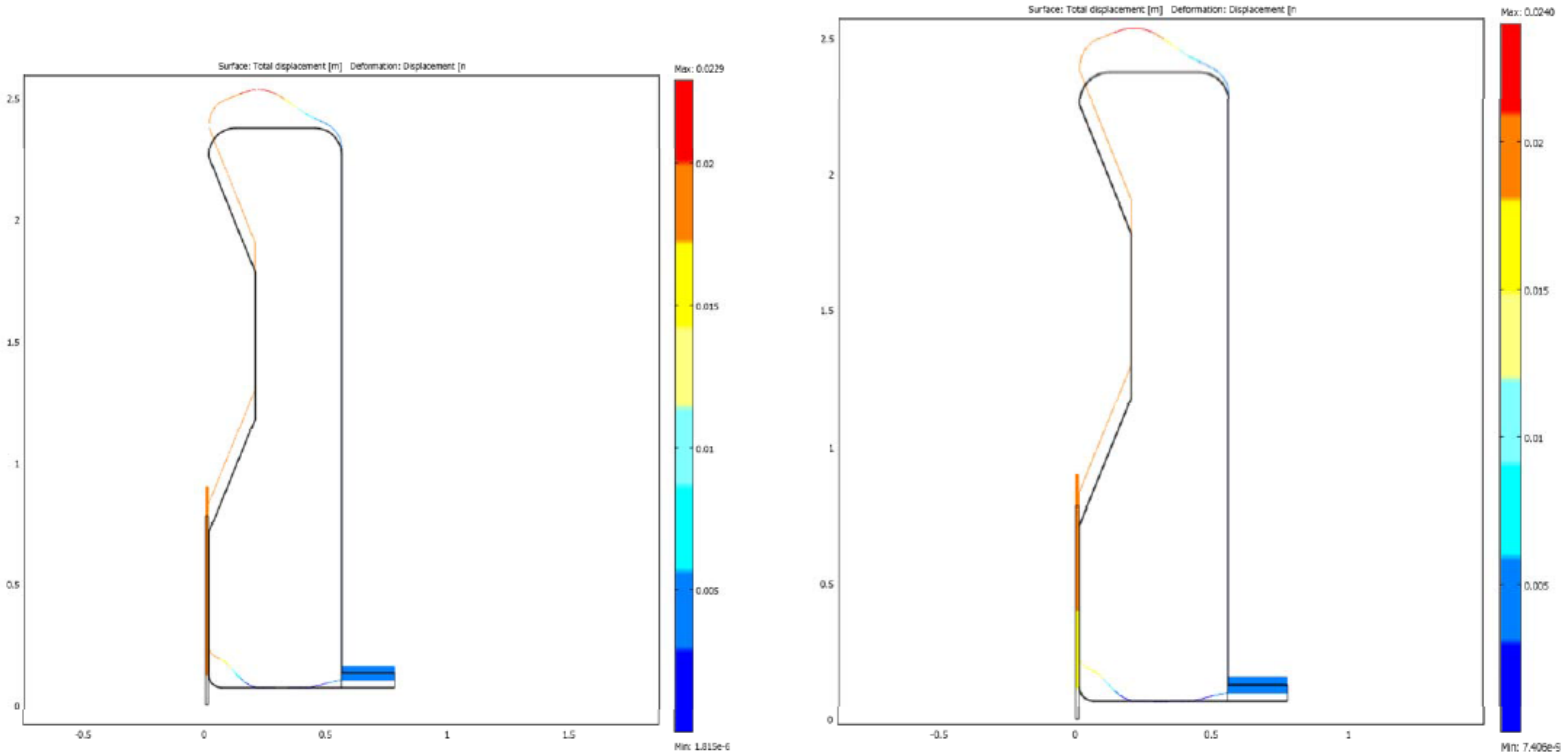


a) b)

FIGURE: Temperature field, max temperature 332 $^\circ C$, $\{h_{horn}, h_{target}\} = \{1, 10\}$ kW/(m^2K) for cooling scenario 1 a), b)

Horn Studies

Displacement Field

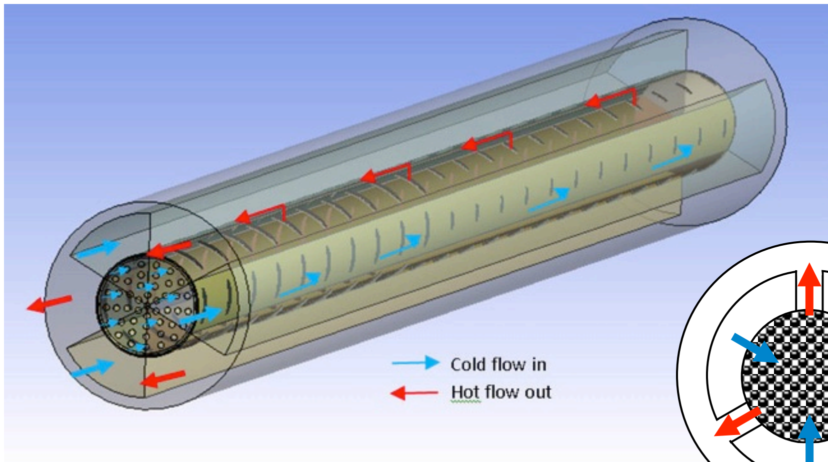


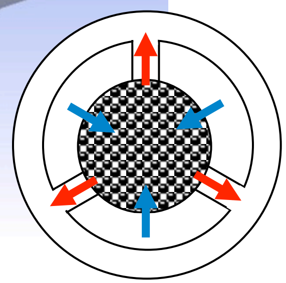
a) b)

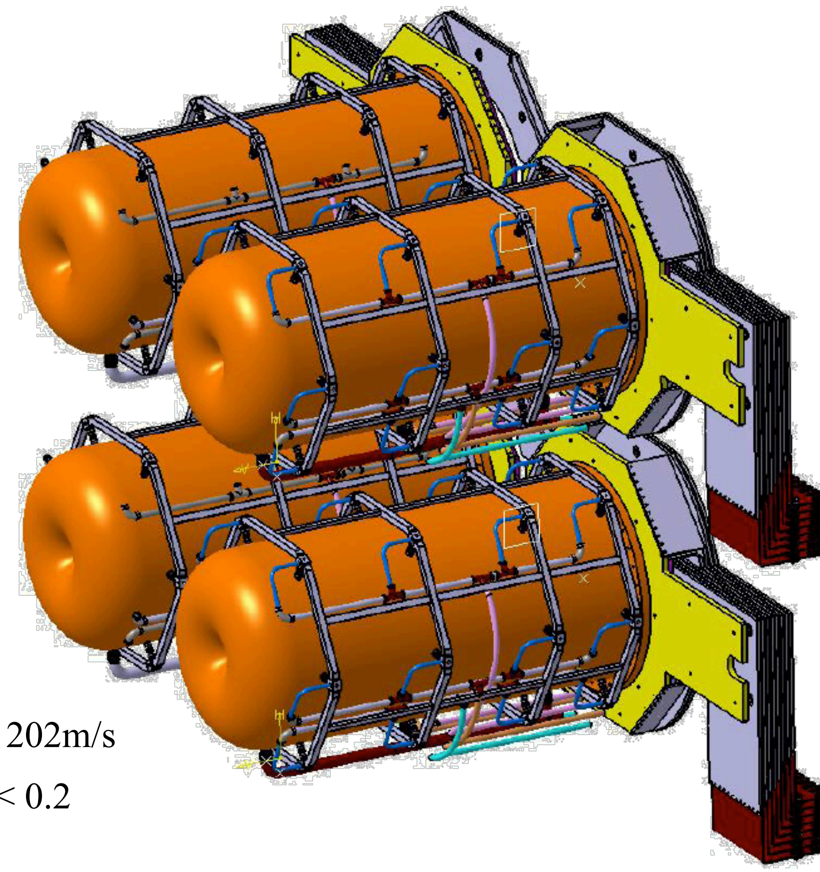
FIGURE: Displacement field for the horn with thickness $t = 3$ mm, magnetic pressure $u_{max} = 23$ mm a) and magnetic pressure + thermal dilatation $u_{max} = 24$ mm b) for cooling scenario 2

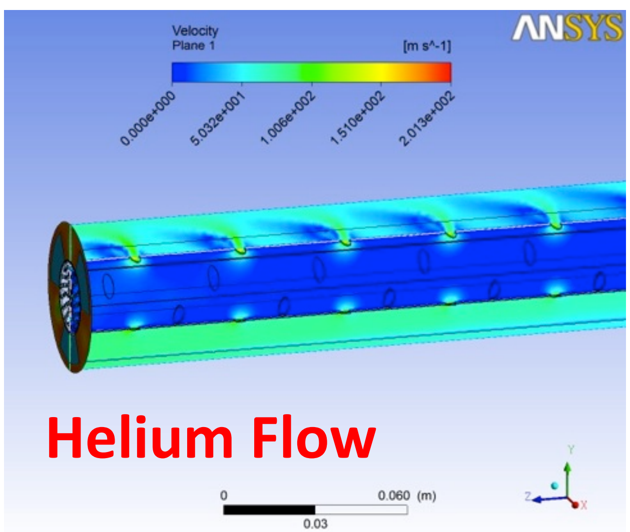
4-Target/Horn system

Packed bed canister in symmetrical transverse flow configuration (titanium alloy spheres)









<u>Helium Velocity</u>

Maximum flow velocity = 202m/s

Maximum Mach Number < 0.2

<u>Helium Gas Temperature</u>

Total helium mass flow = 93 gr/s

Maximum Helium temperature = 584°C

Helium average outlet Temperature = 109°C

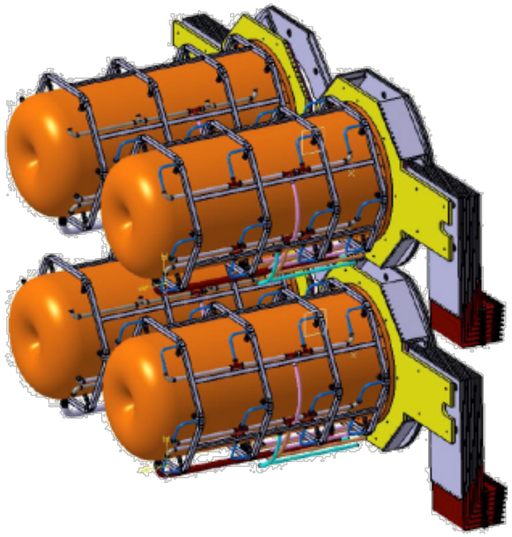
First tests with beam in the new HiRadMat@SPS facility at CERN in 2014

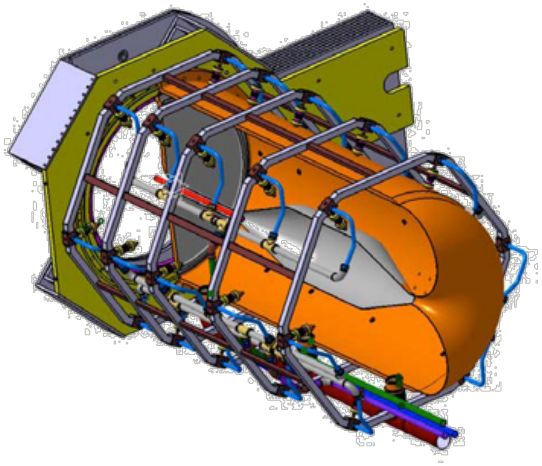
The Horn for ESSnuSB

- ❑ A key element for generating a neutrino beam is the hadron collector: used to focus in the forward direction the charged pions produced in the proton-target collisions
- ❑ The time duration of this high current pulse can only be of a few microseconds to not overheat the horn

-> implies the use of an accumulator.

- ❑ To obtain these few microseconds pulse the ring should have at least 376 m circumference.
- ❑ A pulsed power supply able of providing the very high current (~350 kA) to be circulated inside the horn at the required pulse rate has not been produced so far and thus needs to be prototyped.





- *Targetry*
- *Horn/Collector*
- **Power Supply**
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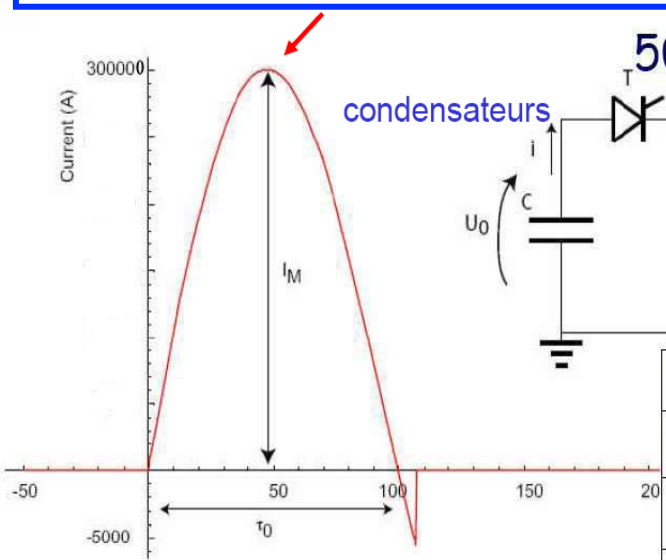
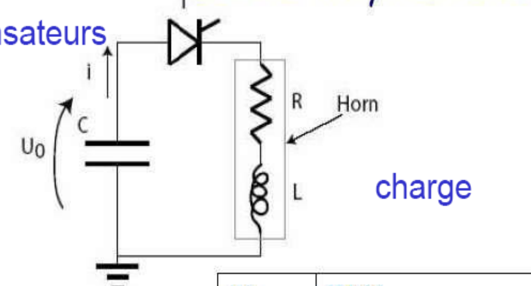
- Layout

Power Supply for horn pulsing (major issue)

- Focusing done during this "plateau";
- Proton pulse duration must be limited (<5 µs)

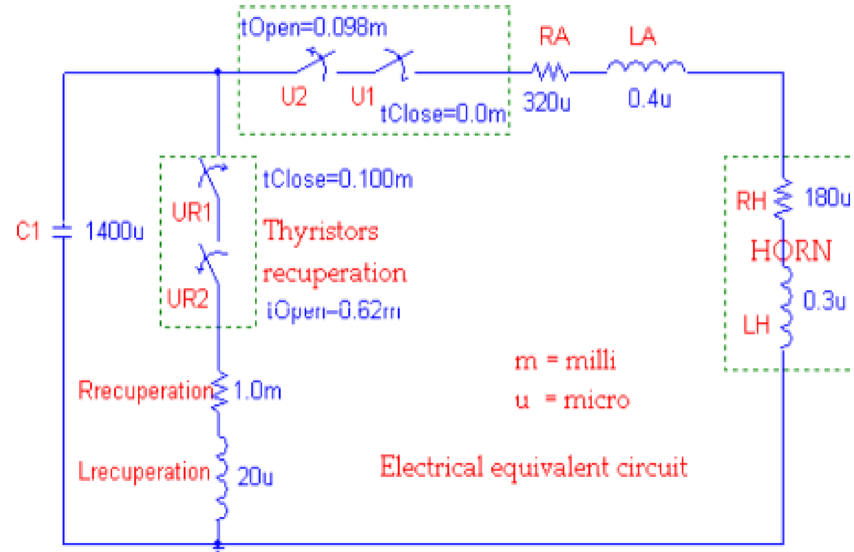


50Hz thyristors



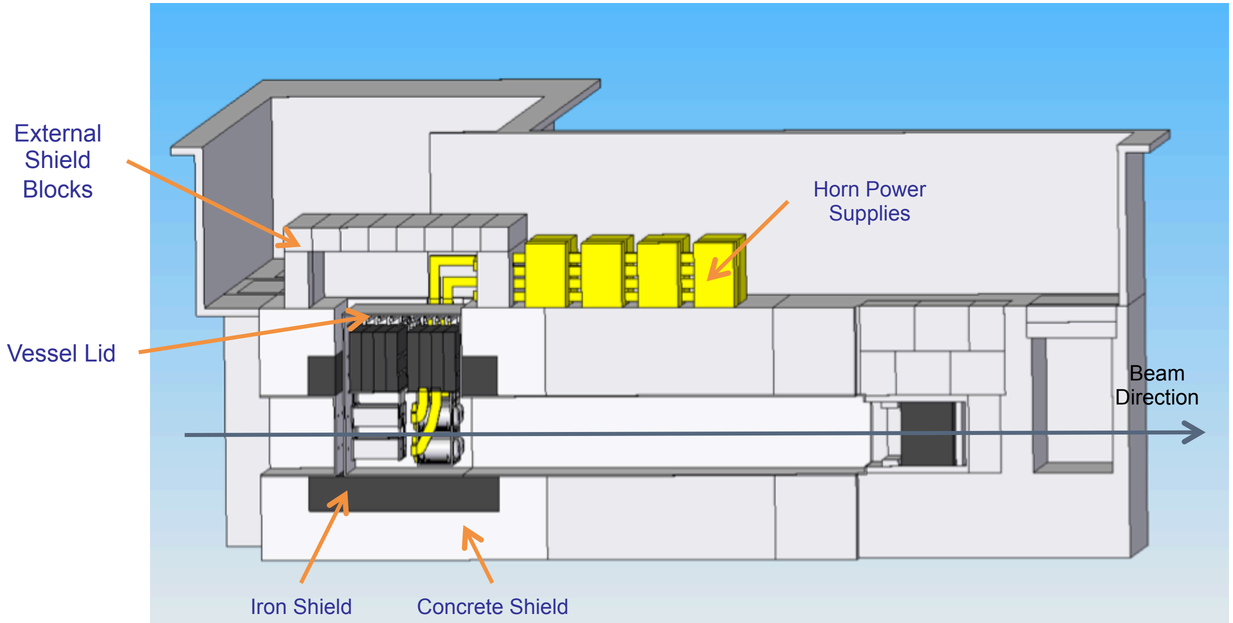
U_o	7kV
I_M	300kA (14,5 rms)
τ_o	100µs
L	0.6 (0.4 Horn)µH
R	500 (180 Horn) µΩ
C	1500µF

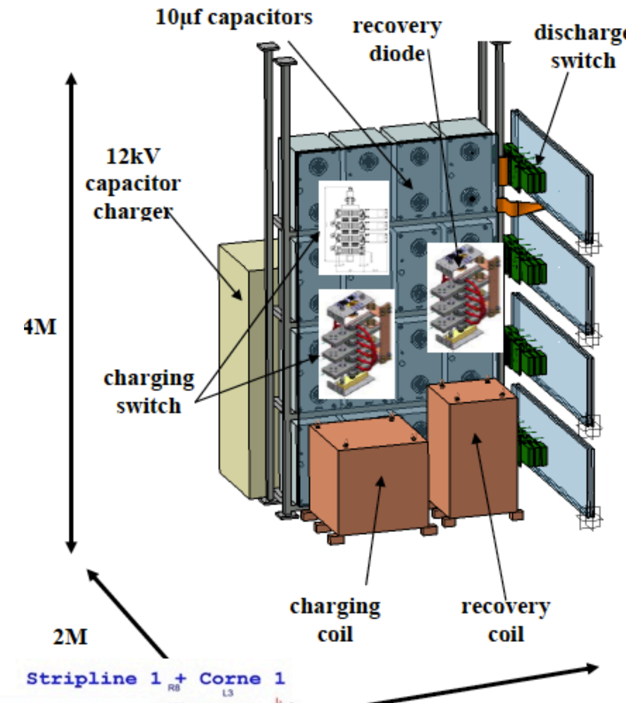
values considered by CERN

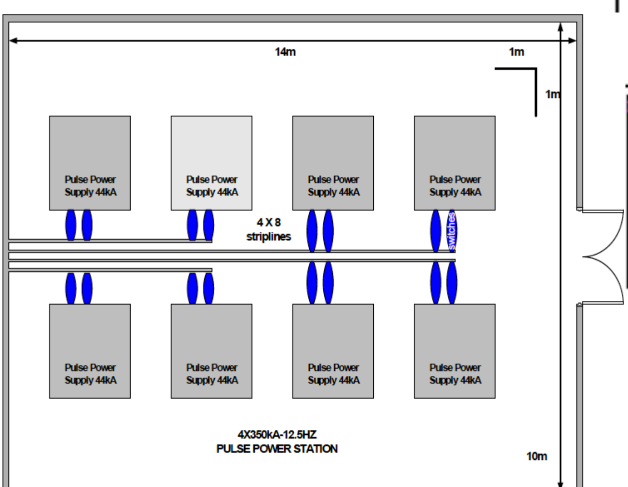


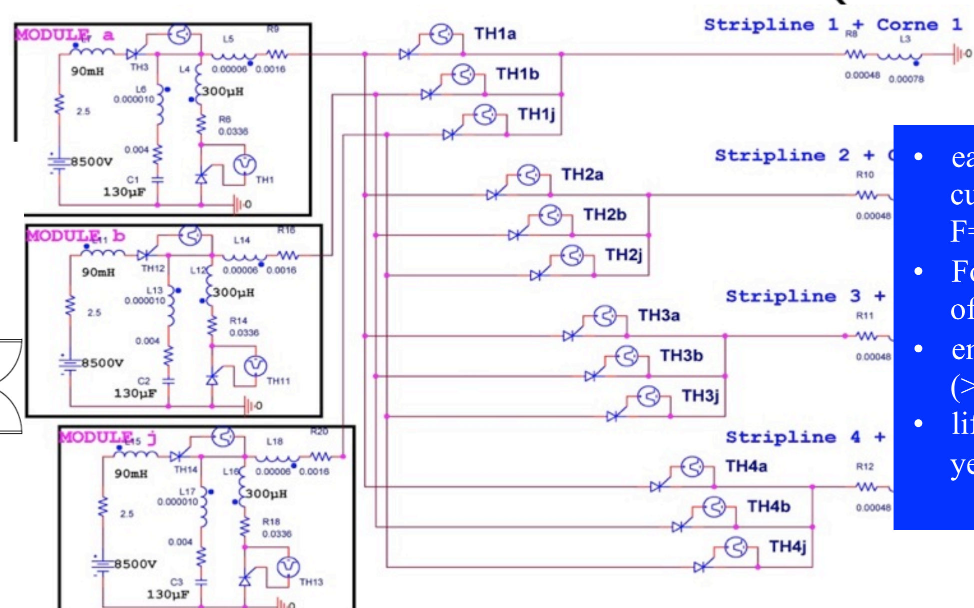
energy recuperation (>60%) and reinjection

Horn Power Supply and Strip Lines





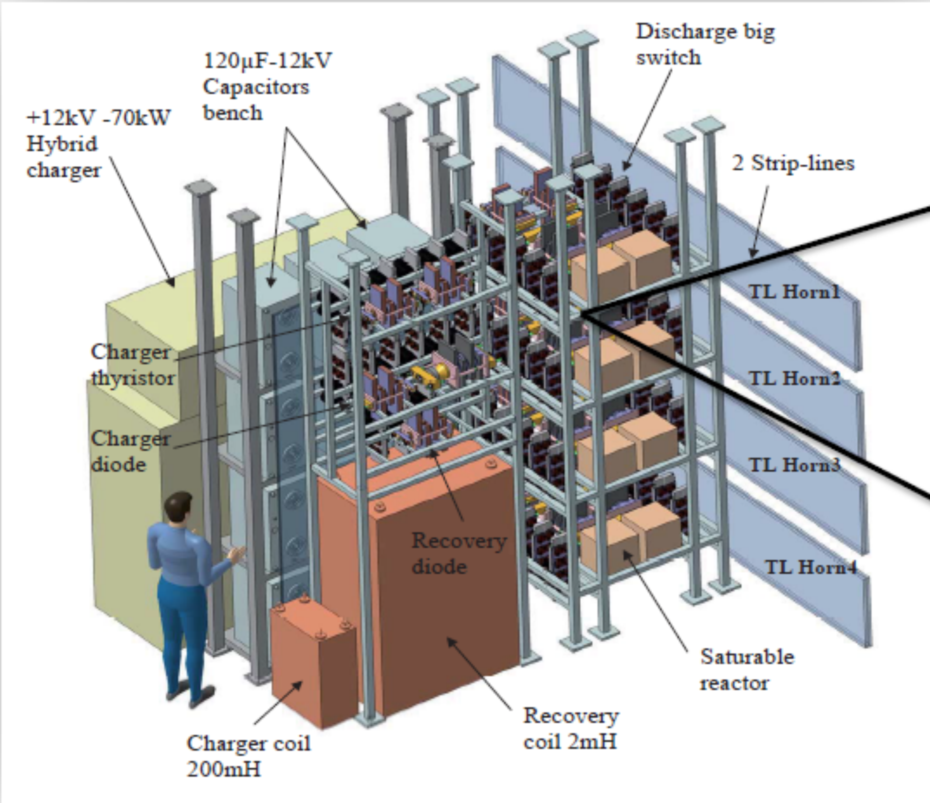




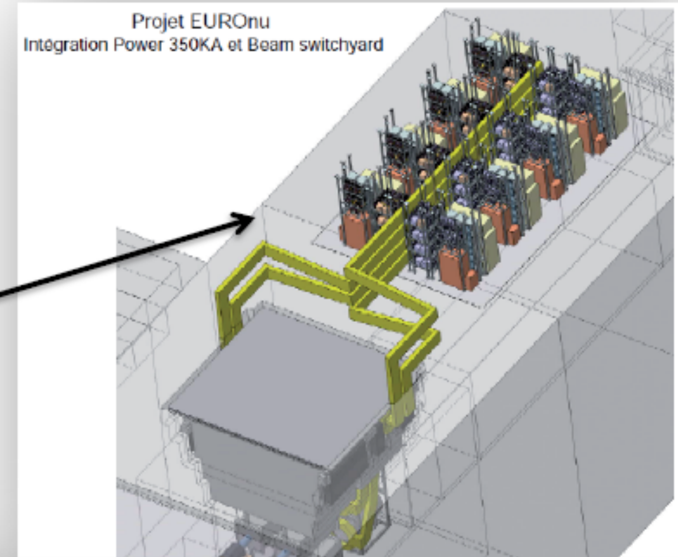
- each MODULE delivers a current of 44kA max at F=50HZ
- For each HORN : current of 350kA max at 12.5HZ
- energy recuperation (>90%) and reinjection
- lifetime > 13 Bcycles (10 years, 200 days/year)

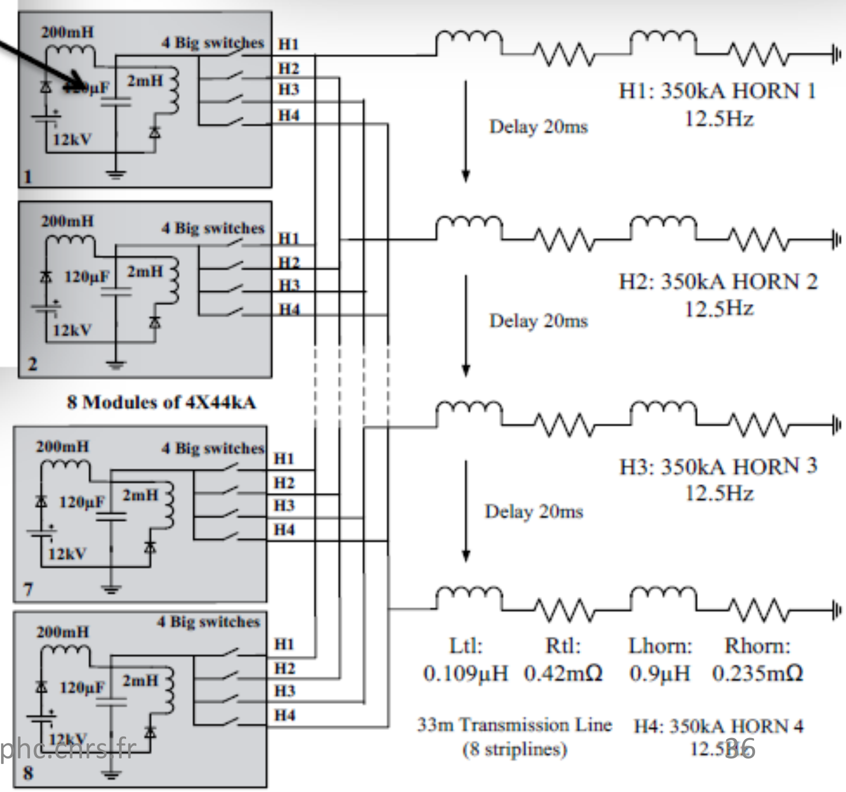
PSU EUROnu

a 4x44 kA module



x 8





- 8 times 4x44 kA modules
- 1-charger/capacitor/coil, 4-switches per 4x44 kA module
- 8 strip lines merged into 4 transmission lines in-out/horn
- 97 % Energy recuperation

How flat is the current pulse at peak ?
How it correlates with H^- beam width τ_{H-}?

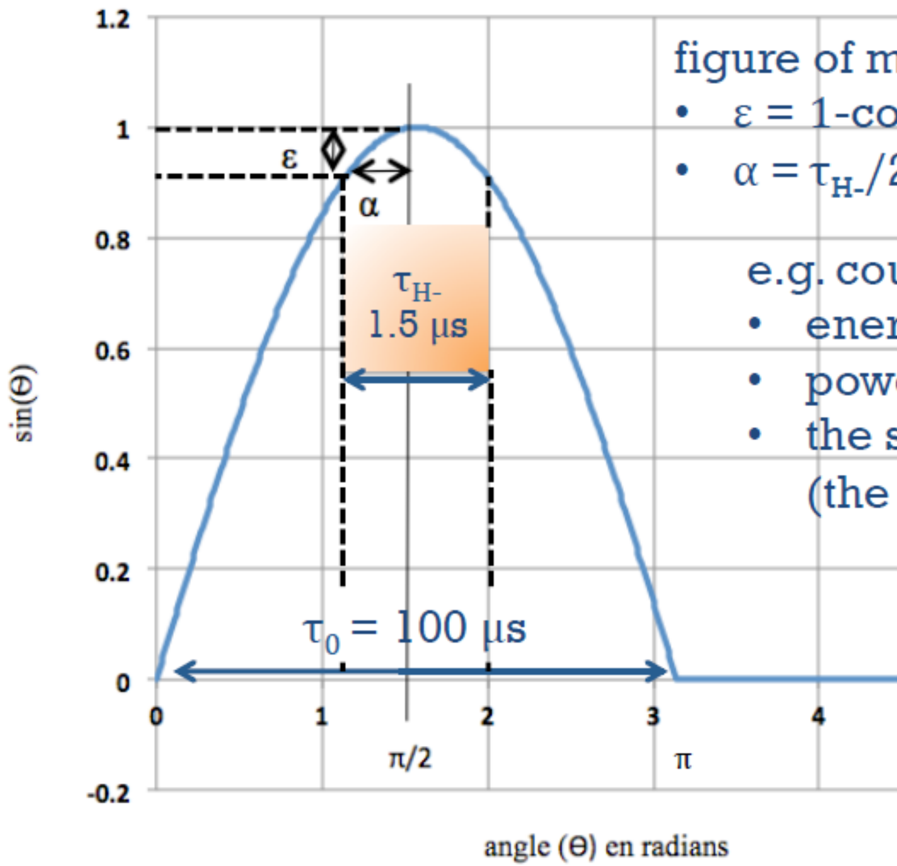
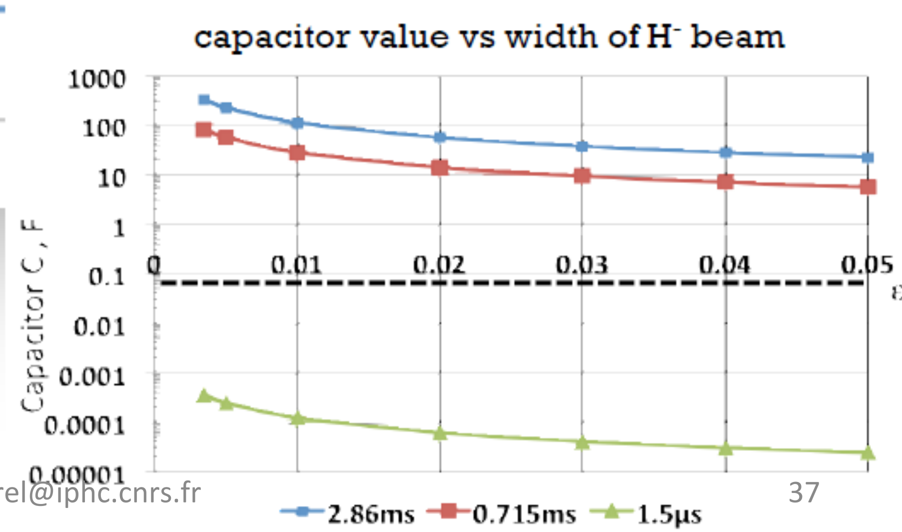


figure of merit, parameter ε "variance"

- $\varepsilon = 1 - \cos\alpha$
- $\alpha = \tau_{H-}/2 \cdot \pi/\tau_0$ in radians

e.g. could be correlated to

- energy storage
- power consumption
- the smaller ε the costlier or not feasible (the larger the integral I x Time)



PSU options

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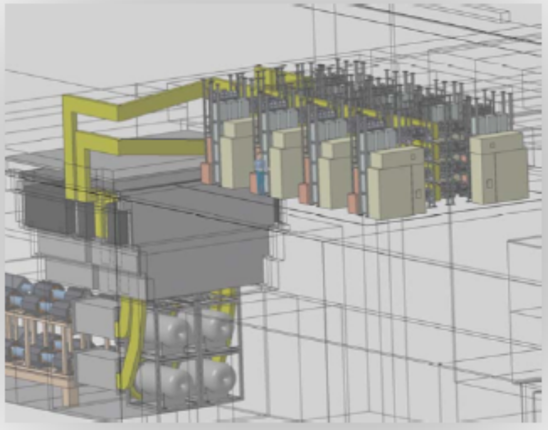
EUROnu modifications in terms of

- equivalent Area, reflecting any changes for the coil or capacitor values (thus sizes) (ref. 194 m^2 ~ 960 μF, 16 mH)
- Power consumption (ref. 560 kW)
- Cost (ref. ~ 4 MEuro)



for different

- Beam widths τ_{H-}= 1.5, 715, 2860 μs
- PSU frequencies 56, 112, … Hz

Versus

all possible configurations of the accumulator ring(s)

- 4 or 1 or none rings
- Protons only
- Protons and H^-

1.a) 4-rings, 426 m perimeter each, ν 56 Hz

2013, JINST, 8, T07006
arXiv: 1304.7111

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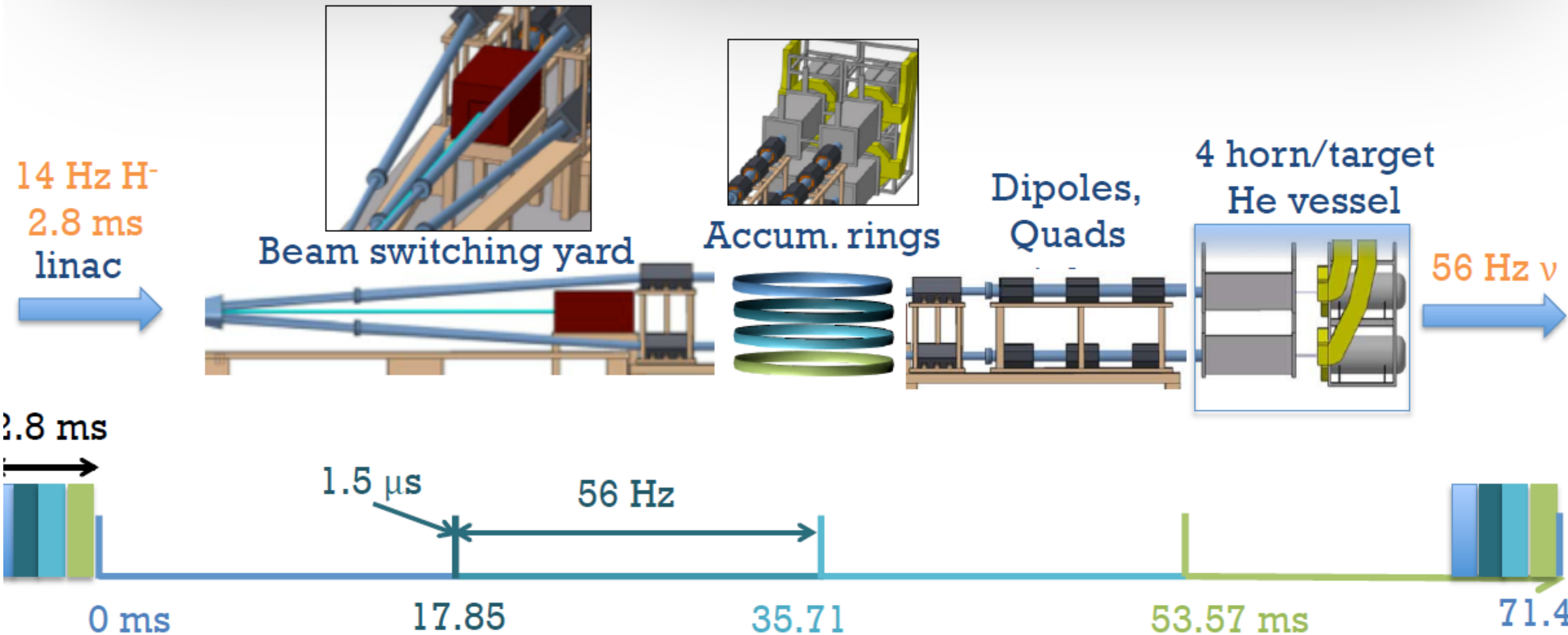
P. Poussot

baseline

In : H^- (Hz)	Out : ν (Hz)	PSU
14	56	EUROnu

Area PSU (m^2)	Power Consumption (kW)	Cost MEuro
194	560 kW	~4



1.a) 4-rings, 426 m perimeter each, ν 56 Hz, ε analyses

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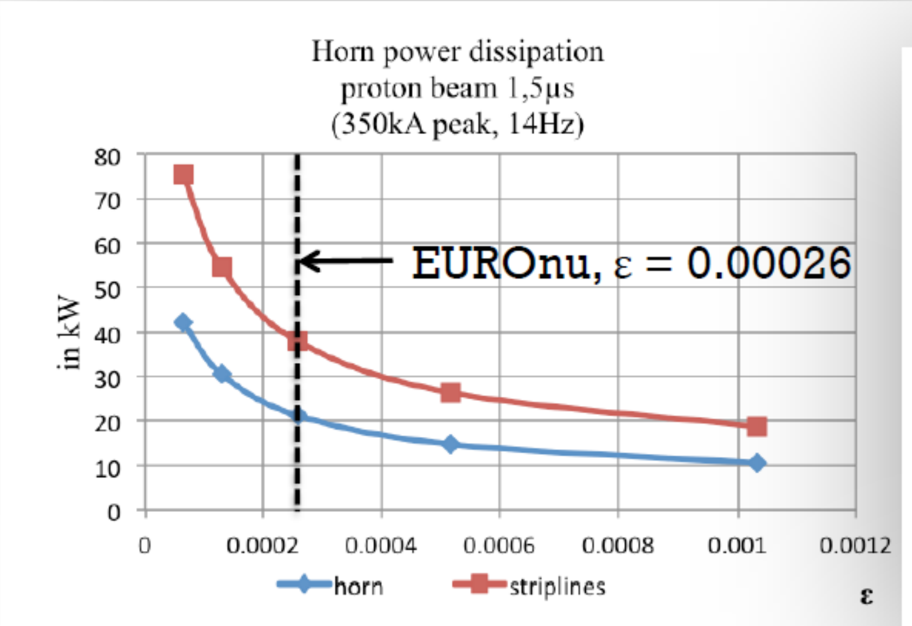

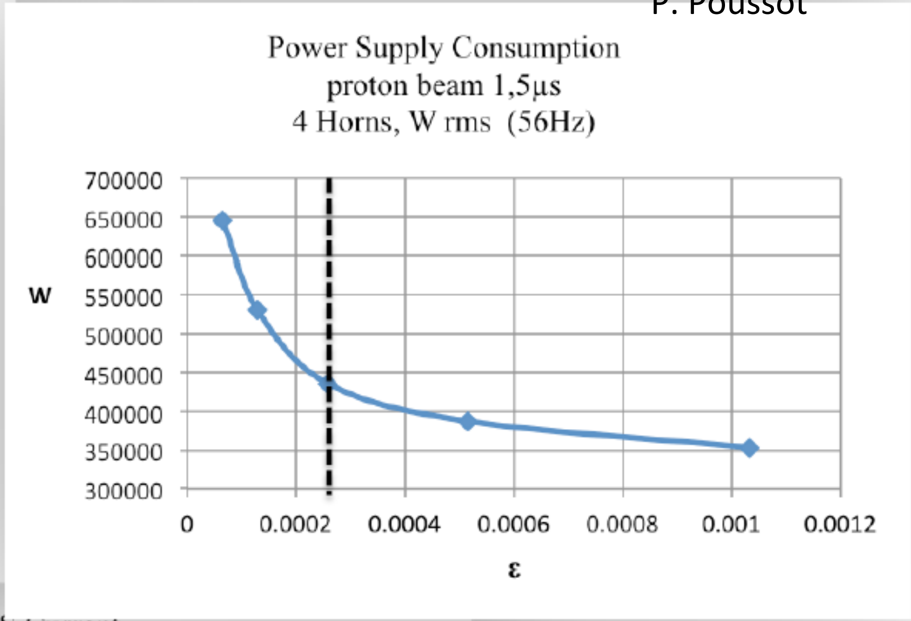

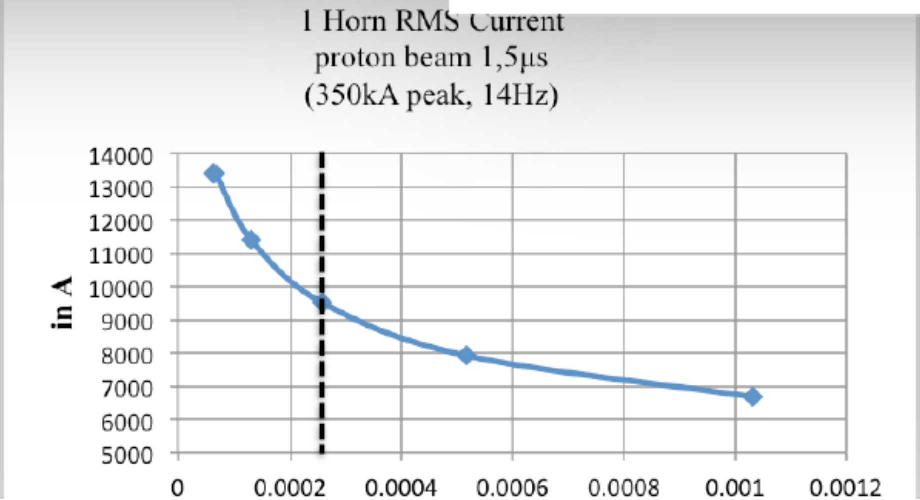

1.b) 4-rings, ν at 112 Hz + 35.71 ms gap for neutron users

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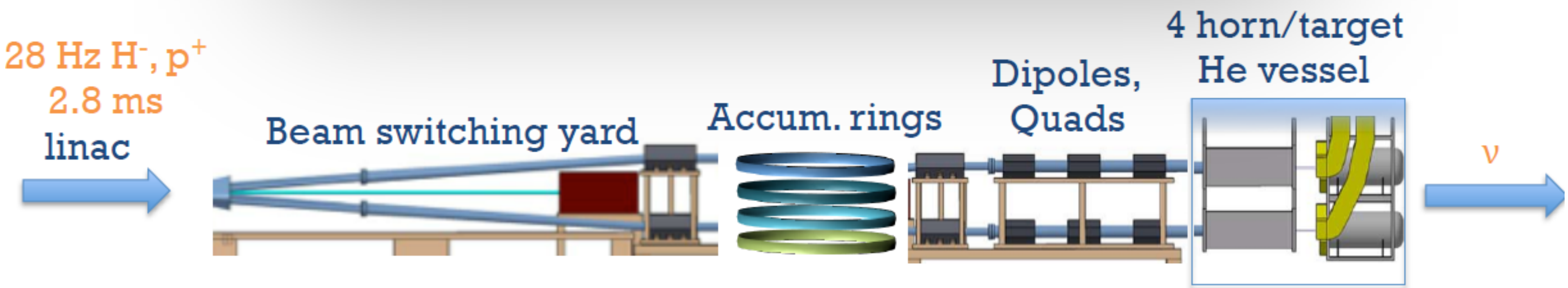
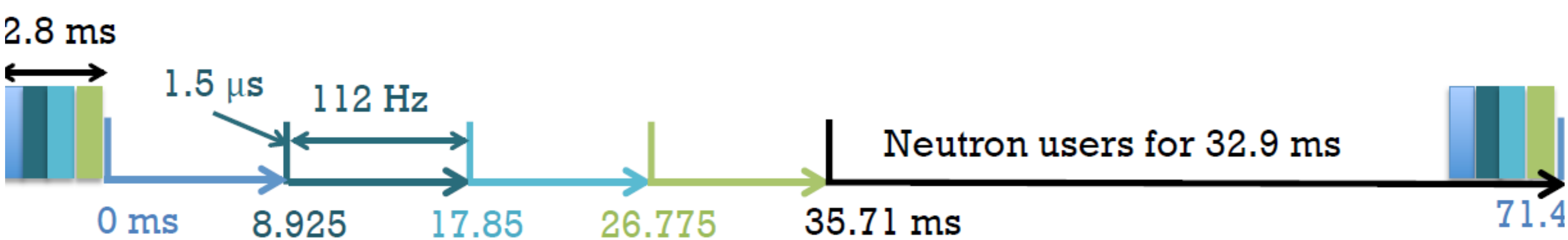
P. Poussot

EURONu modifications

	Capacitor charger	Area PSU	Power consumption	Cost
1.b.i)	2 x 56 Hz	x 1.3	x 1	x 1.5
1.b.ii)	1 x 112 Hz	x 1.2	x 1.5	x 1.1





2.a) 4-rings, ν at 14 Hz-simultaneously

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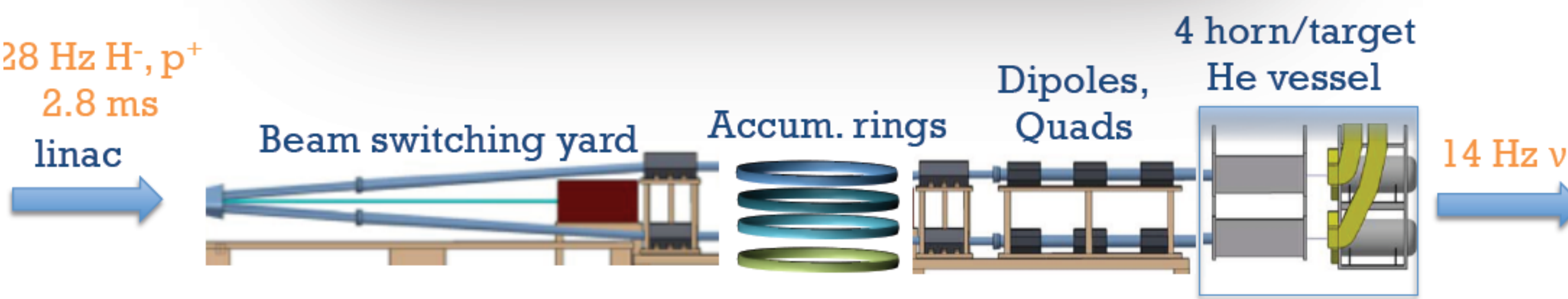
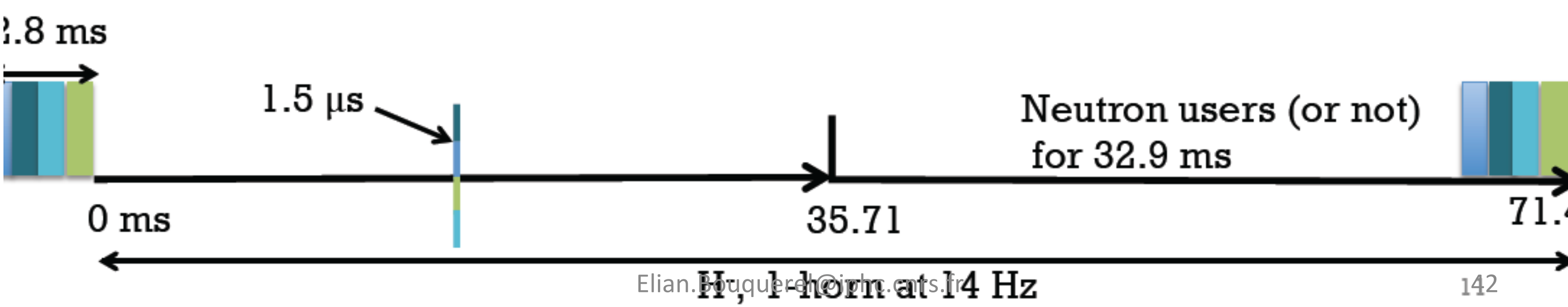
EUROnu modifications

Capacitor charger	Area PSU	Power consumption	Cost
4 x 14 Hz	x 1.7	x 1	x 2.5





2.b) 4-rings, ν at 14 Hz-simultaneously, 4-horns chained in series, transformer

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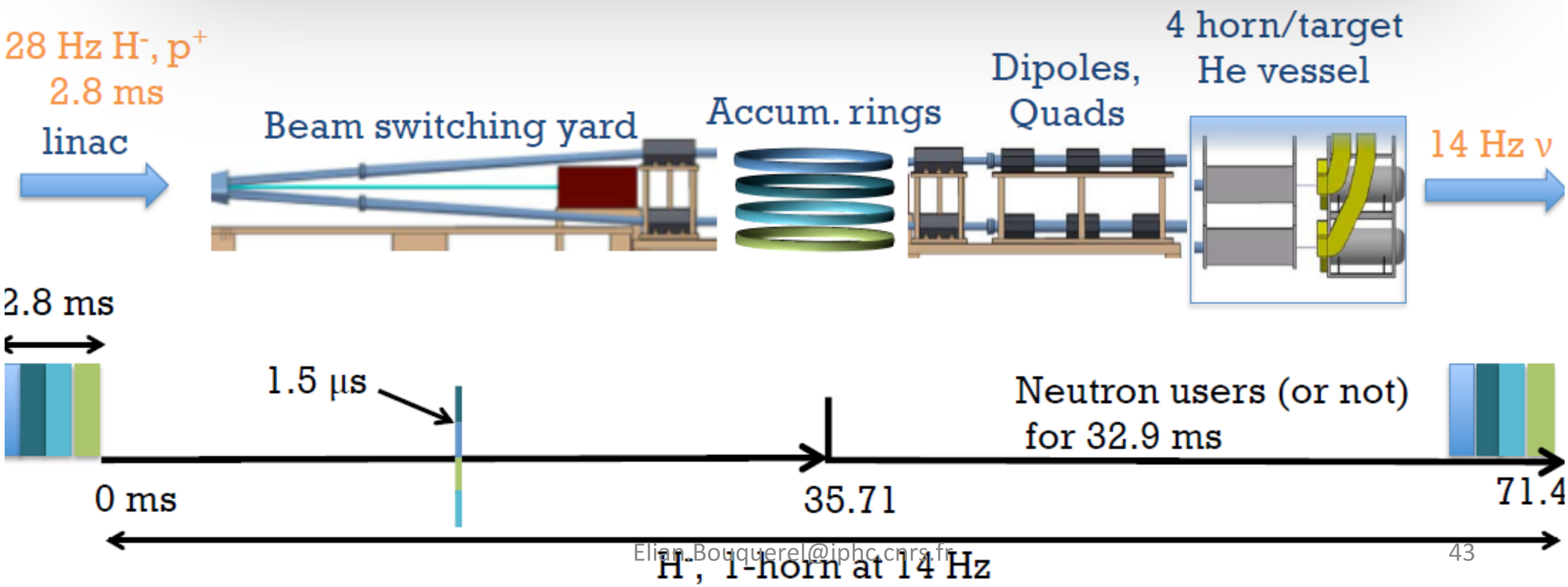
EUROnu modifications

Capacitor charger	Area PSU	Power consumption	Cost	Remarks
1 x 14 Hz	x 1.2	x 8	x 2.6	transformer to reduce C
				lower recovery eff.
				1 horn fails-all stop



3.a) 1 ring, ν 1428 Hz (4 times every 0.7 ms) + 68.6 ms gap

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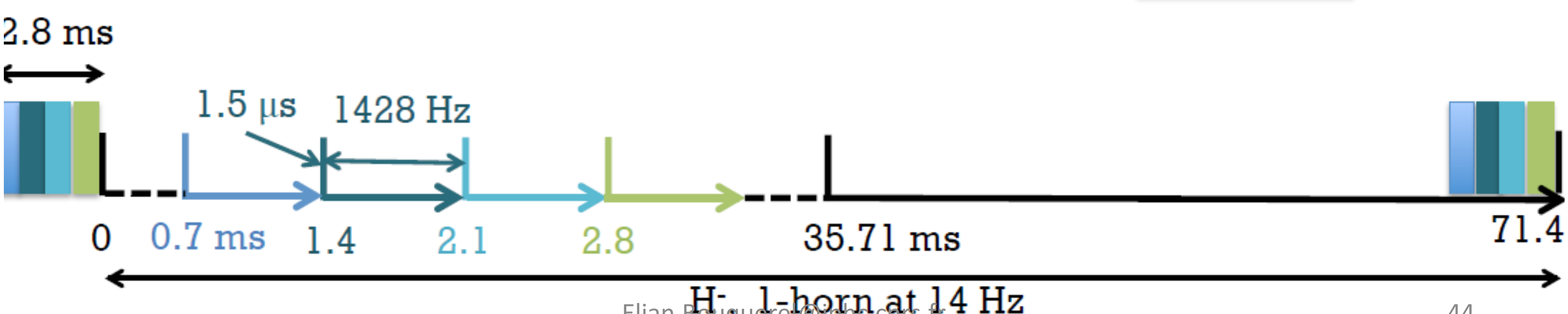
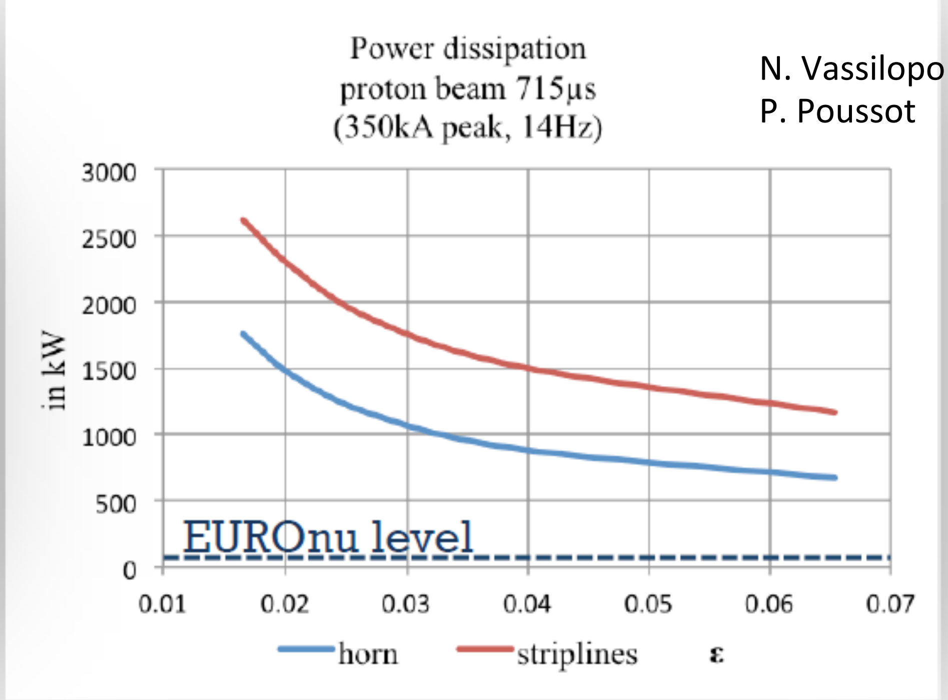
EUROnu modifications (same as 2.a)

Capacitor charger	Area PSU	Power consumption	Cost
4 at 14 Hz	x 1.7	x 1	x 2.5



4.a) no ring,ν during 2.8 ms (4 horns x 0.7 ms) + 68.6 ms gap, trasnformer

Area PSU	Power consumption	Cost
not feasible high power dissipation on horn and striplines and consumption		



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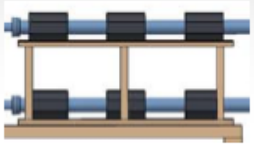
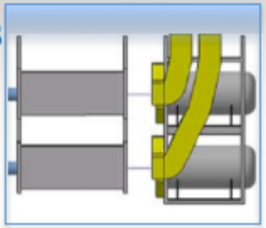
14 Hz H-
2.8 ms
linac

Beam switching yard

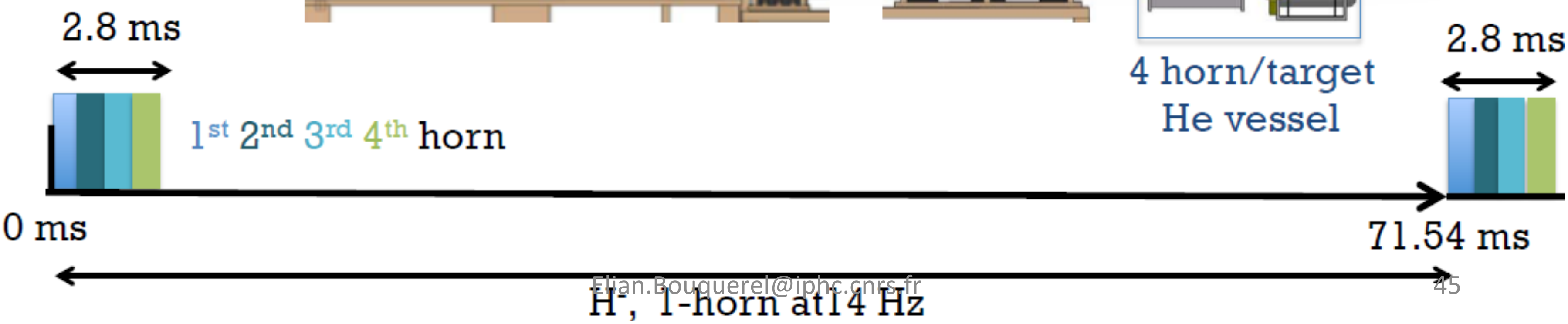
Dipoles+Quads





4 horn/target
He vessel

14 Hz ν



4.a) no ring,ν during 2.8 ms (4 horns x 0.7 ms) + 68.6 ms gap, transformer, ε analyses

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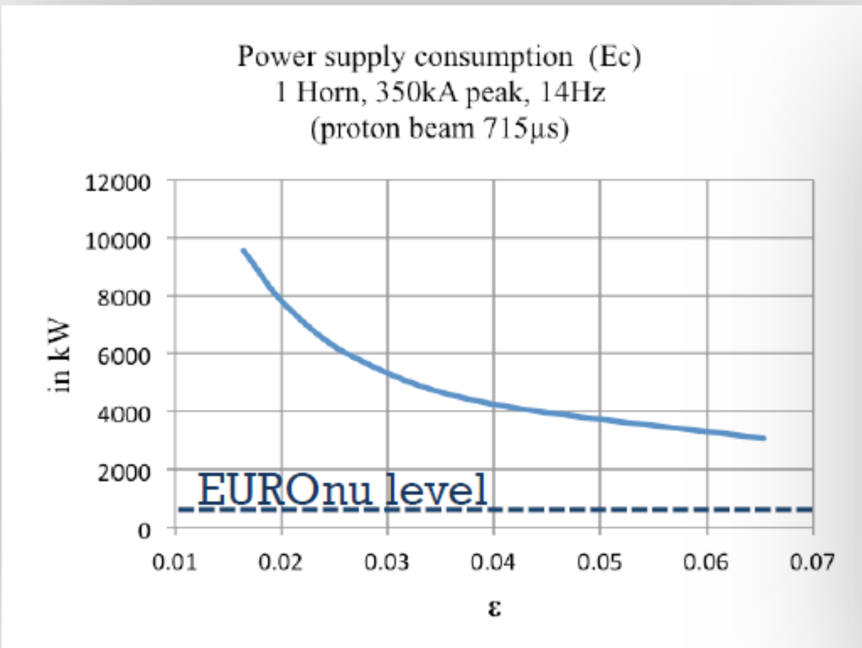

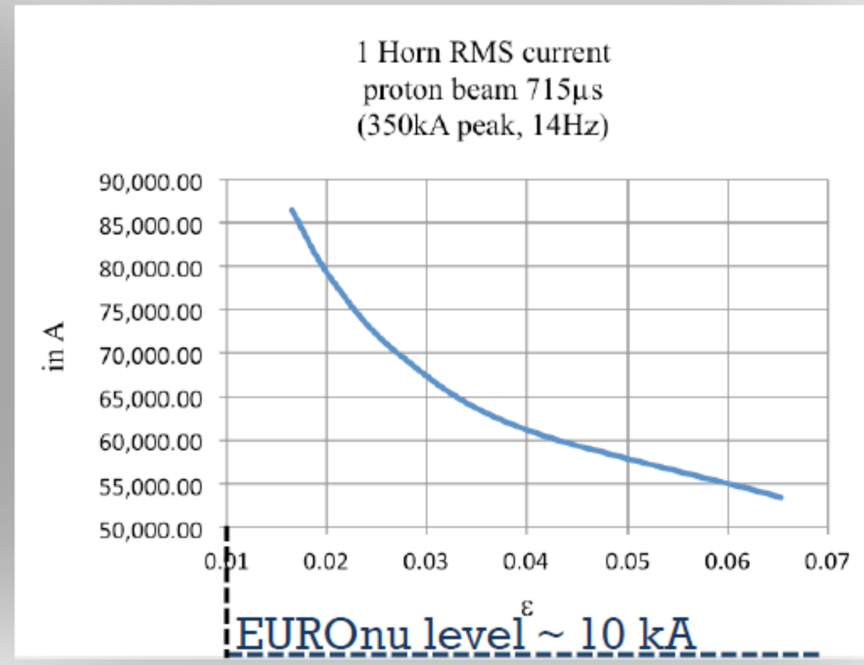

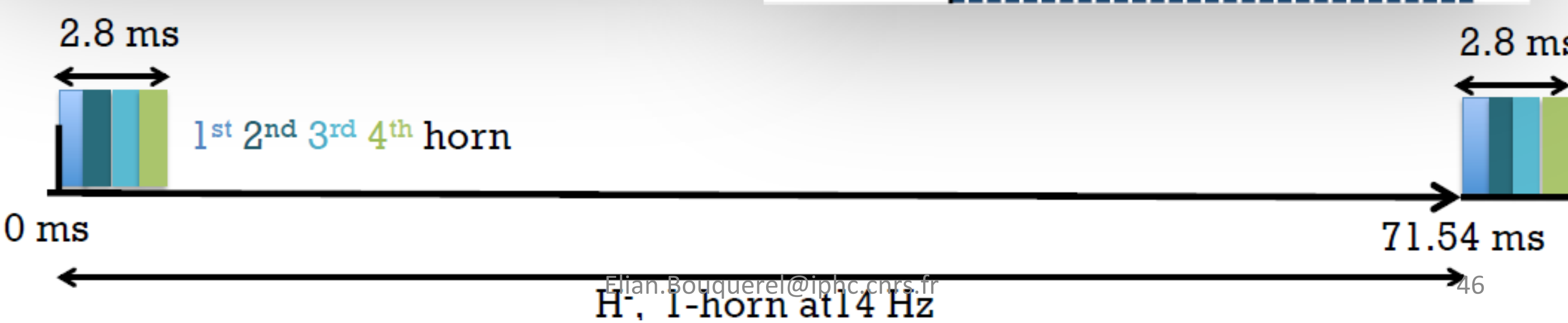

4.b) no ring,ν during 2.8 ms (1 horn) + 68.6 ms gap, each horn at 3.5 Hz

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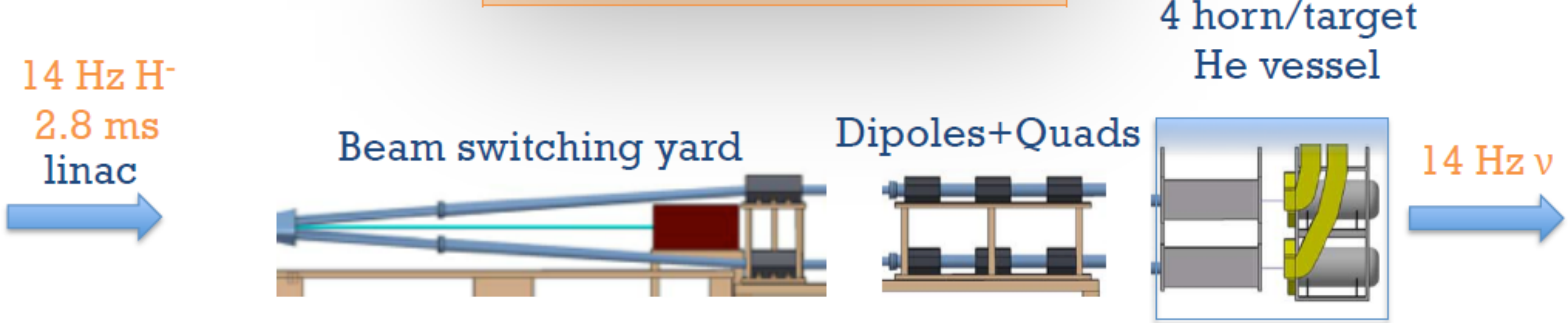
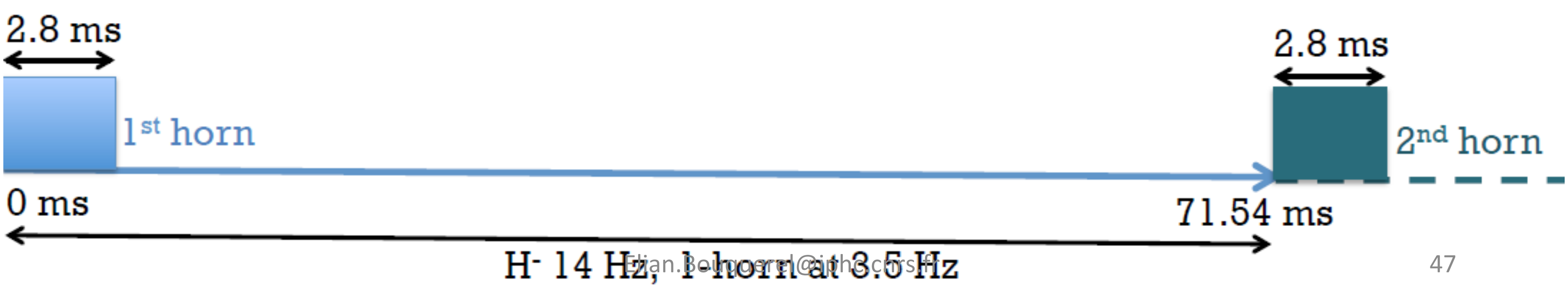
EUROnu modifications

Area PSU	Power consumption	Cost
not feasible high power dissipation on horn and consumption		





PSU Conclusions

preliminary

N. Vassilopoulos
P. Poussot

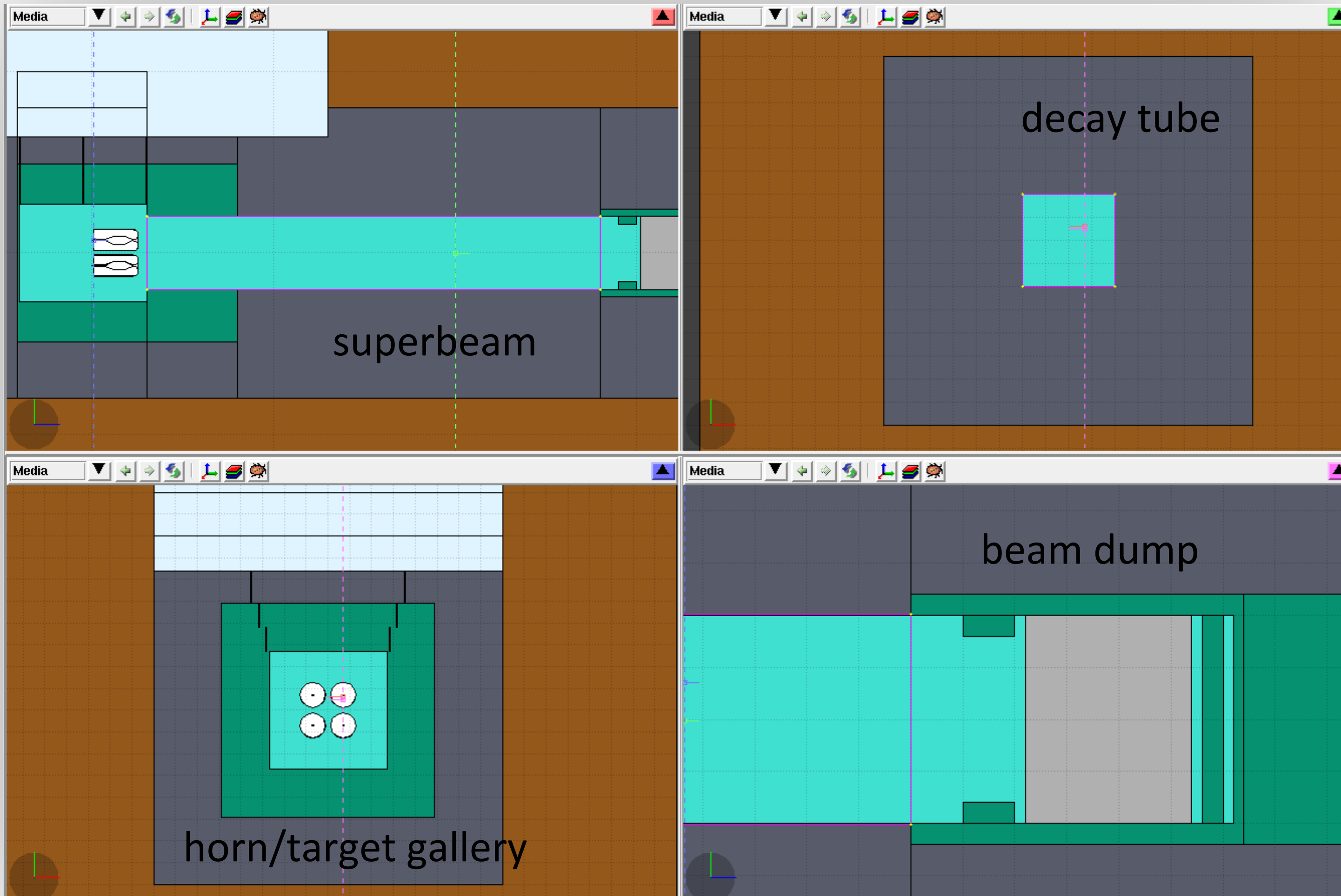
<table>
<tr><td colspan="21">RINGS</td></tr>
<tr><td colspan="12">4</td><td colspan="3">1</td><td colspan="6">none</td></tr>
<tr><td colspan="3" rowspan="2">1.a)
H^-
(baseline)
1 x 56 Hz</td><td colspan="3" rowspan="2">1.b)
H^-, p^+
2 x 56 Hz
1 x 112 Hz</td><td colspan="6">2.
H^- (p^+)
Simultaneously</td><td colspan="3">3.
H^-</td><td colspan="6">4.
H^-</td></tr>
<tr><td colspan="3">a)
Horns
parallel
4 x 14 Hz</td><td colspan="3">b)
horns
in series
transformer 14 Hz</td><td colspan="3">a)</td><td colspan="3">a)
2.8 ms on
horn</td><td colspan="3">b)
0.7 ms on
horn</td></tr>
<tr><td>A</td><td>P</td><td>C</td><td>A</td><td>P</td><td>C</td><td>A</td><td>P</td><td>C</td><td>A</td><td>P</td><td>C</td><td>A</td><td>P</td><td>C</td><td>A</td><td>P</td><td>C</td><td>A</td><td>P</td><td>C</td></tr>
<tr><td rowspan="2">1</td><td rowspan="2">1</td><td rowspan="2">1</td><td>1.3</td><td>1</td><td>1.5</td><td rowspan="2">1.7</td><td rowspan="2">1</td><td rowspan="2">2.5</td><td rowspan="2">1.2</td><td rowspan="2">8</td><td rowspan="2">2.6</td><td colspan="3" rowspan="2">same as 2.a</td><td colspan="3" rowspan="2">not feasible power consumption, horn</td><td colspan="3" rowspan="2">not feasible power consumption, horn</td></tr>
<tr><td>1.2</td><td>1.5</td><td>1.1</td></tr>
</table>

A = equivalent area, P = power consumption, C = cost

- Baseline PSU option has the best Cost vs Power Consumption performance

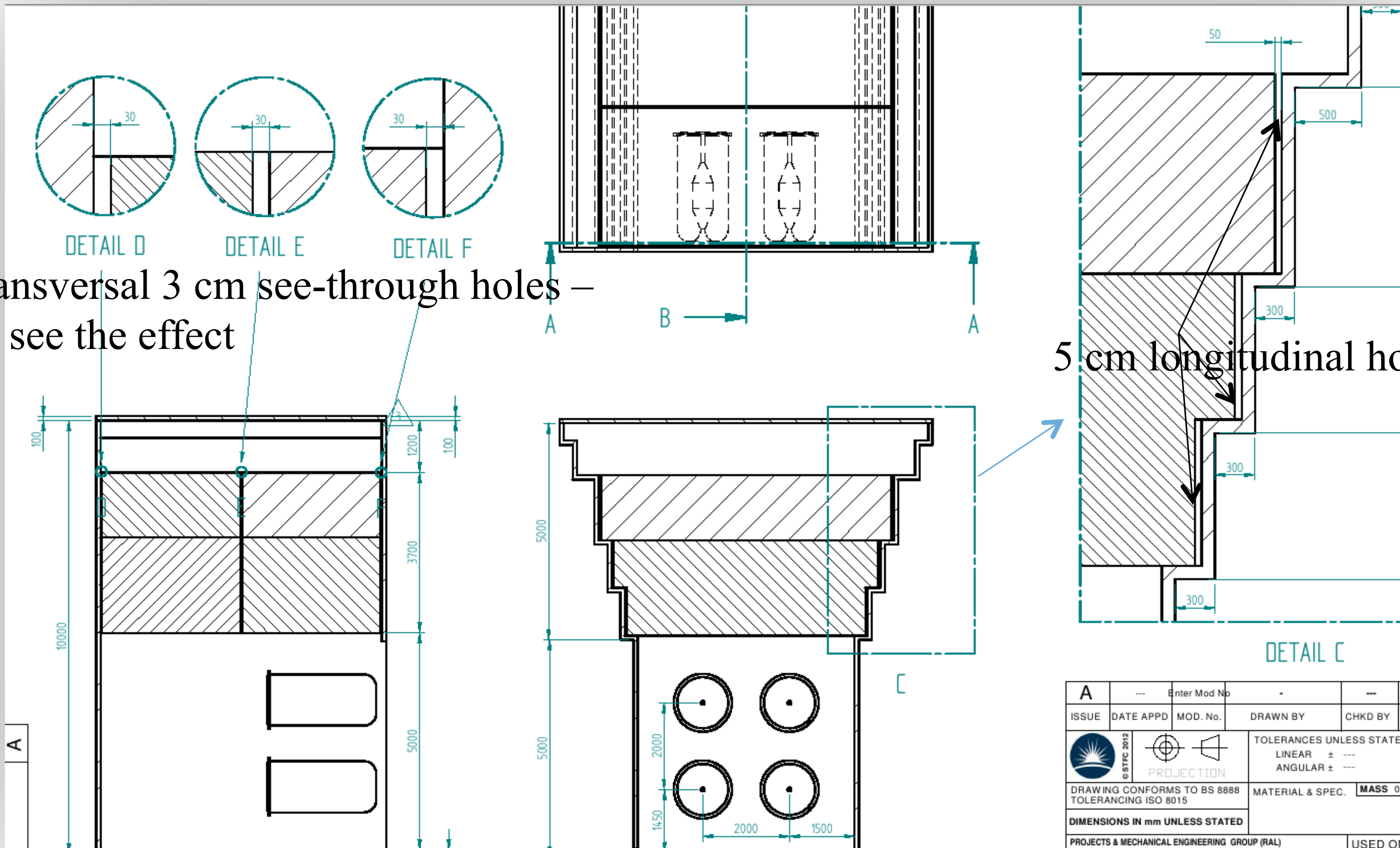
- *How to produce Neutrino Beams?*
- *Targetry*
- *Horn/Collector*
- *Power Supply*
- **Shielding**
- Layout

Simulation layout for radiation
fluka, flair gui/analysis
iron-shields, concrete, molasse, He



Horn/Target Gallery

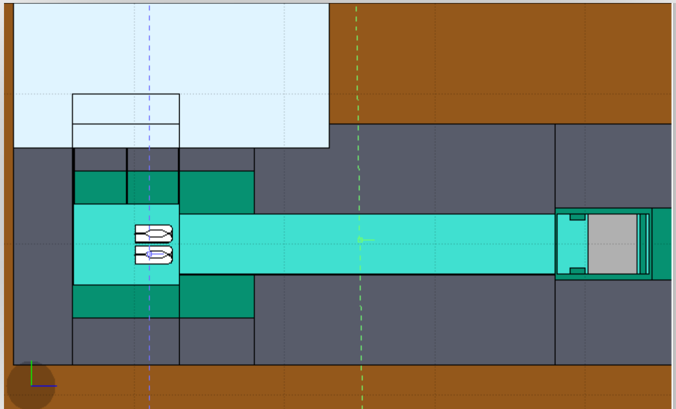
Geometry for horn/target gallery – including holes:

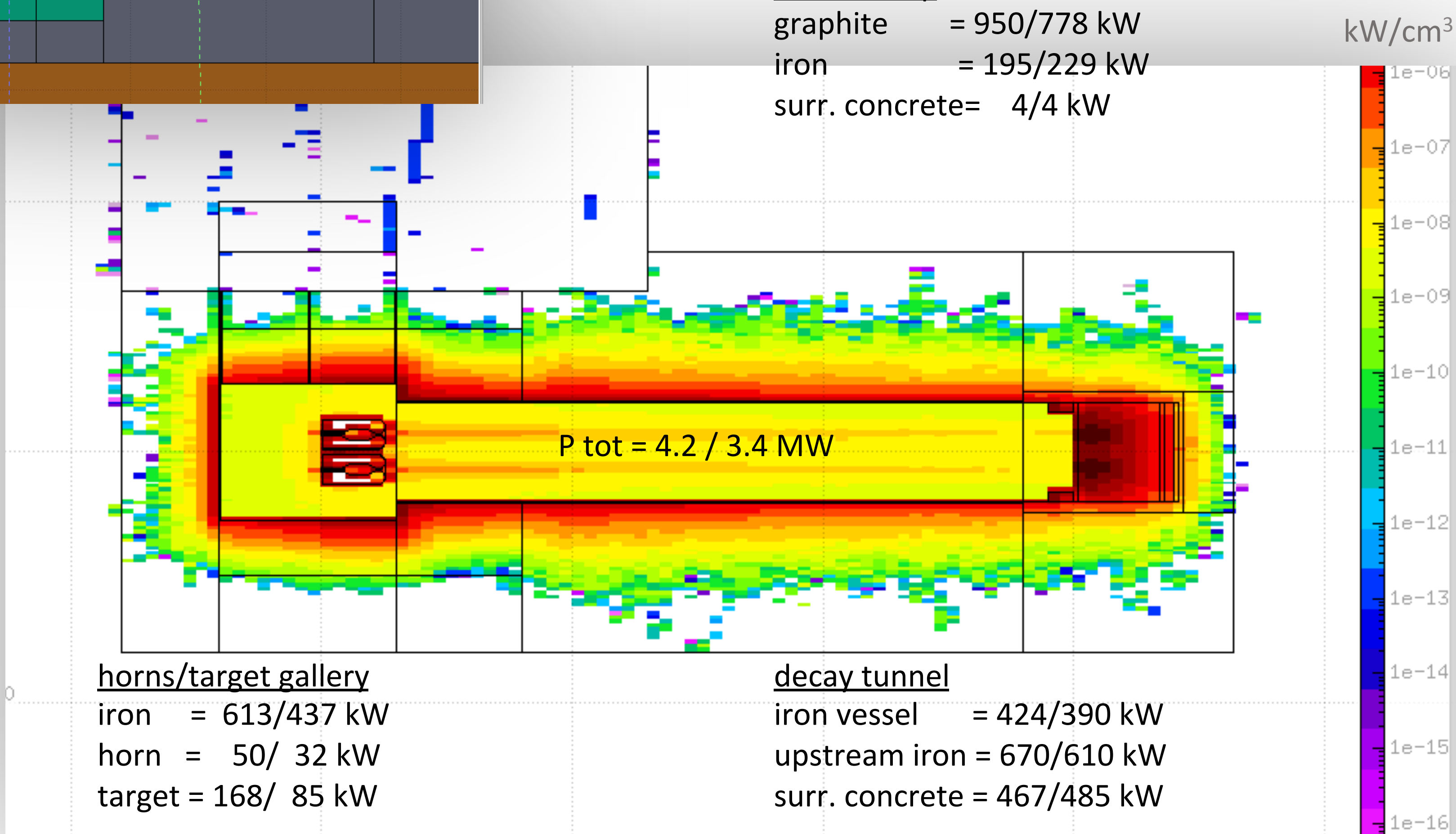


transversal 3 cm see-through holes – to see the effect

5 cm longitudinal holes

ESS/SPL power distribution
iron, concrete, molasse, He





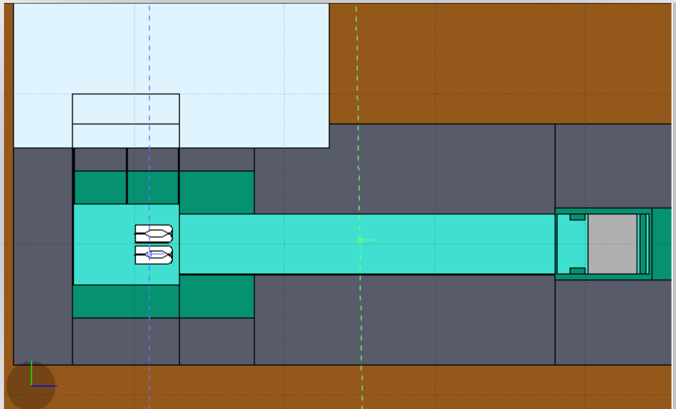
beam dump
graphite = 950/778 kW
iron = 195/229 kW
surr. concrete= 4/4 kW

horns/target gallery
iron = 613/437 kW
horn = 50/ 32 kW
target = 168/ 85 kW

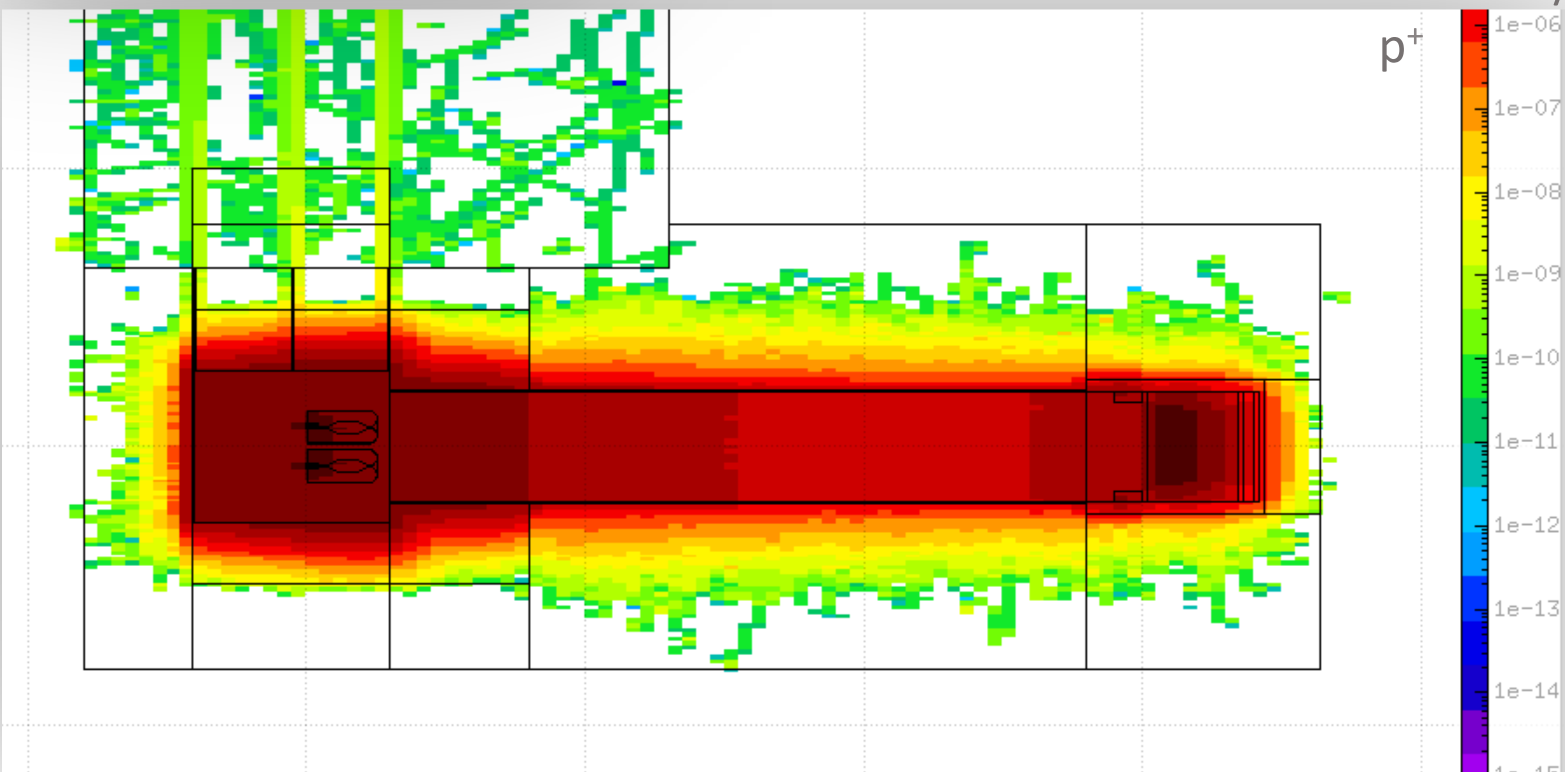
decay tunnel
iron vessel = 424/390 kW
upstream iron = 670/610 kW
surr. concrete = 467/485 kW

ESS neutron flux

iron, concrete, molasse, He



- SPL shielding achieves 10 µSv/h above target and horn, for ESS might be sufficient
- On-going studies



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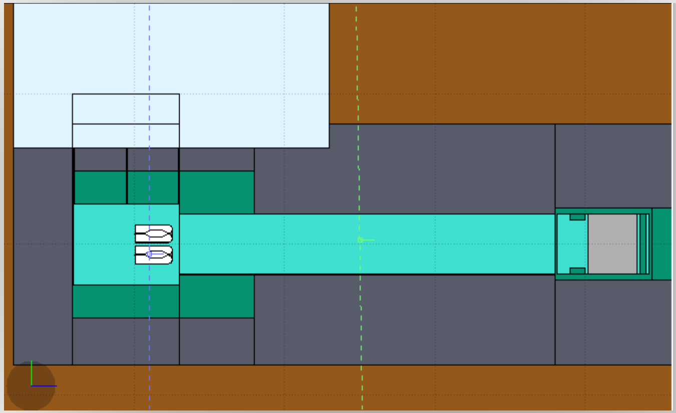
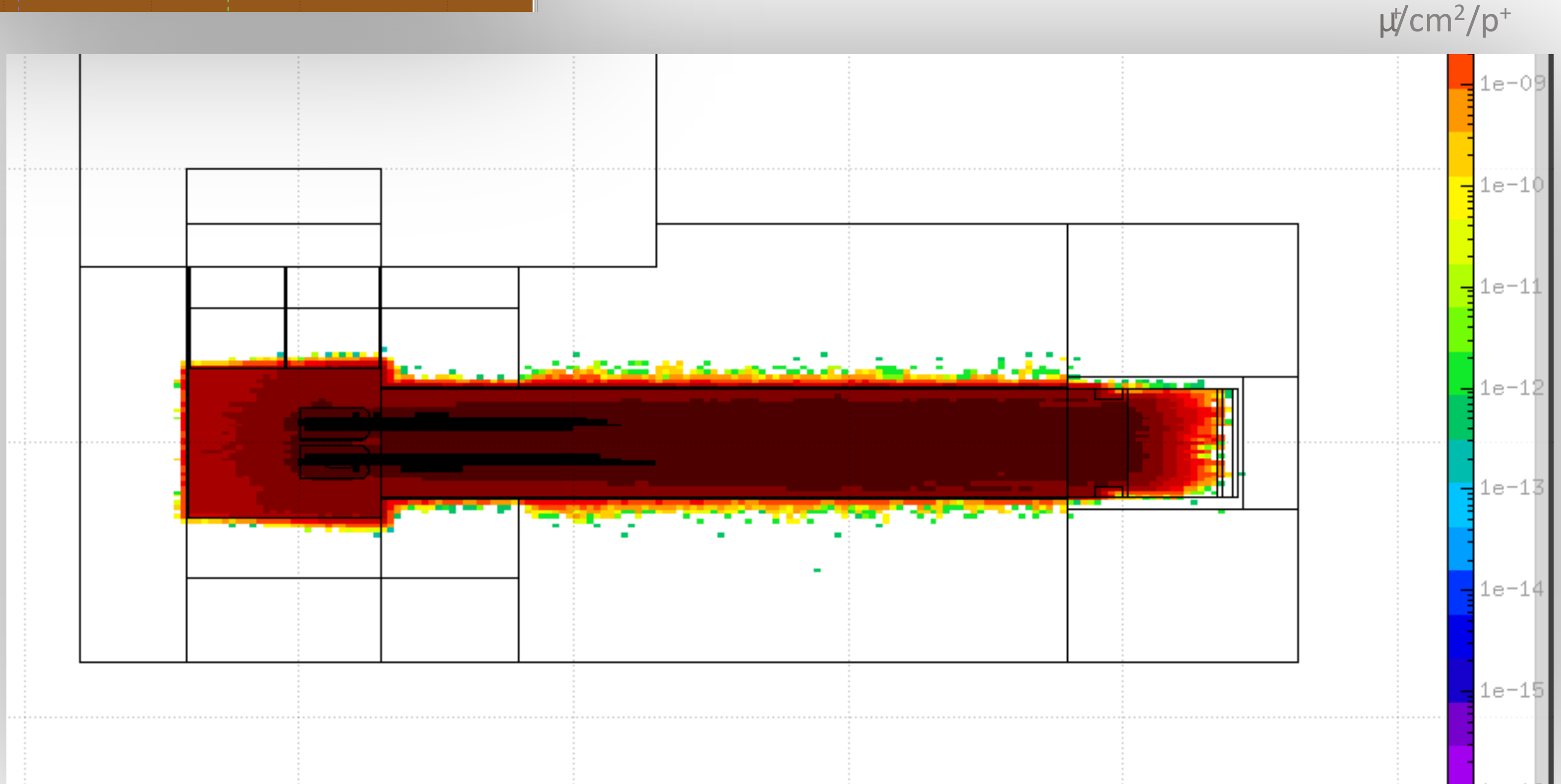
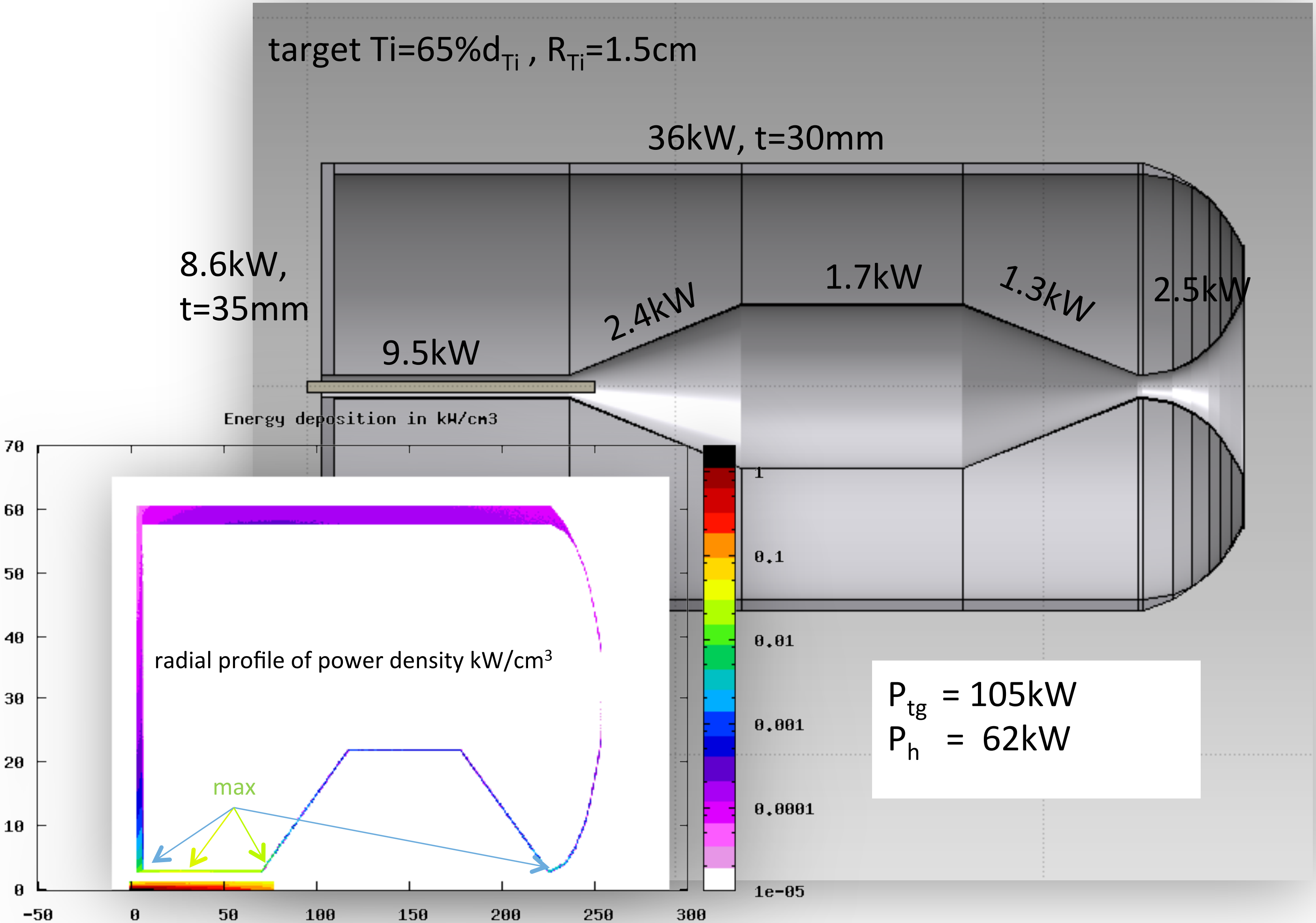
ESS muon flux
iron, concrete, molasse, He



- Preliminary, needs more stats
- Near detector could be placed few 10ths of meters after the bump dump gallery



Energy Deposition from secondary particles @1.3 MW (EUROnu Studies)



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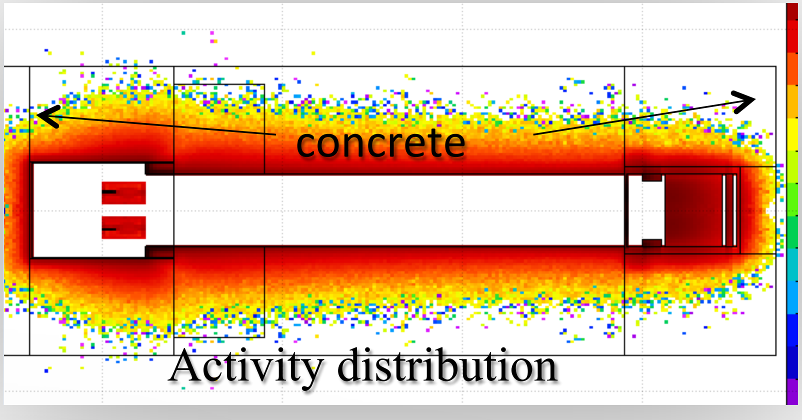
SPL: Activation in molasse

molasse @ CERN



Study set up:
✓ packed Ti target, 65%d_{Ti}
✓4MW beam, 4horns, 200days of irradiation

- minimum activation leads to minimum water contamination
- ^{22} Na and tritium could represent a hazard by contaminating the ground water

CERN annual activity constraints in molasse (0.3mSv/year for the public through water)		Super Beam
^{22} Na	4.2 x 10^{11} Bq	~10^{8} Bq
tritium	3.1 x 10^{15} Bq	~10^{8} Bq

- Activation lower than CERN's limits

Radiation simulation : Shielding Investigation

Beam Features:
- Proton Energy : 4,5 GeV/c
- Intensity : 18. 10^{14} pps
- Irradiation time : 200 days

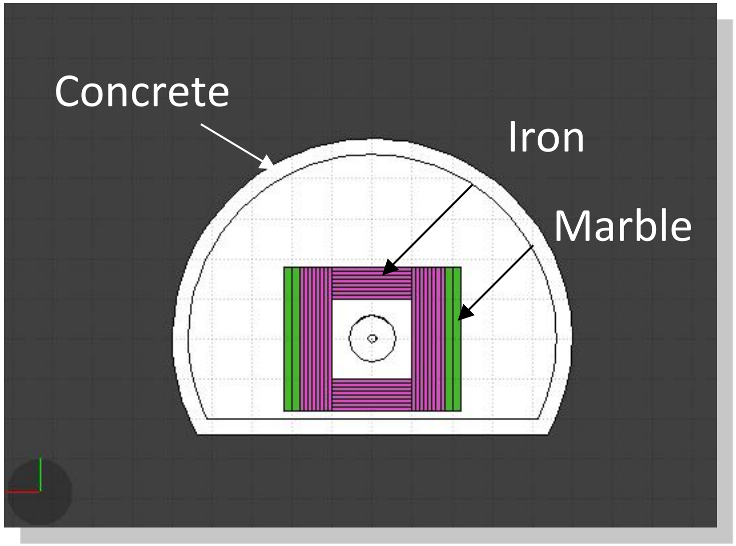
To be updated for ESSnSB

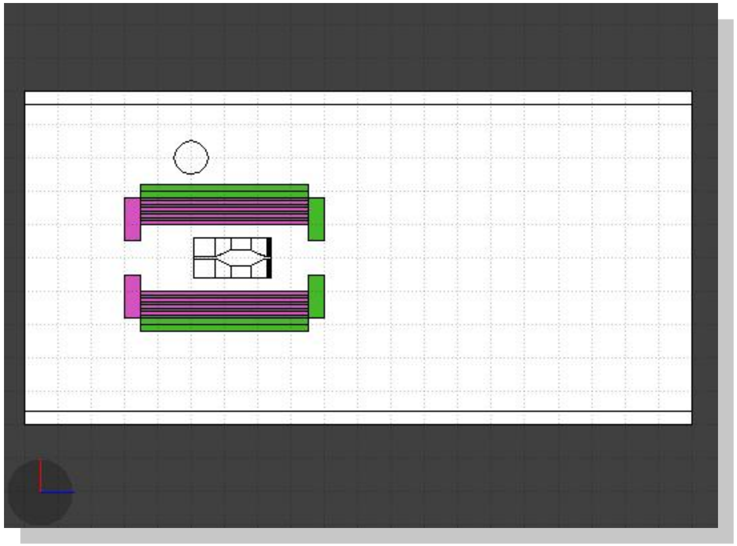
Target:
- Material : Titanium
- Cylinder : 78 cm x 1.5mm (Diameter)

Horn:
- Material : Anticorodal 110

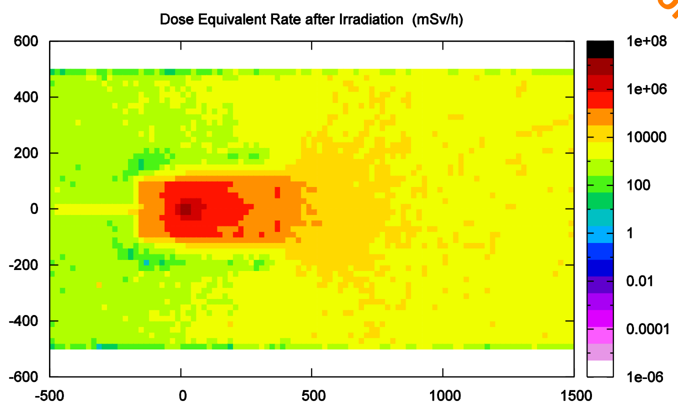
Shielding for the Target Station :
- Walls and roof: 80 cm of Iron,
  8 Slabs (2.5m x 2m x10cm)
- Lateral and Front Marble Slabs
- Front Iron Slab

⇒ Evolution of the DER with time performed with FLUKA 2011.2.3



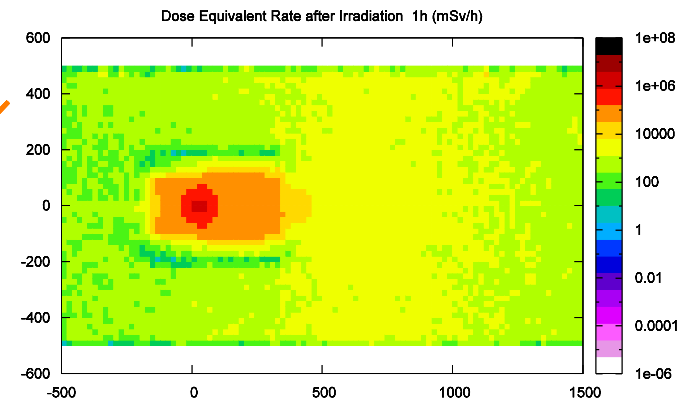


Radiation simulation : Shielding Investigation

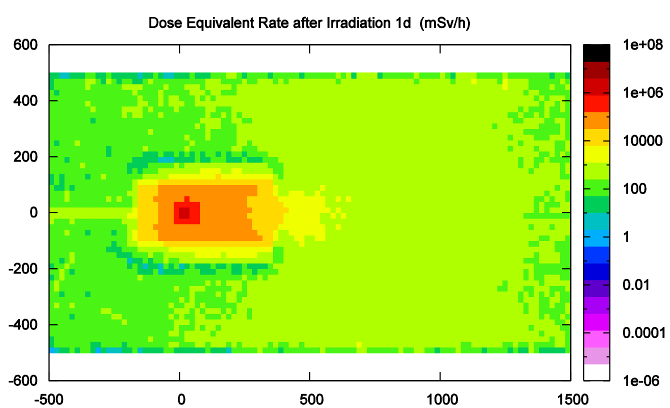


DER (mSv/h) after stopping irradiation

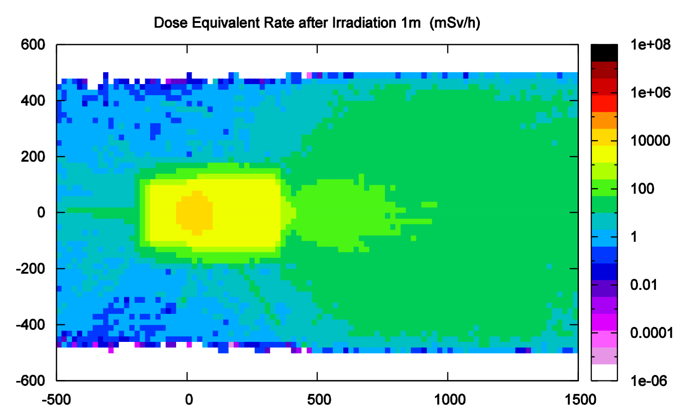
To be updated for ESSnSB



DER (mSv/h) after 1 hour of cooling time



DER (mSv/h) after 1 day of cooling time



DER (mSv/h) after 1month of cooling time

Radiations simulations : Four Horn Station

Chemical composition of Material:

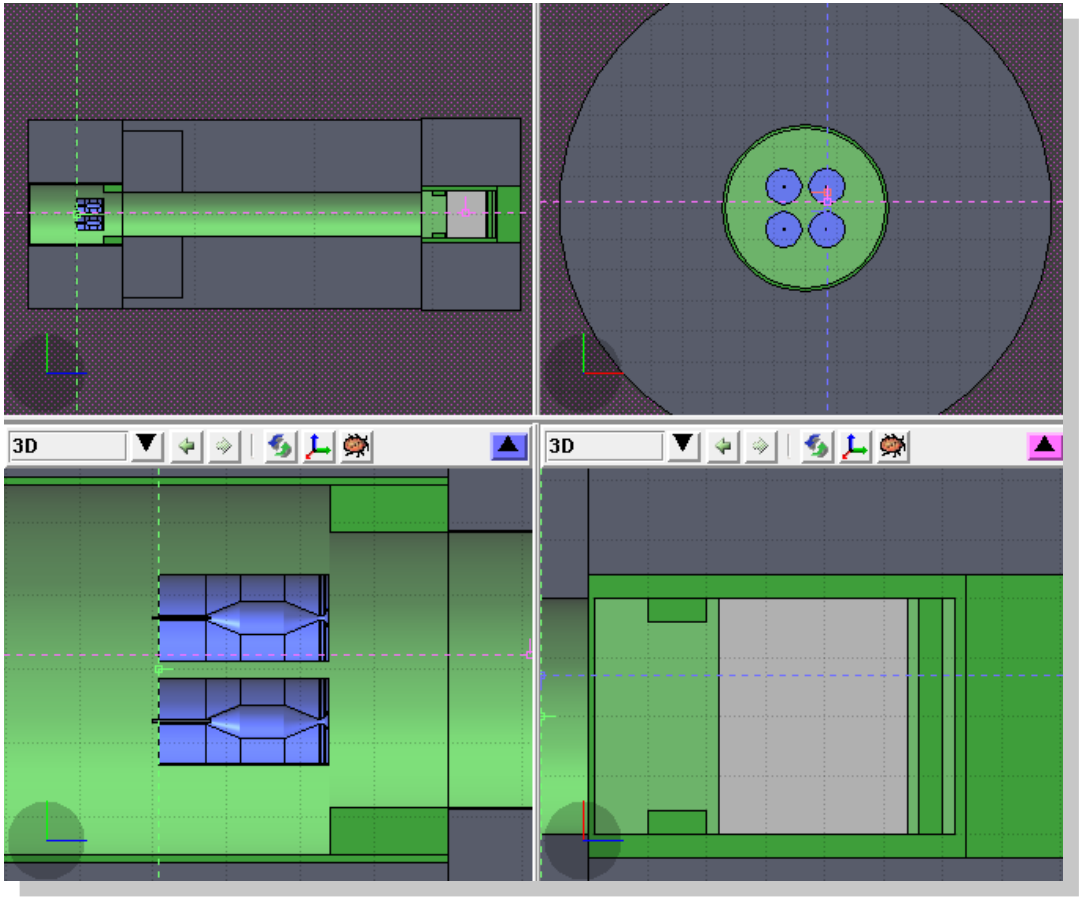
Target => Ti(100%)

Horn => Anticorodal 110 alloy
Al (95.5%), Si(1,3%), Mg(1,2%), Cr(0.2%), Mn(1%), Fe (0.5%), Zn(0.2%), Cu(0.1%)

Decay Pipe => Steel P355NH
Fe(96.8%), Mn(1.65%), Si(0.5%), Cr(0.3%), Ni(0.3%), C(0.2%)

Tunnel => Concrete
O(52.9%), Si(33.7%), Ca(4.4%), Al(3,49%), Na(1,6%), Fe(1.4%), K(1,3%), H(1%), Mn(0.2%), C(0.01%)

Surrounding Environment => Molasse
O(49%), Si(20%), Ca,(9.7%), Al(6.4%), C(5%), Fe(3.9%), Mg(3.2%), K(1%), Na(0.5%), Mn(0.1%)

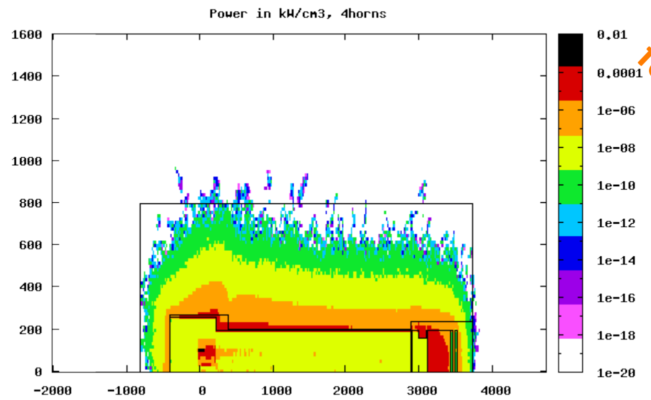


Four horn station layout

Simulations : Energy deposition for the Four Horn Station

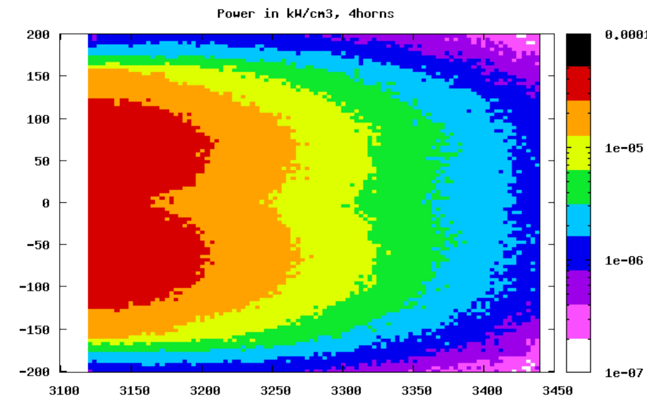
To be updated for ESSnSB

Transverse view



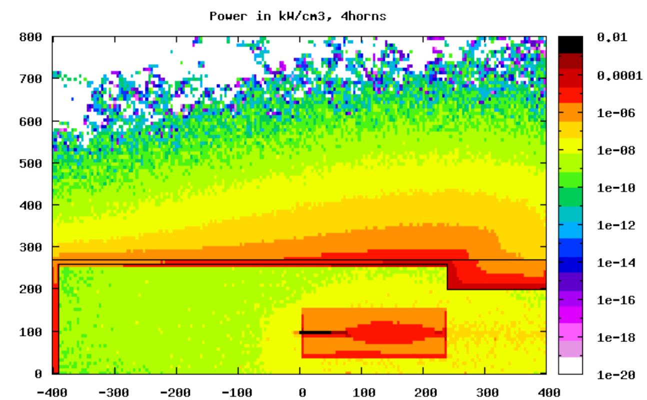
Energy deposition (kW/cm^3) in the all layout

Transverse view



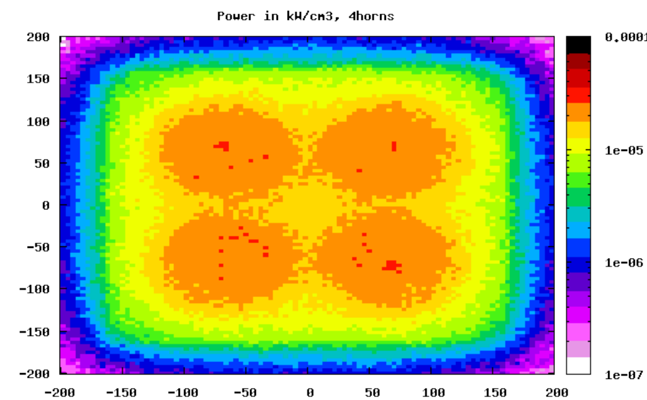
Beam dump energy deposition (kW/cm3)

Transverse view



Target station energy deposition (kW/cm3)

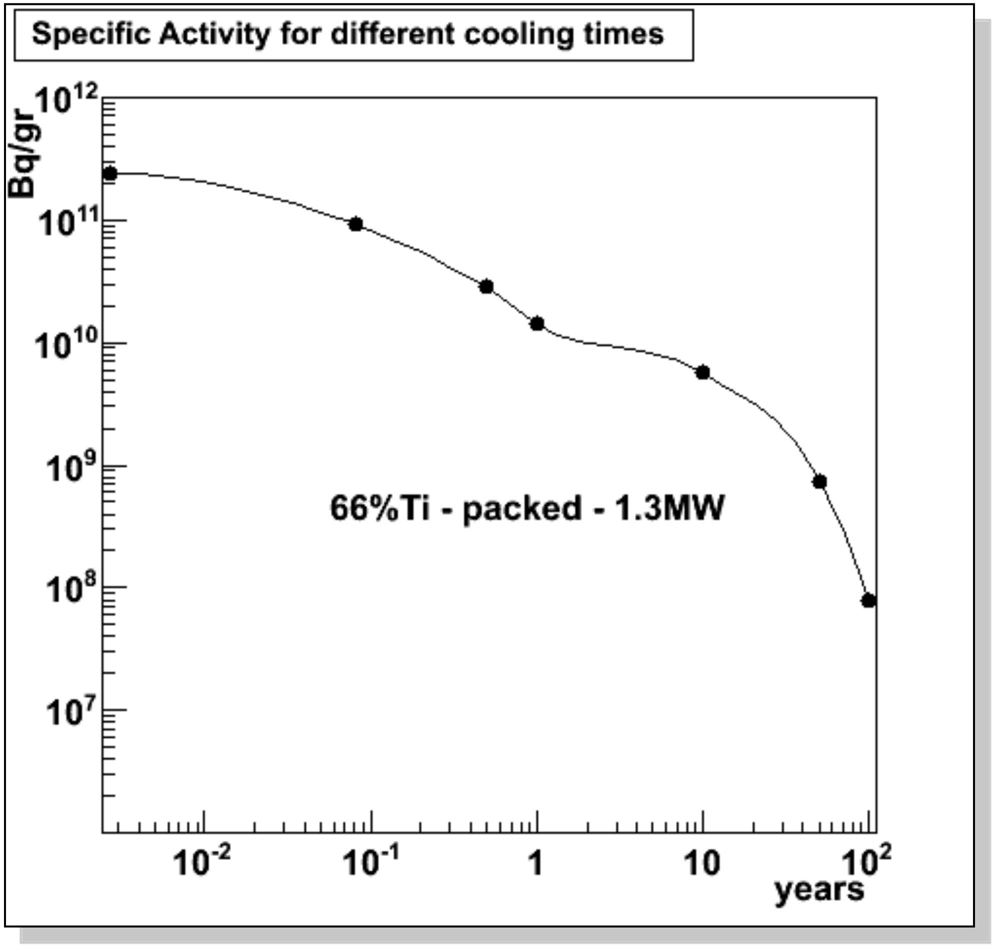
Front view

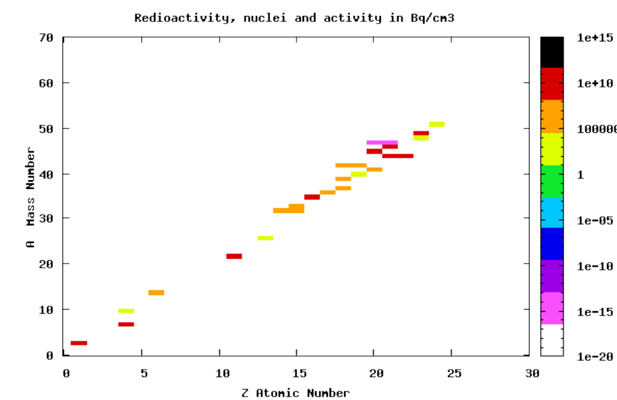


Beam dump energy deposition (kW/cm3)

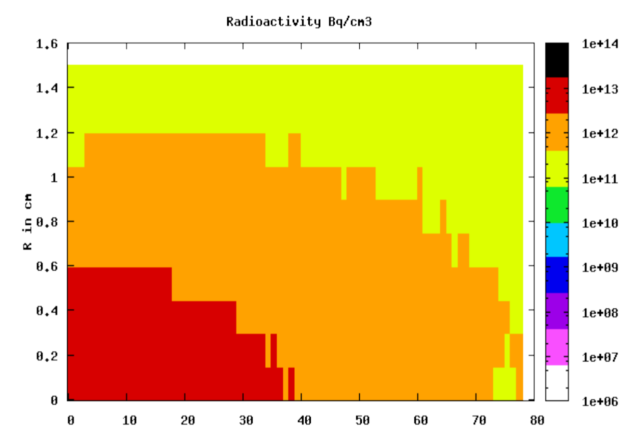
Radiations simulations : Four Horn Station

Evolution of the target activity with cooling time:





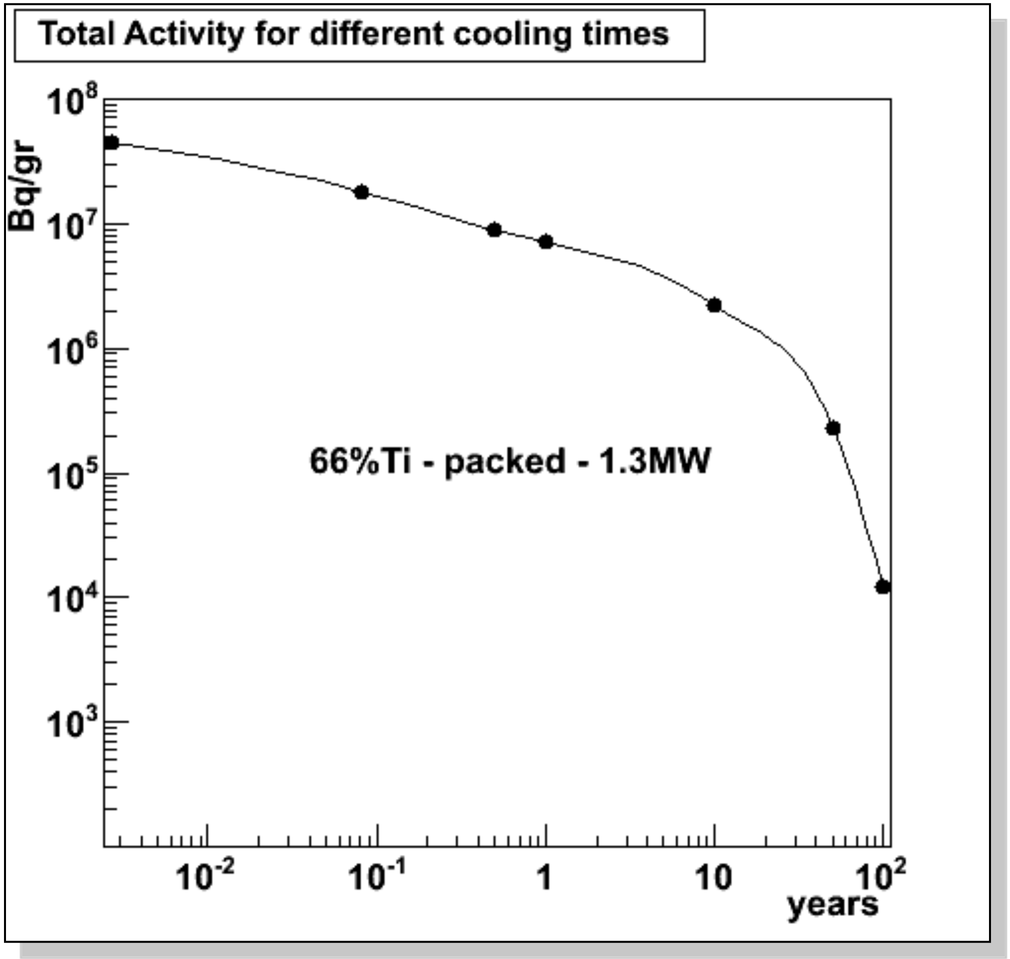
Radionucleides after 1 day (Z,A)

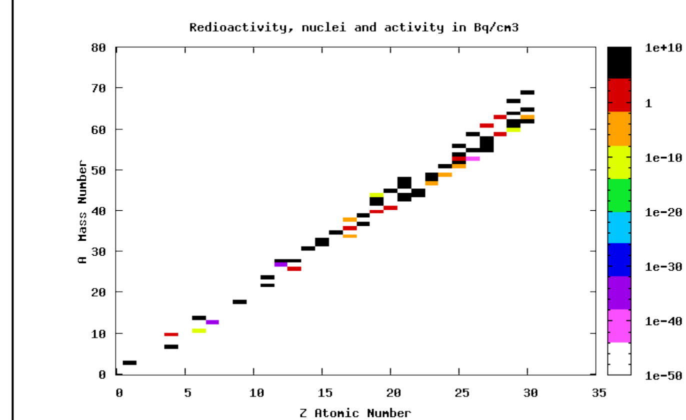


Radioactivity after 1 day (Bq.cm^{-3})

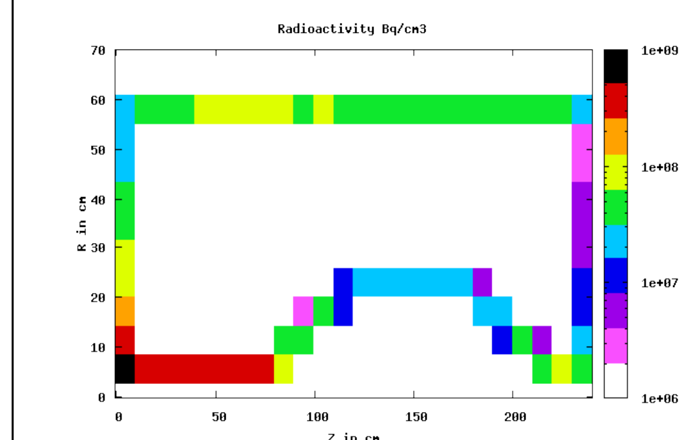
Radiations simulations : Four Horn Station

Evolution of the horn activity with cooling time:





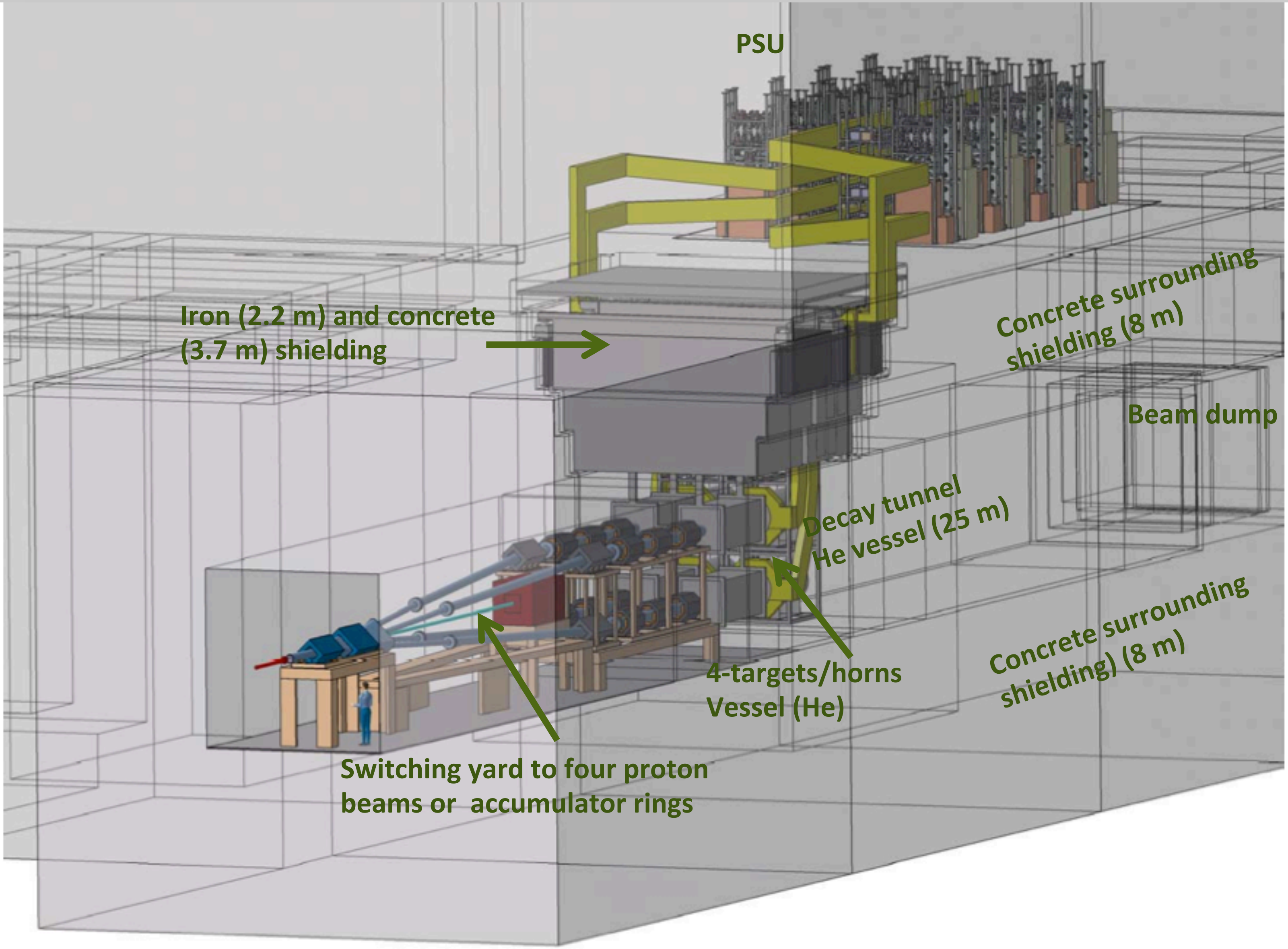
Radionucleides after 1 day (Z,A)



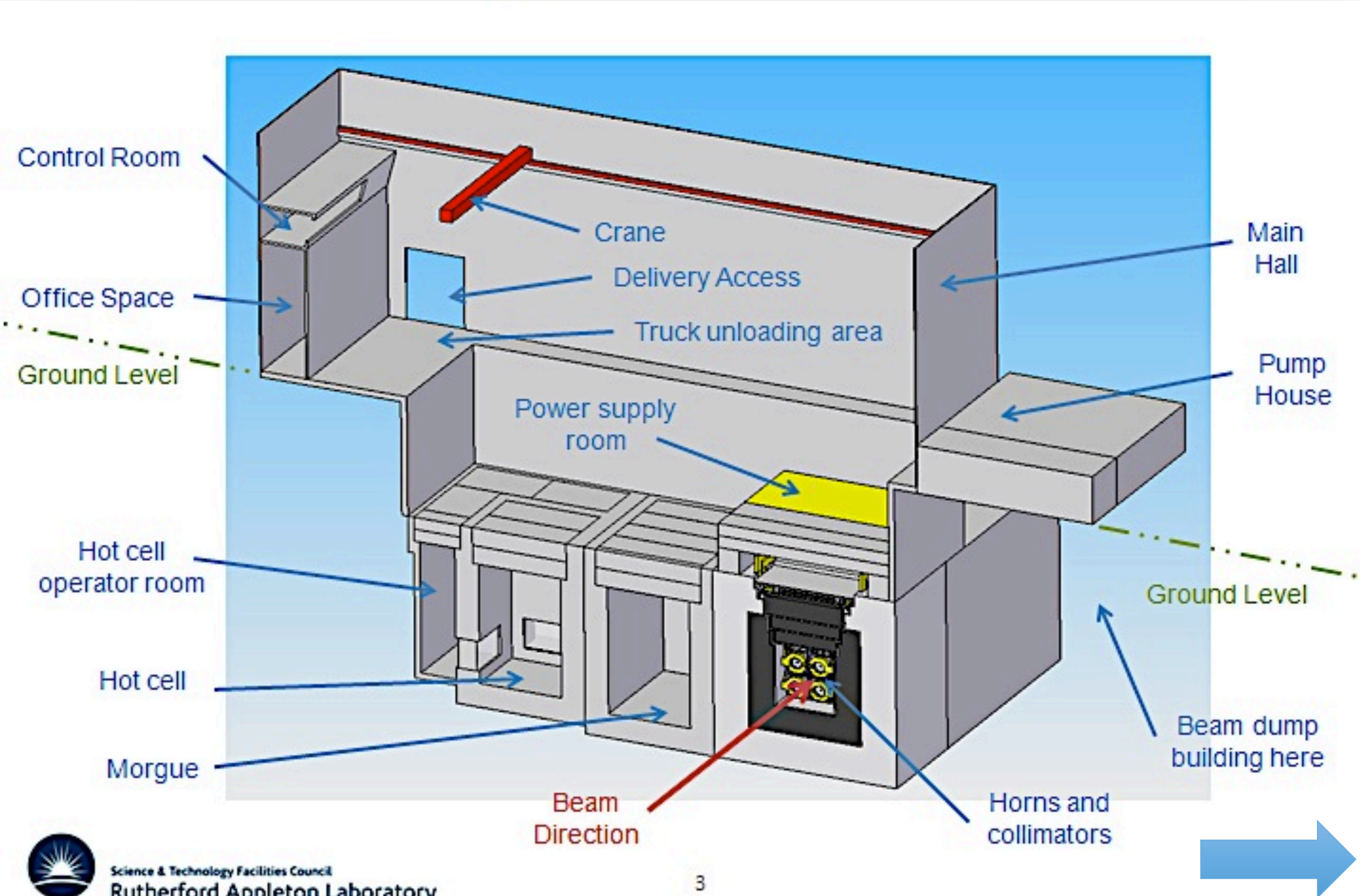
Radioactivity after 1 day (Bq.cm^{-3})

- *Targetry*
- *Horn/Collector*
- *Power Supply*
- *Shielding*
- **Layout**

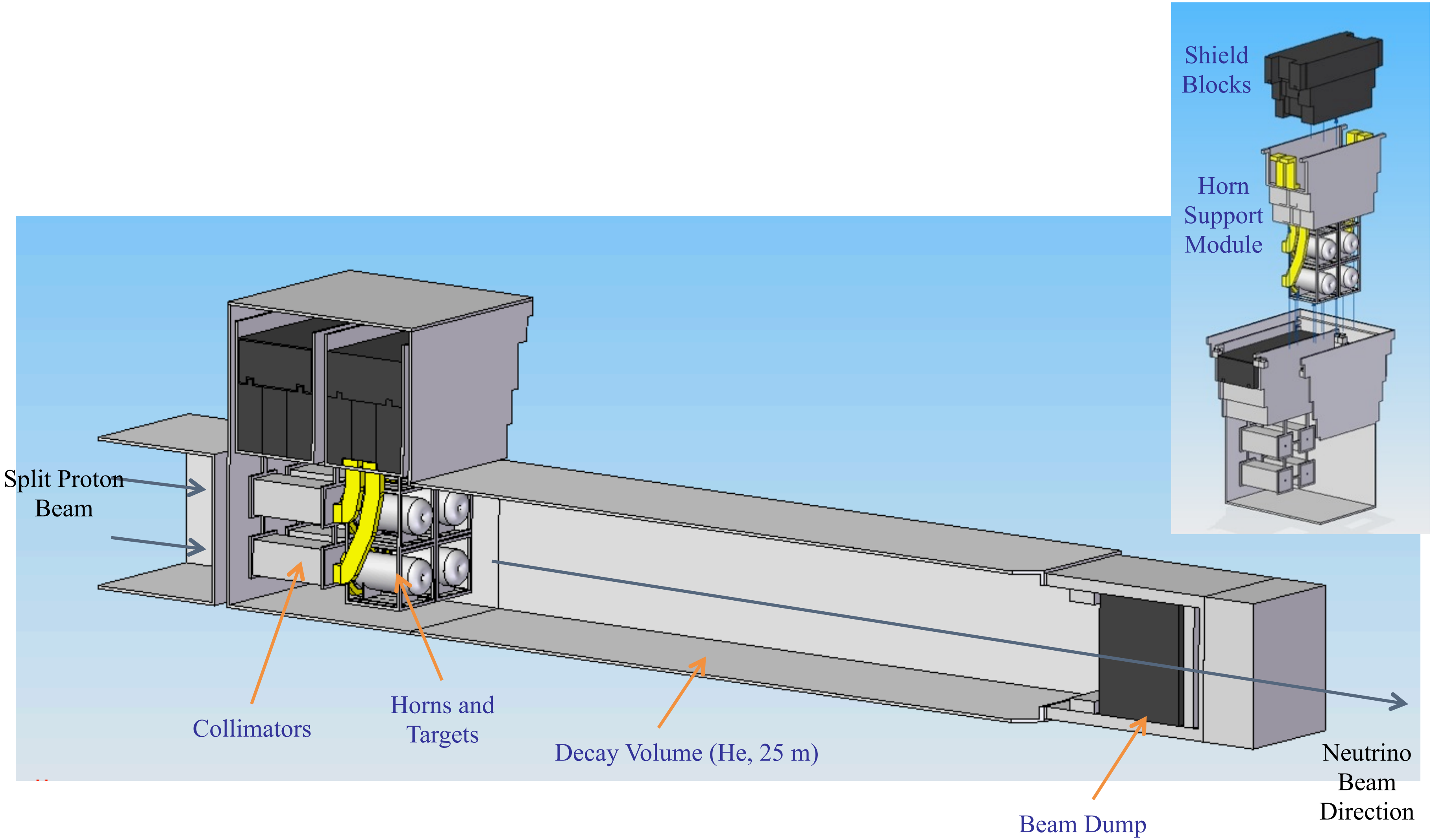
ESS Super beam layout
(adopted from EUROnu)



Super beam Four-horn/target station



General Layout



Thank you for your attention

This work was mainly done by:

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P. Poussot…

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also by:

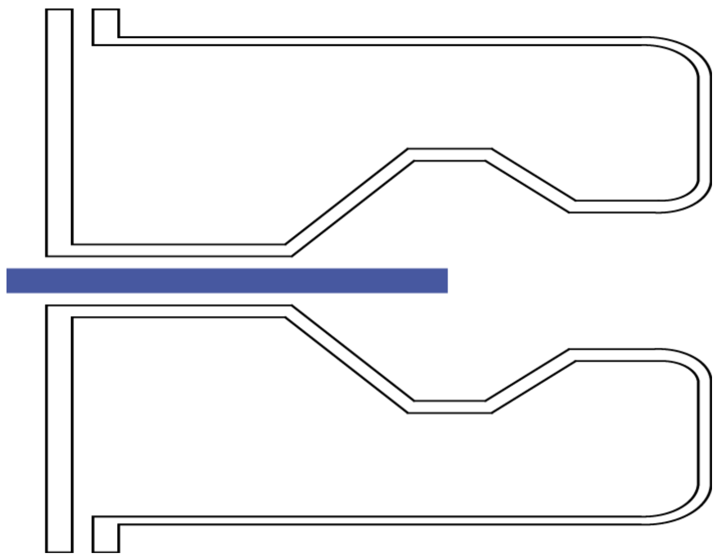
AGH

cea

Science & Technology Facilities Council Rutherford Appleton Laboratory

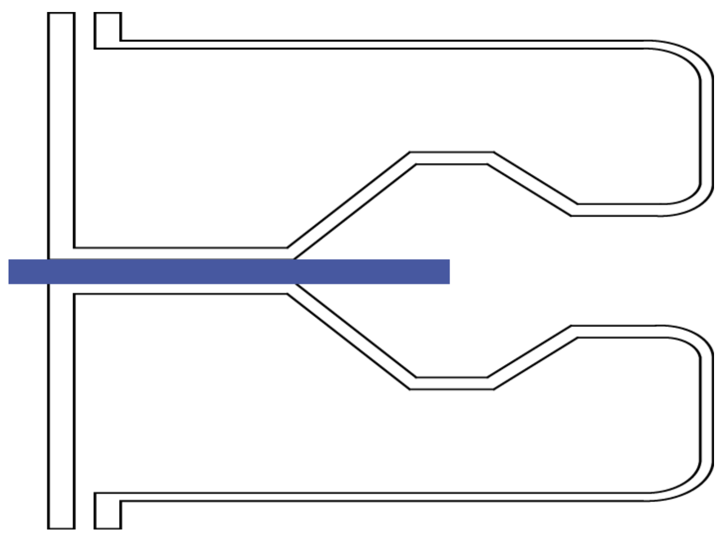
Back up

Cooling is a critical point



Separate target and horn

- easy target replacement
- cooling by gas He (probably not enough)
- supports have to be placed inside the horn to keep the target straight
- guides are needed for the target insertion
- relatively big horn inner cylinder (r~5 cm)



Integrated target and horn

- target replacement not possible
- cooling by water sprayers inside the horn
- the current will pass through the skin of the target (r~1.2 cm)
- magnetic field close to the target (better physics performance)
- no guiding system needed
- same material has to be used by the target and horn internal cylinder (Beryllium?)