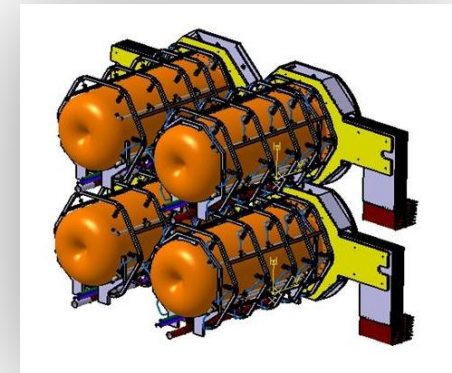
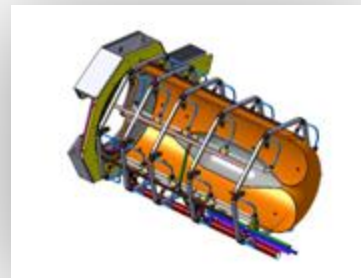
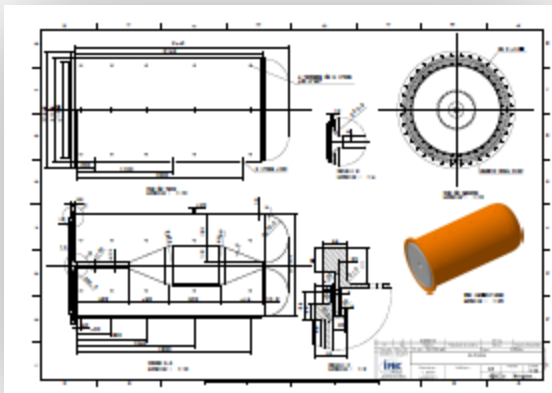




Horn design for the CERN to Fréjus neutrino Super Beam

Nikolas Vassilopoulos IPHC/CNRS

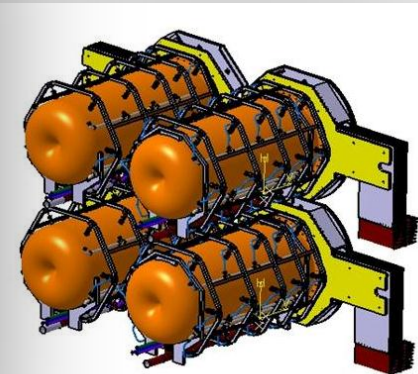
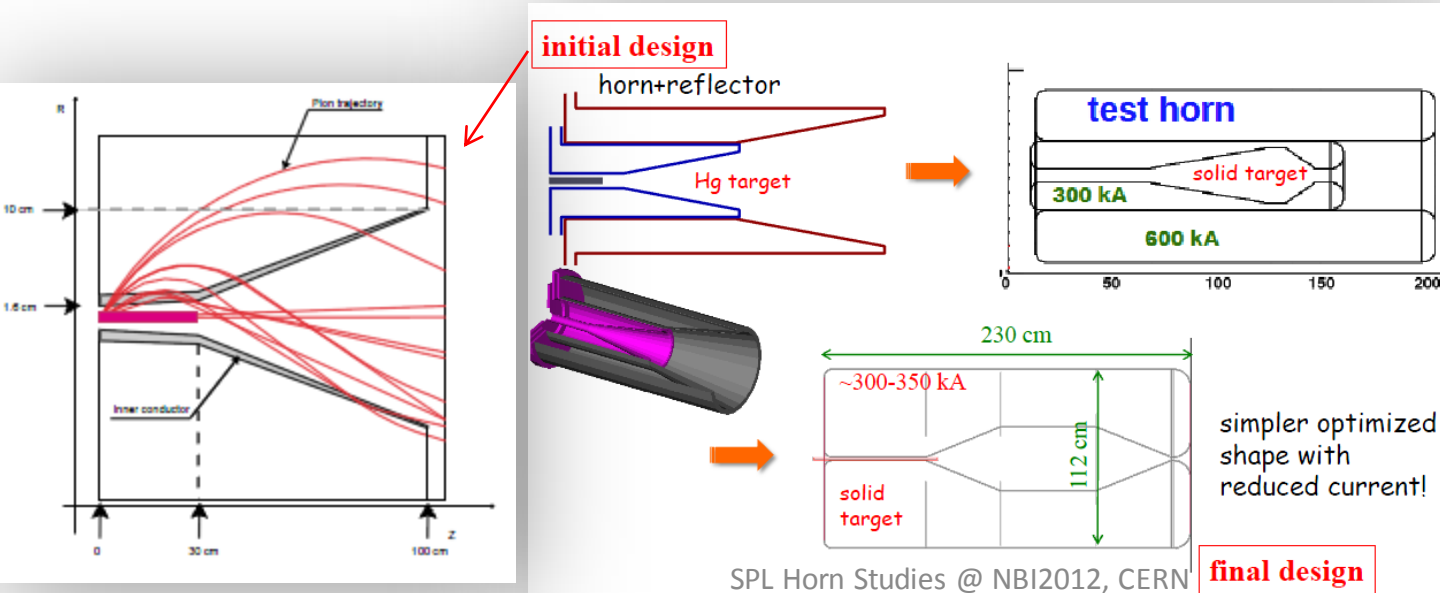
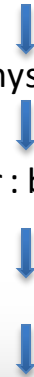


Horn evolution

details in WP2 notes @
<http://www.euronu.org/>

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



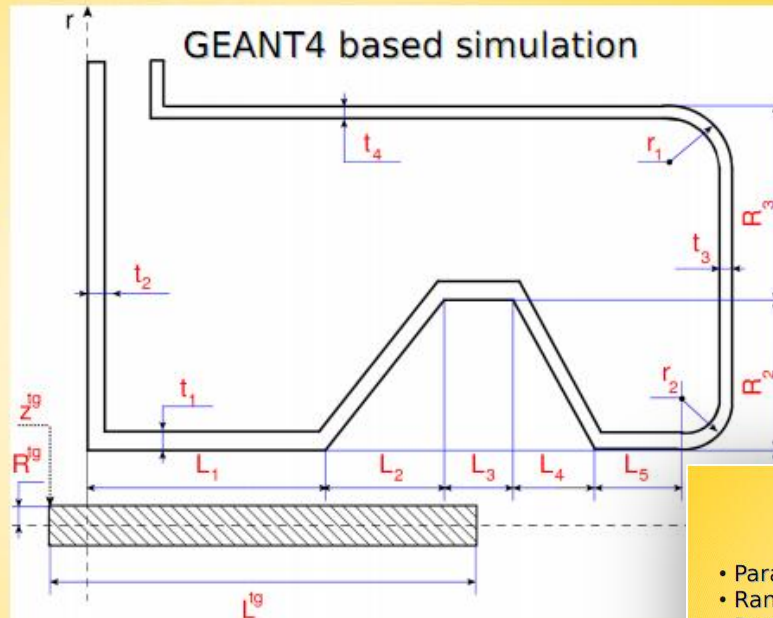
Horn shape and SuperBeam geometrical Optimization I

Horn geometrical model

à la MiniBoone
("forward closed")

large acceptance for
forward produced particles

This shape is well suited
for long targets



Good suppression of wrong charge pion
dangerous in "-" focusing mode due to
 ν_e from $\pi^+ \rightarrow \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ and $K^+ \rightarrow \pi^0 e^+ \nu_e$

← EUROnu-WP2 note 05

A. Longhin

Third EUROnu annual meeting, RA

Optimization strategy

- Parametric model of magnetic horns
- Random sampling of parameters
- Ranking of configurations based on achievable θ_{13} limits

Figure of merit: $\lambda \equiv$
 θ_{13} sensitivity limit at 99% C.L. averaged over the δ_{CP} phase

$$\lambda = \frac{10^3}{2\pi} \int_0^{2\pi} \lambda_{99}(\delta_{CP}) d\delta_{CP}$$

We want as
low as
possible λ

- Broad sampling of the (many) parameters to identify the most relevant variables. Then restrict the ranges of variation and iterate.

→

A. Longhin

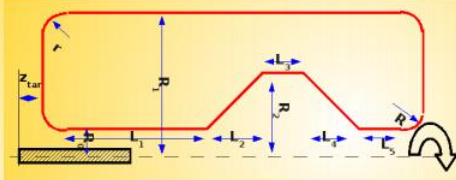
Third EUROnu annual meeting, RAL 19 Jan 2011

- parameterise the horn and the other beam elements as decay tunnel dimensions, etc...
- parameters allowed to vary independently
- minimize the δ_{cp} -averaged 99% CL sensitivity limit on $\sin^2 2\theta_{13}$

Horn Shape and SuperBeam geometrical Optimization II

Broad scan

Allow parameters to vary independently

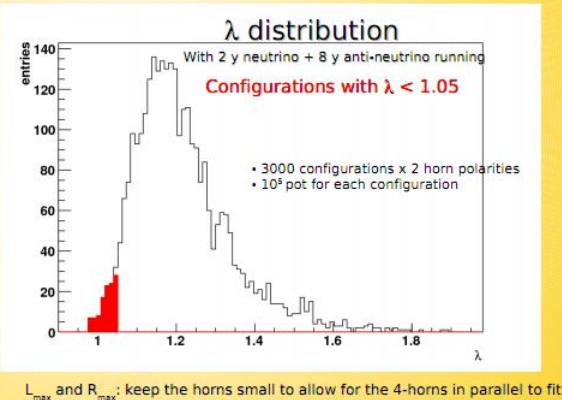


6

Limit	value
L_{max}	250 cm
R_{max}	80 cm
R_{min}	1.2 cm

Parameter	Interval
L_1	$[50, L_{max}]$ cm
L_2, L_3, L_4	$[1, L_{max}]$ cm
L_5	$[1, 15]$ cm
R, R_1, R_2	$[R_{min}, R_{max}]$
R_0	$[R_{min}, 4]$ cm
z_{tar}	$[-30, 0]$ cm
L_{tun}	$[35, 45]$ m
r_{tun}	$[1.8, 2.2]$ m

Parameter	Value
L_{tar}	0.78 m
r_{tar}	1.5 cm
i	300 kA
s	3 mm
r	5.08 cm

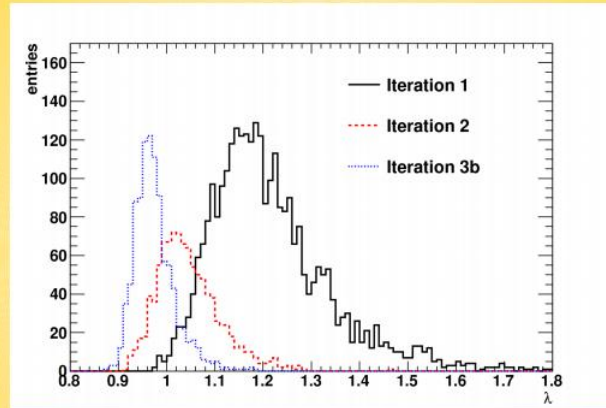


A. Lonohin

Third EUROnu annual meeting, RAL 19 Jan 2011

fix & restrict parameters then re-iterate for best horn parameters & SuperBeam geometry

Converging to better limits



- broad parameters' scan
- restricted intervals for effective parameters \rightarrow horn with min λ
- vary tunnel parameters in L [15-35] m r [1.5-4.5] m

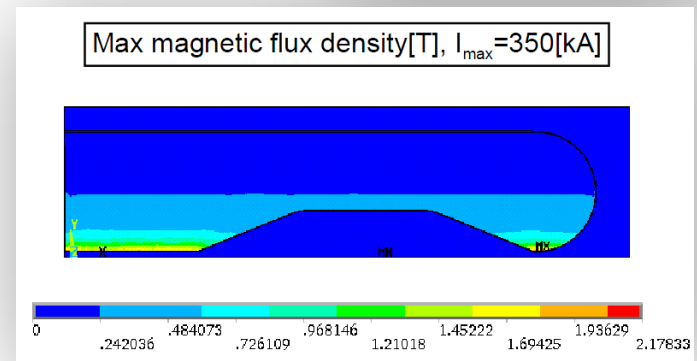
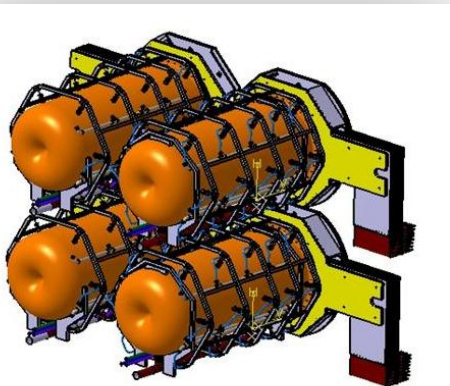
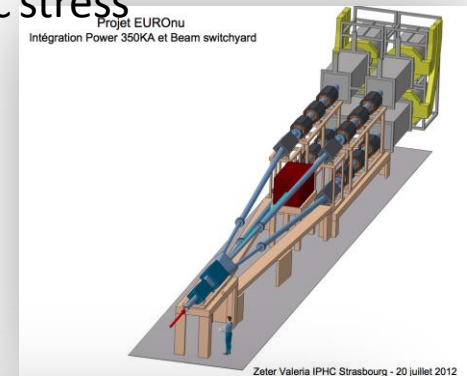
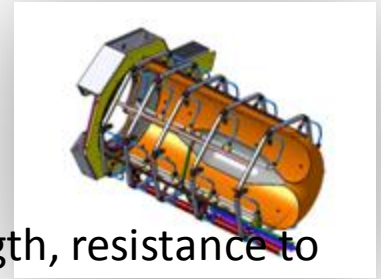
A. Lonohin

Third EUROnu annual meeting, RAL 19 Jan 2011

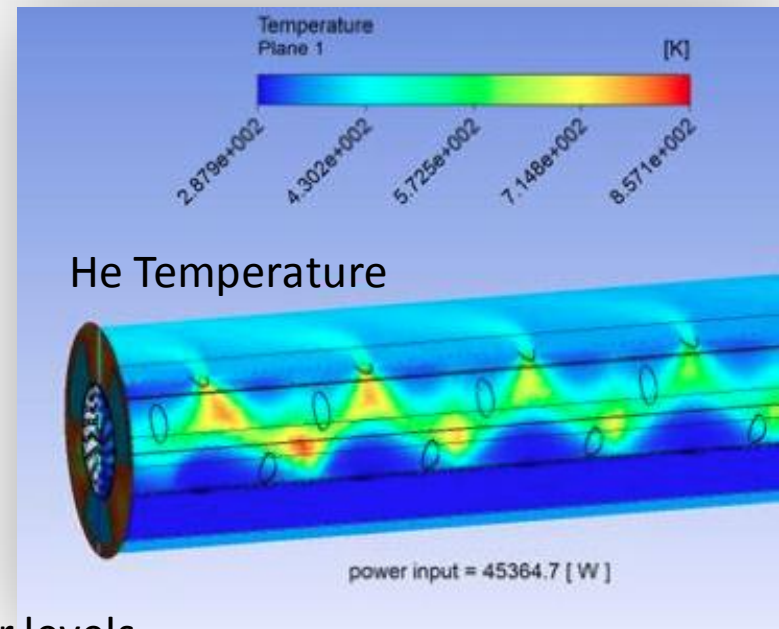
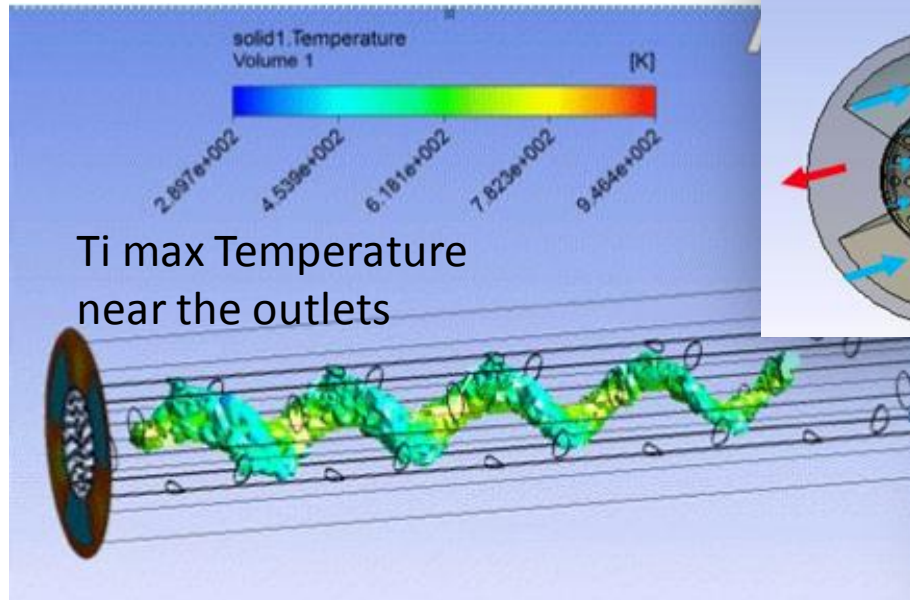
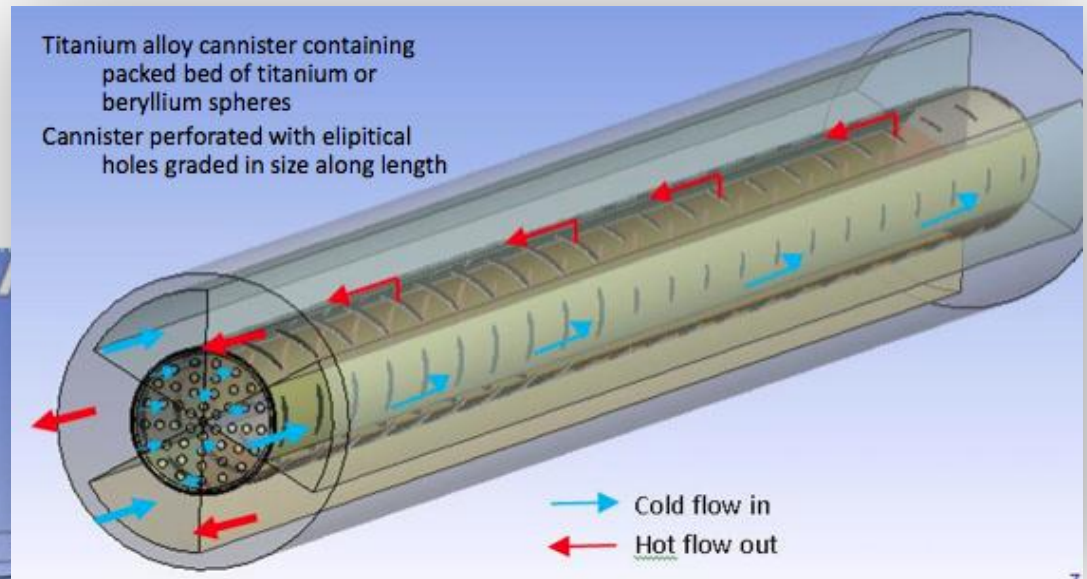
Parameters	value [mm]
L_1, L_2, L_3, L_4, L_5	589, 468, 603, 475, 10.8
t_1, t_2, t_3, t_4	3, 3, 3, 3
r_1, r_2	108
r_3	50.8
R^{tg}	12
L^{tg}	780
z^{tg}	68
R_2, R_3	191, 359
R_1 combined	12
R_1 separate	30

Horn Stress 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
 - ✓ static mechanical model, thermal dilatation
 - ✓ magnetic pressure pulse, dynamic displacement
 - ✓ COMSOL, ANSYS software
- cooling
 - ✓ water jets



Packed-bed target



- Large surface area for heat transfer
- Coolant able to access areas with highest energy deposition
- Minimal stresses
- Potential heat removal rates at the hundreds of kW level
- Pressurised cooling gas required at high power levels

Energy Deposition from secondary particles @1.3 MW

target $Ti=65\%d_{Ti}$, $R_{Ti}=1.5cm$

36kW, $t=30mm$

8.6kW,
 $t=35mm$

9.5kW

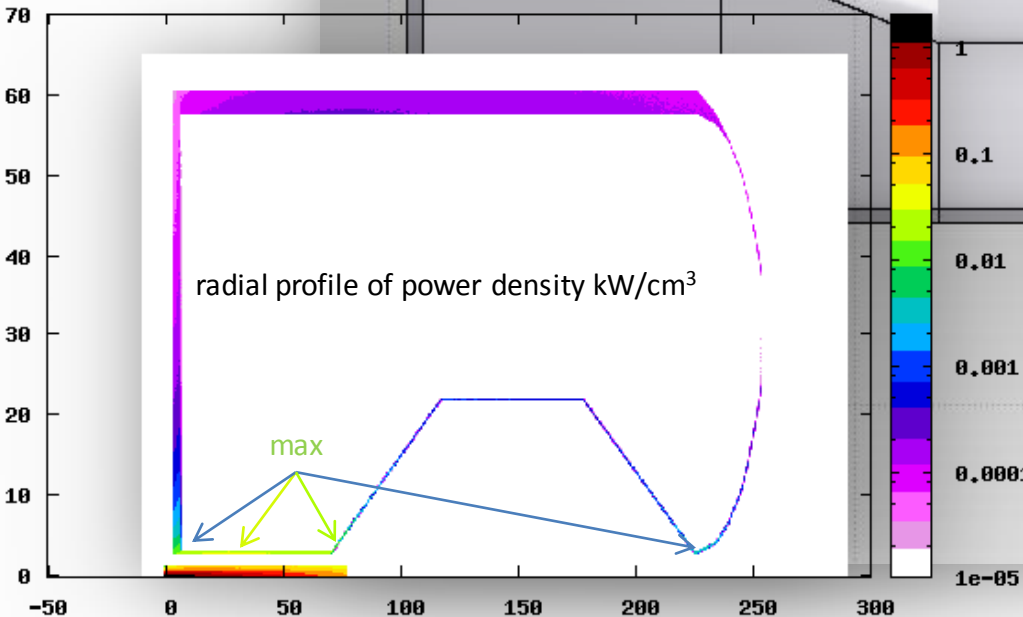
2.4kW

1.7kW

1.3kW

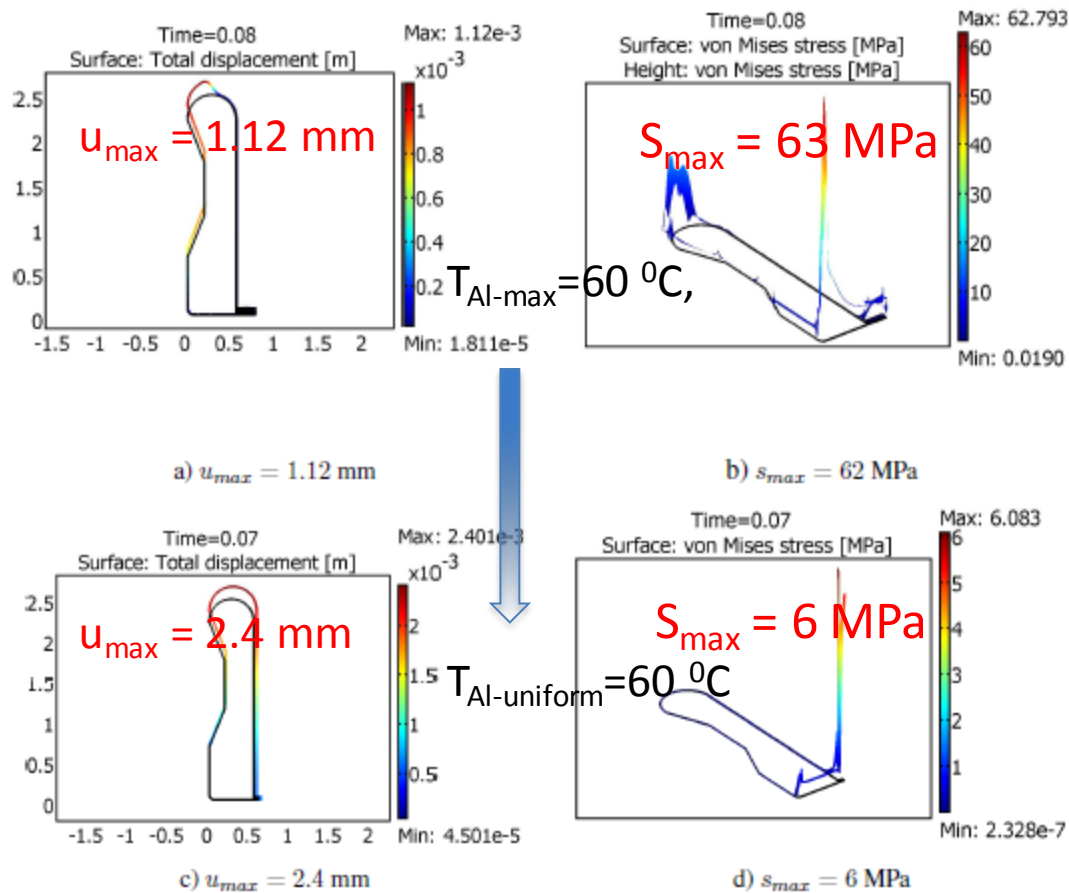
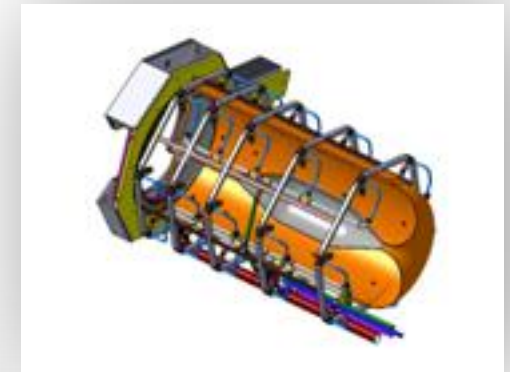
2.5kW

Energy deposition in kW/cm³



Stress Analysis

- Thermo-mechanical stresses:
 - ✓ secondary particles energy deposition and joule losses
 - ✓ $T=60\text{ms}$, (worst scenario, 1 horn failed), $\tau_{01}=100\mu\text{s}$, electrical model: $I_0 = 350\text{kA}$, $f=5\text{kHz}$, $I_{\text{rms}}=10.1\text{kA}$



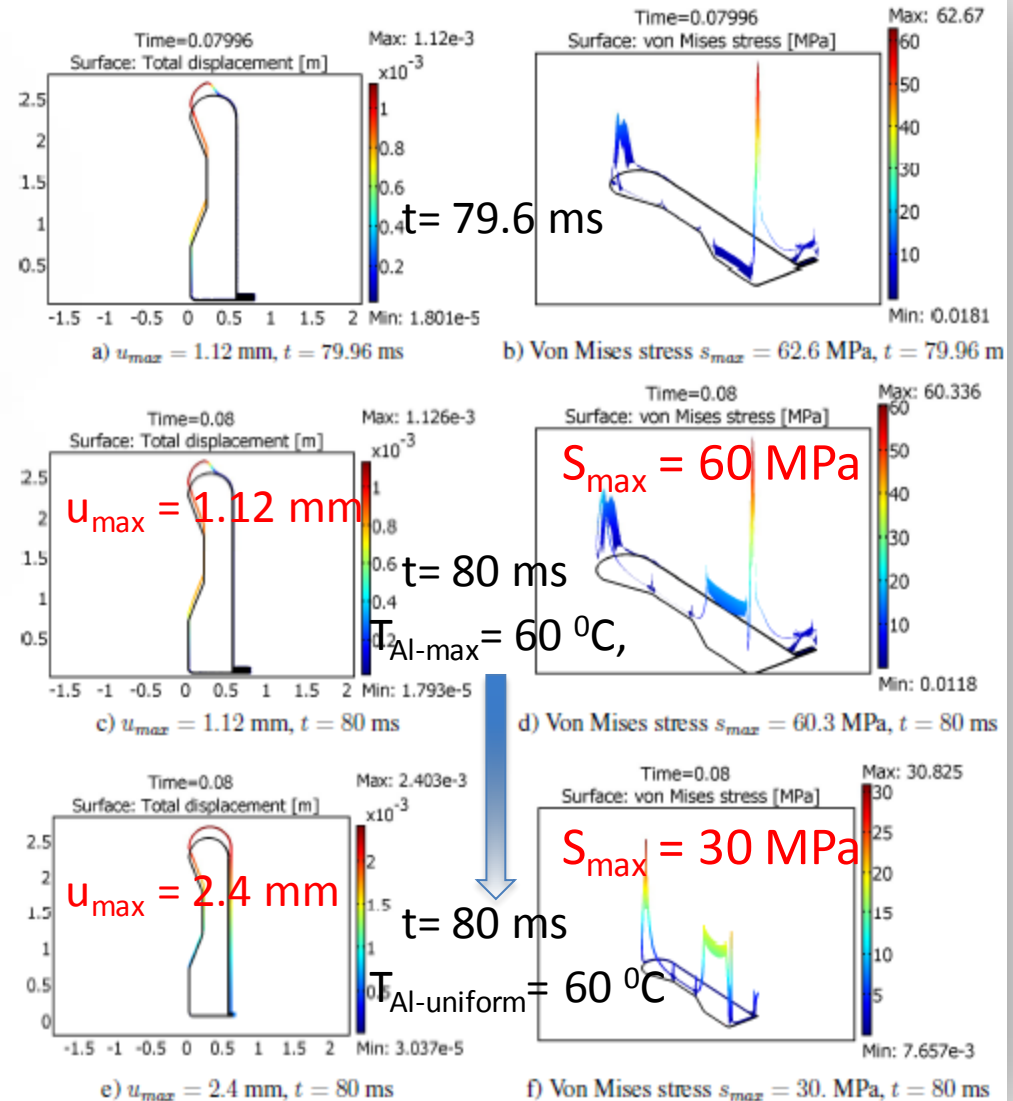
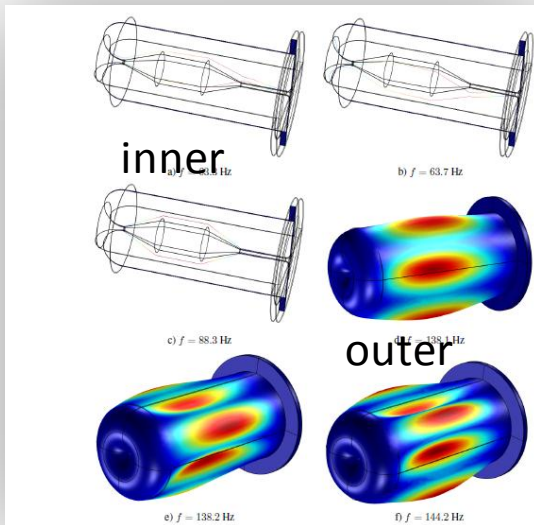
stress minimized when horn has uniform temperature



G. Gaudiot, B. Lepers,
F. Osswald, V. Zeter/IPHC,
P. Cupial, M. Koziem, L. Lacny,
B. Skoczen *et al.* /Cracow Univ. of Tech.

Stress due to thermal dilatation and magnetic pressure

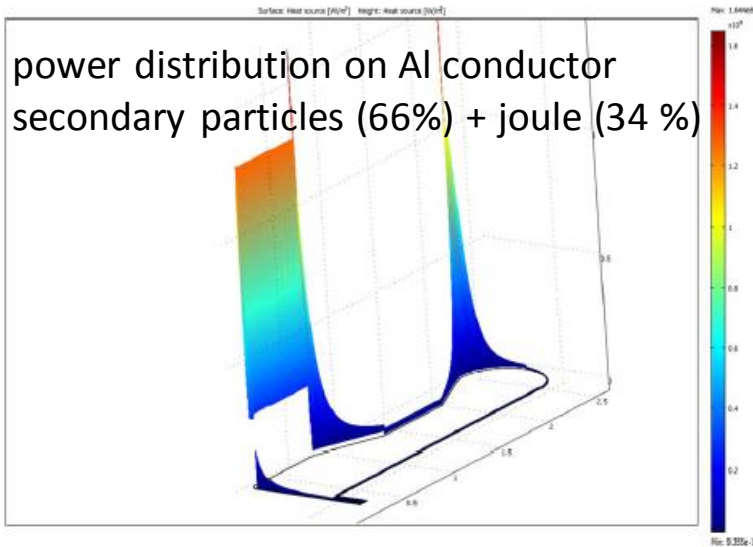
- displacements and stress plots just before and on the peak
 - ✓ stress on the **corner** and **convex** region
 - ✓ stress on **the upstream inner** due to pulse
 - ✓ uniform temperature minimizes stress
-
- modal analysis, eigenfrequencies
- $f = \{63.3, 63.7, 88.3, 138.1, 138.2, 144.2\}$ Hz



peak magnetic field each $T=80$ ms (4-horns operation)

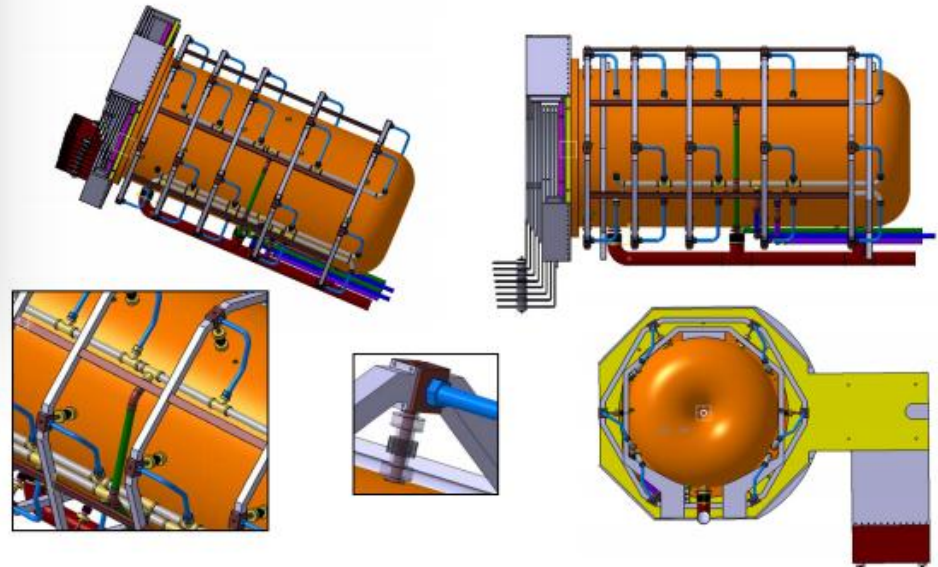
Horn cooling

power distribution on Al conductor
secondary particles (66%) + joule (34 %)



Projet EUROnu
La Corne

L'ensemble de la Corne



IPHC Strasbourg 02/05/2011

Valeria Zeter

cooling system

- planar and/or elliptical water jets
- 30 jets/horn, 5 systems of 6-jets longitudinally distributed every 60°
- flow rate between 60-120l/min, h cooling coefficient 1-7 kW/(m²K)
- longitudinal repartition of the jets follows the energy density deposition
- $\{h_{\text{corner}}, h_{\text{horn}}, h_{\text{inner}}, h_{\text{convex}}\} = \{3.8, 1, 6.5, 0.1\}$ kW/(m²K) for $T_{\text{Al-max}} = 60$ °C

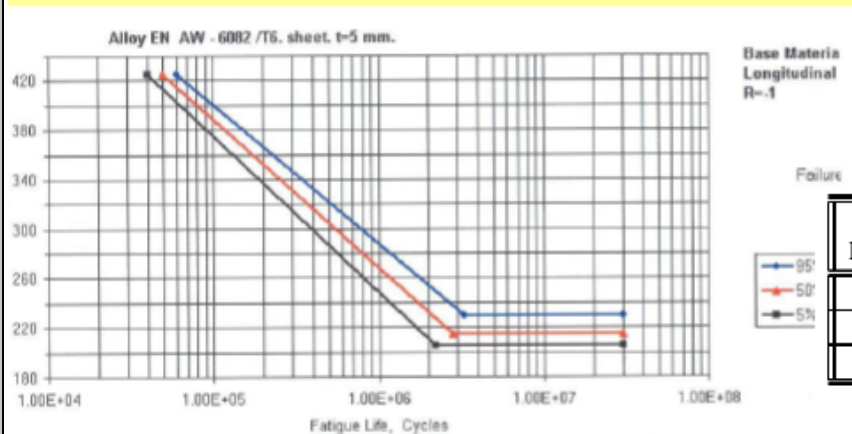
horn lifetime

lower than 60 MPa expected

Horn response under pulse magnetic forces

SINGLE PULSE with static thermal stress SVM=102.5 MPa and maximal magnetic stress SMAX=41 MPa – estimated life time

S-N curve - probability	Life time [s]		
	Rayleigh	Dirlik	Benasciutti-Tovo
95%	2.7076e+007	8.6147e+007	7.9627e+007
50%	6.0195e+006	1.8589e+007	1.7026e+007
5%	2.1816e+006	6.5918e+006	6.0132e+006



NUMBER OF PULSES
Dirlik model
 $f = 12.5 \text{ Hz}$

highly conservative

S-N CURVE PROBABILITY	LIFE TIME [s]	NUMBER OF PULSES
95 %	$8.6 \cdot 10^7$	$1.08 \cdot 10^9$
50 %	$1.9 \cdot 10^7$	$2.38 \cdot 10^8$
5 %	$6.6 \cdot 10^6$	$8.25 \cdot 10^7$

$1.25 \cdot 10^8$ pulses = 200 days = 1 year

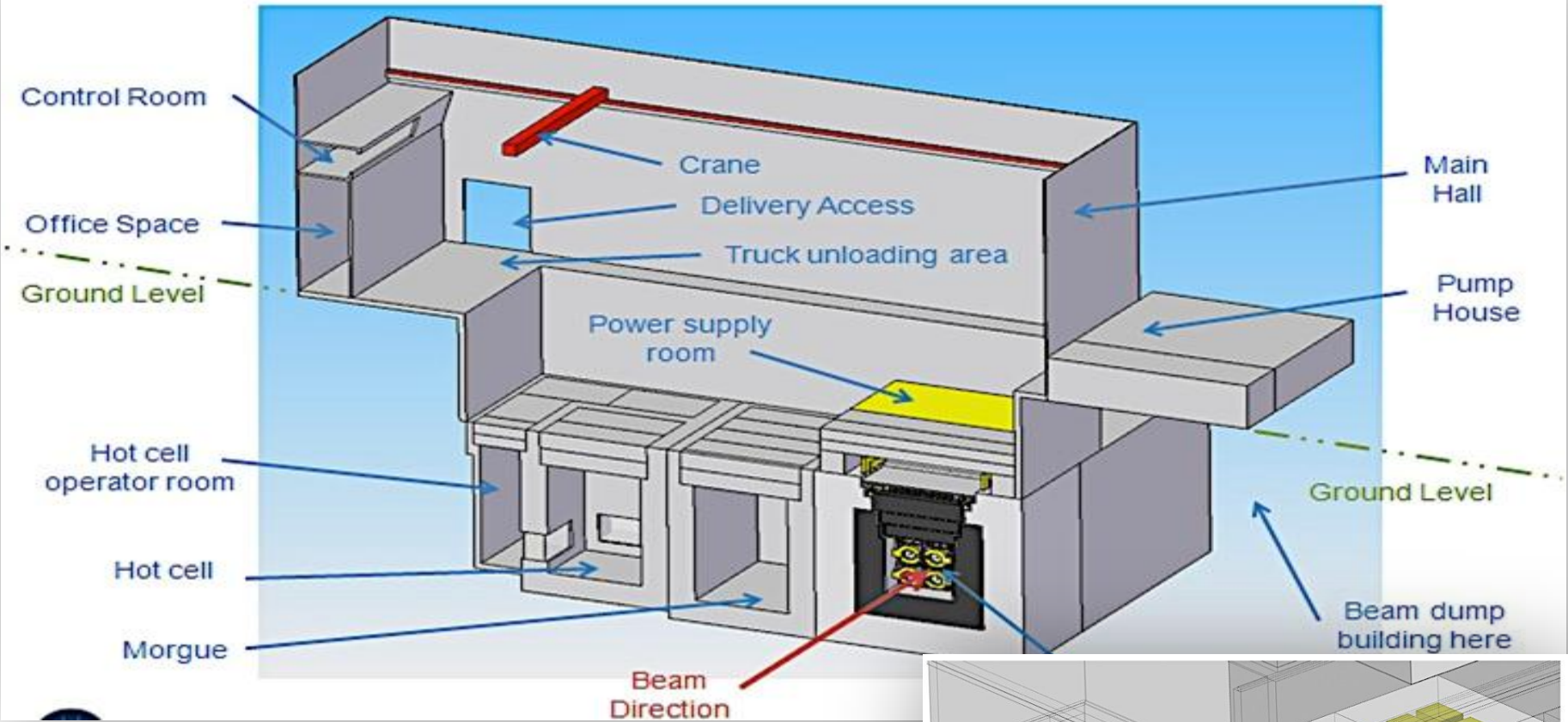
M.S.Kozień

Fourth EUROnu Annual Meeting , June 12-15, 2012, APC, Paris

A.Niesłony

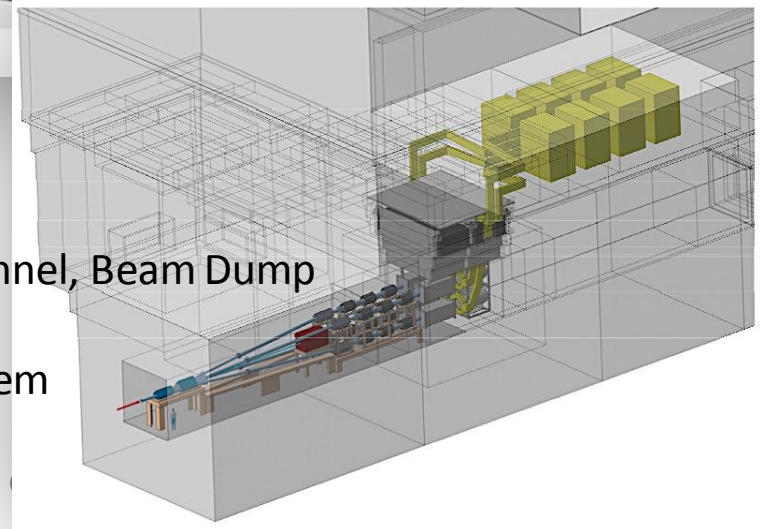
12/13

Target station, service galleries

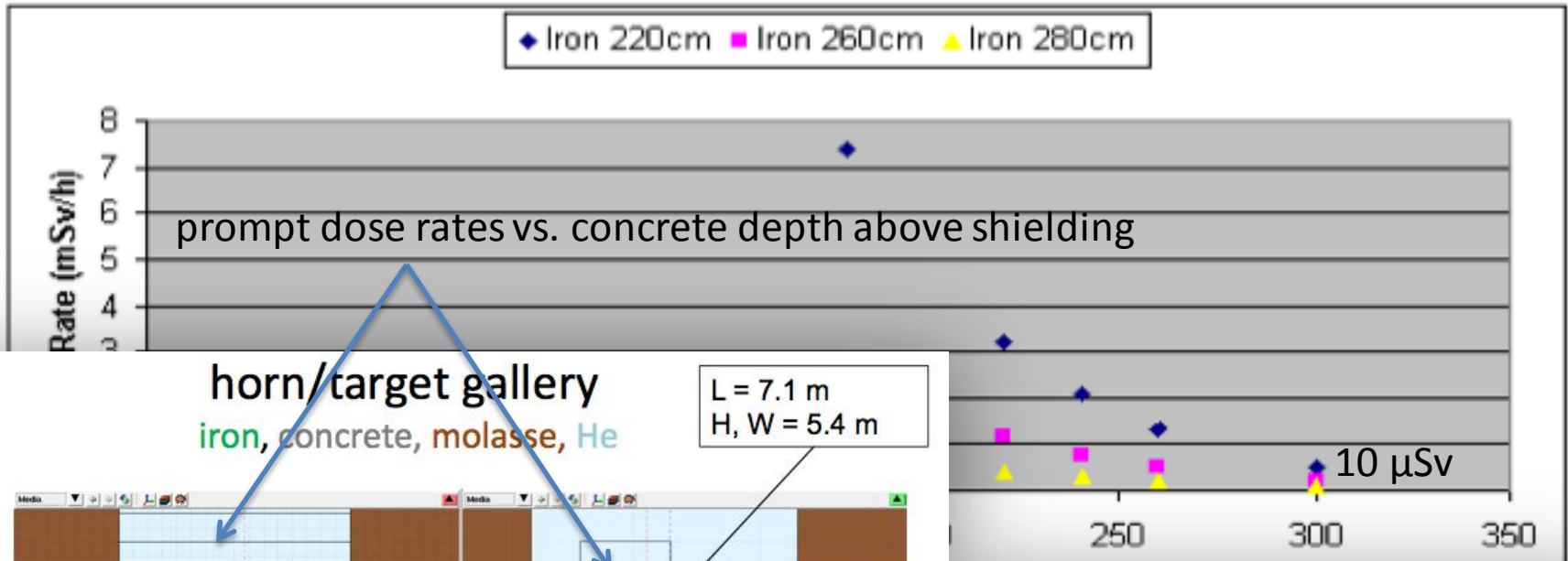


Design includes:

- Proton Driver line
- Experimental Hall: 4 MW Target Station, Decay Tunnel, Beam Dump
- Maintenance Room
- Power supply, Cooling system, Air-Ventilation system
- Waste Area



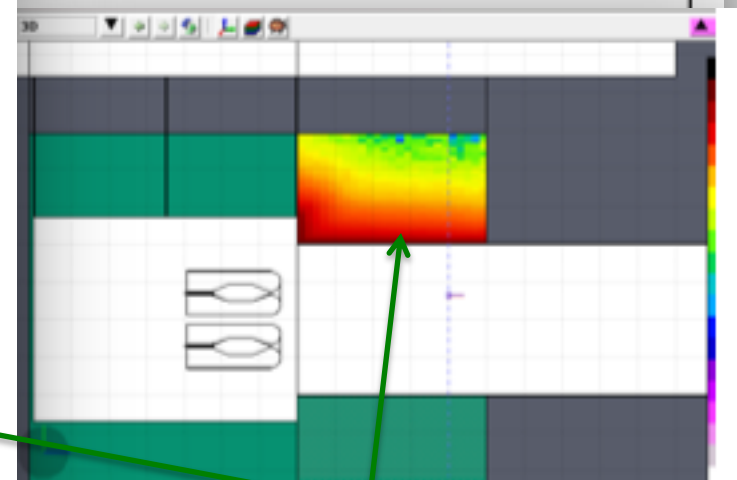
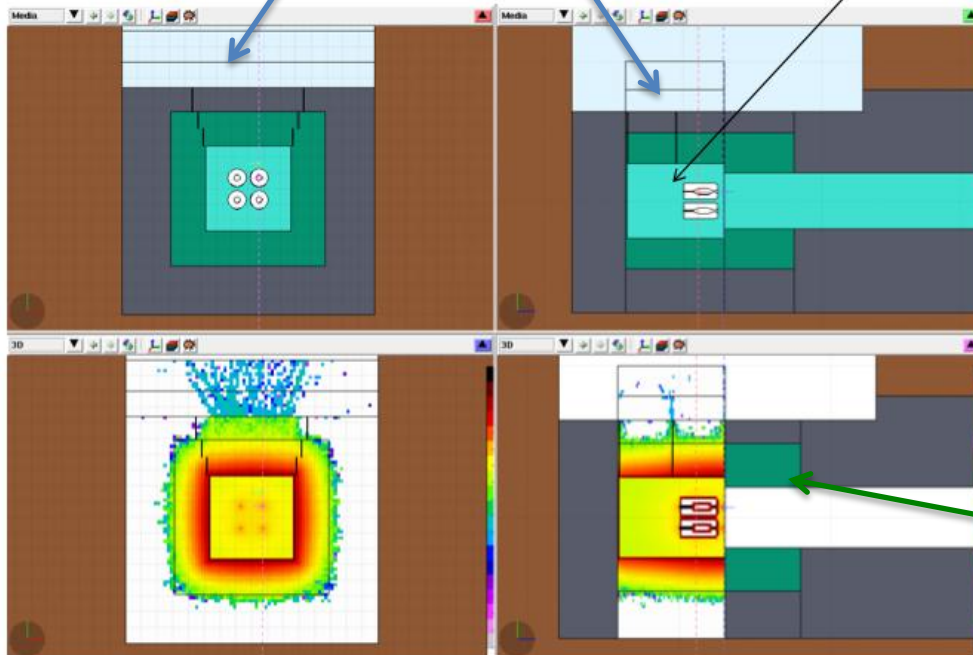
Radiation Studies for horn/target gallery



horn/target gallery

iron, concrete, molasse, He

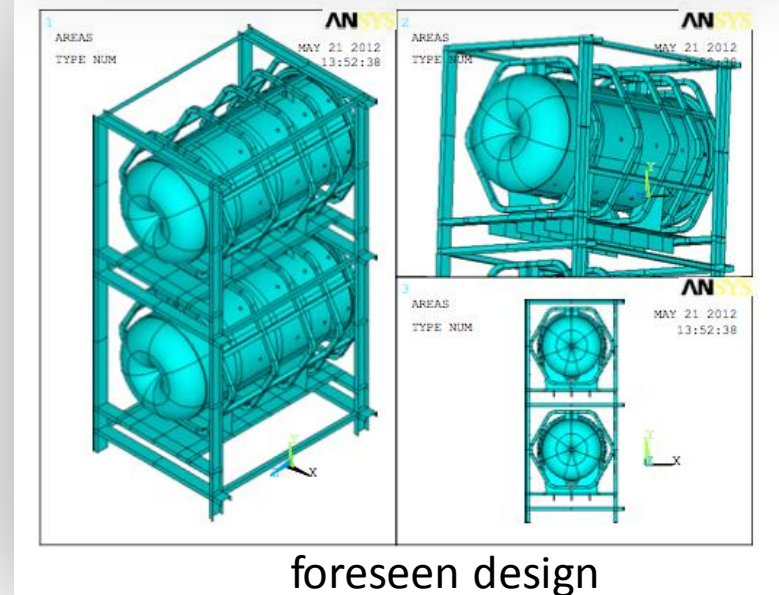
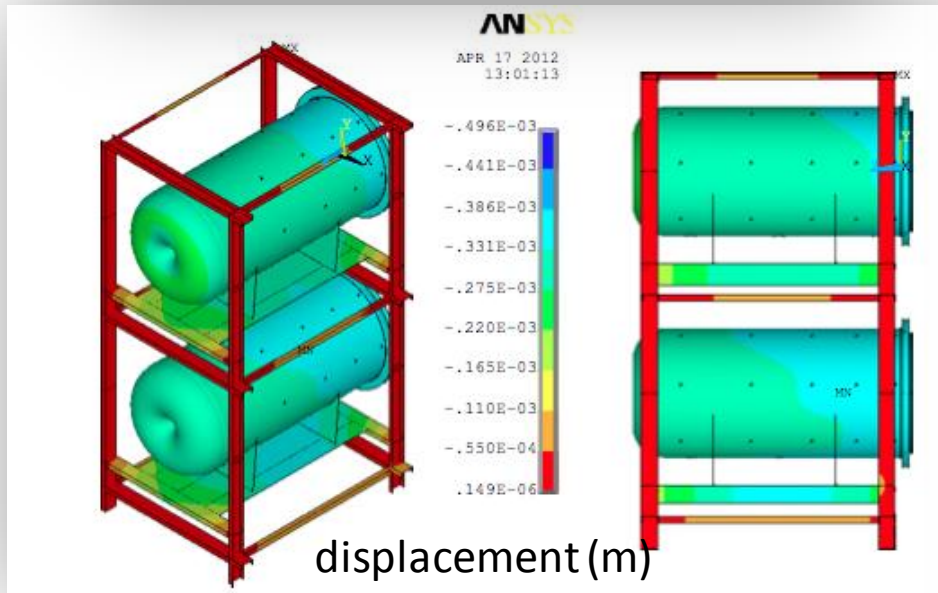
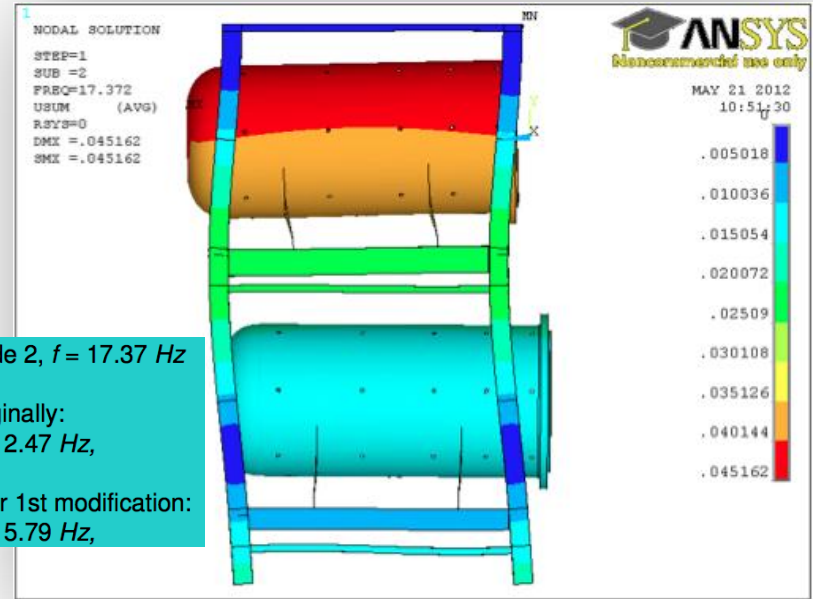
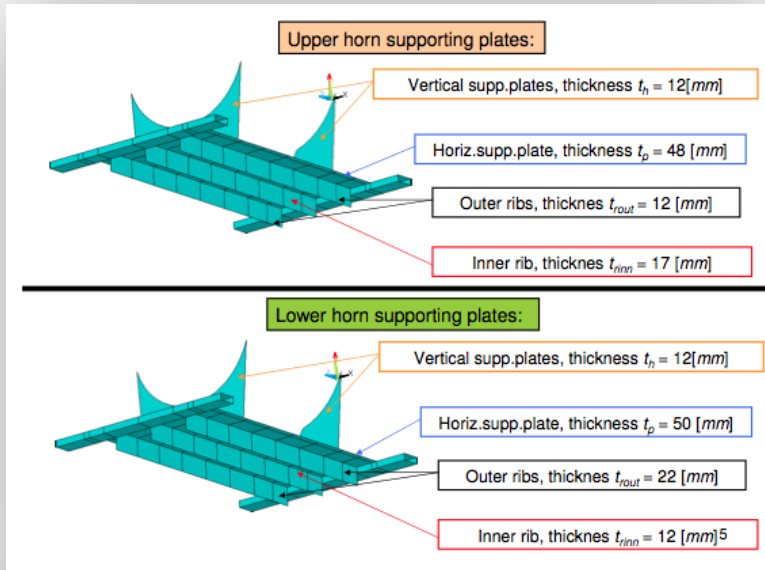
L = 7.1 m
H, W = 5.4 m



iron collimator for power supply area

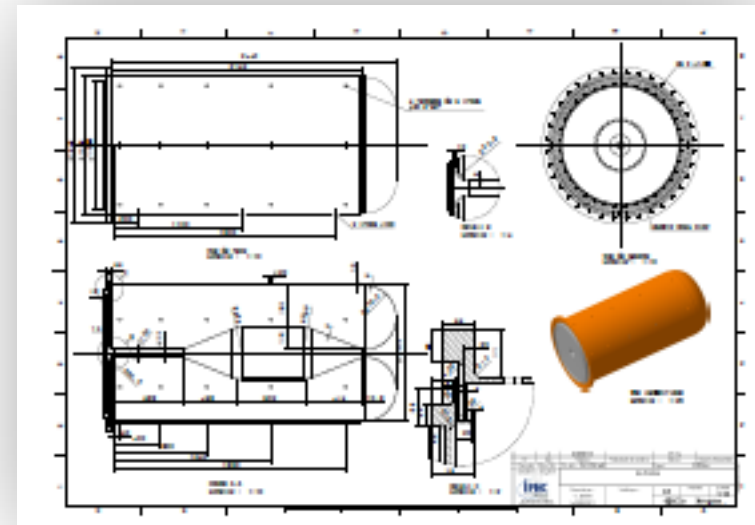
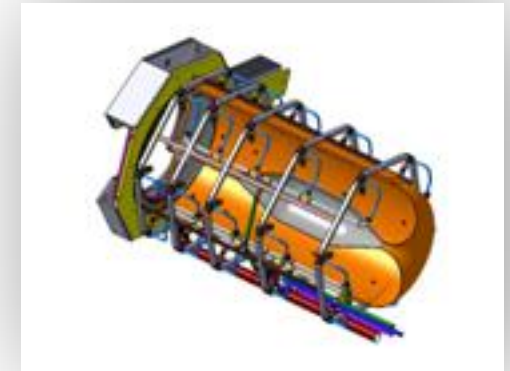
power distributions @ 4 MW

Four-horn support



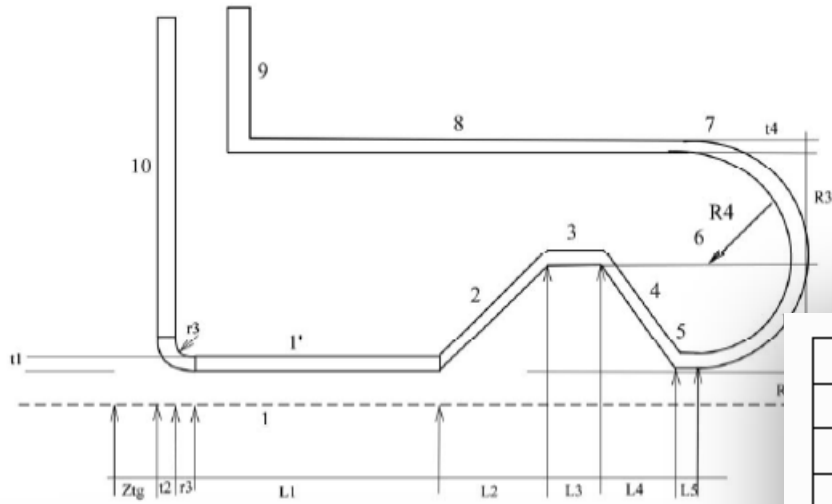
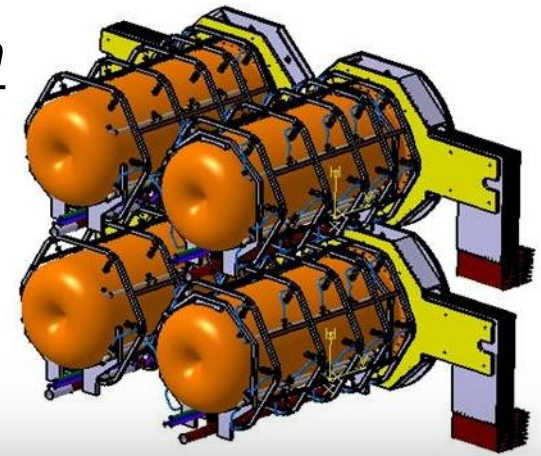
conclusions

- Al 6061 T6 alloy for radiation, reliability and cost
- convex shape defined for optimum physics
- low stress on inner conductor when uniform cooling is applied < 30 MPa
- horn lifetime > 10^8 cycles (1 year)
highly conservative
- support designed
- power supply & cooling R&D needed



Thank you

4-horn system for power accommodation



Parameters	value [mm]
L_1, L_2, L_3, L_4, L_5	589, 468, 603, 475, 10.8
t_1, t_2, t_3, t_4	3, 10, 3, 10
r_1, r_2	108
r_3	50.8
R^{tg}	12
L^{tg}	780
z^{tg}	68
R_2, R_3, R_4	191, 359, 272
R_1 non integrated	30

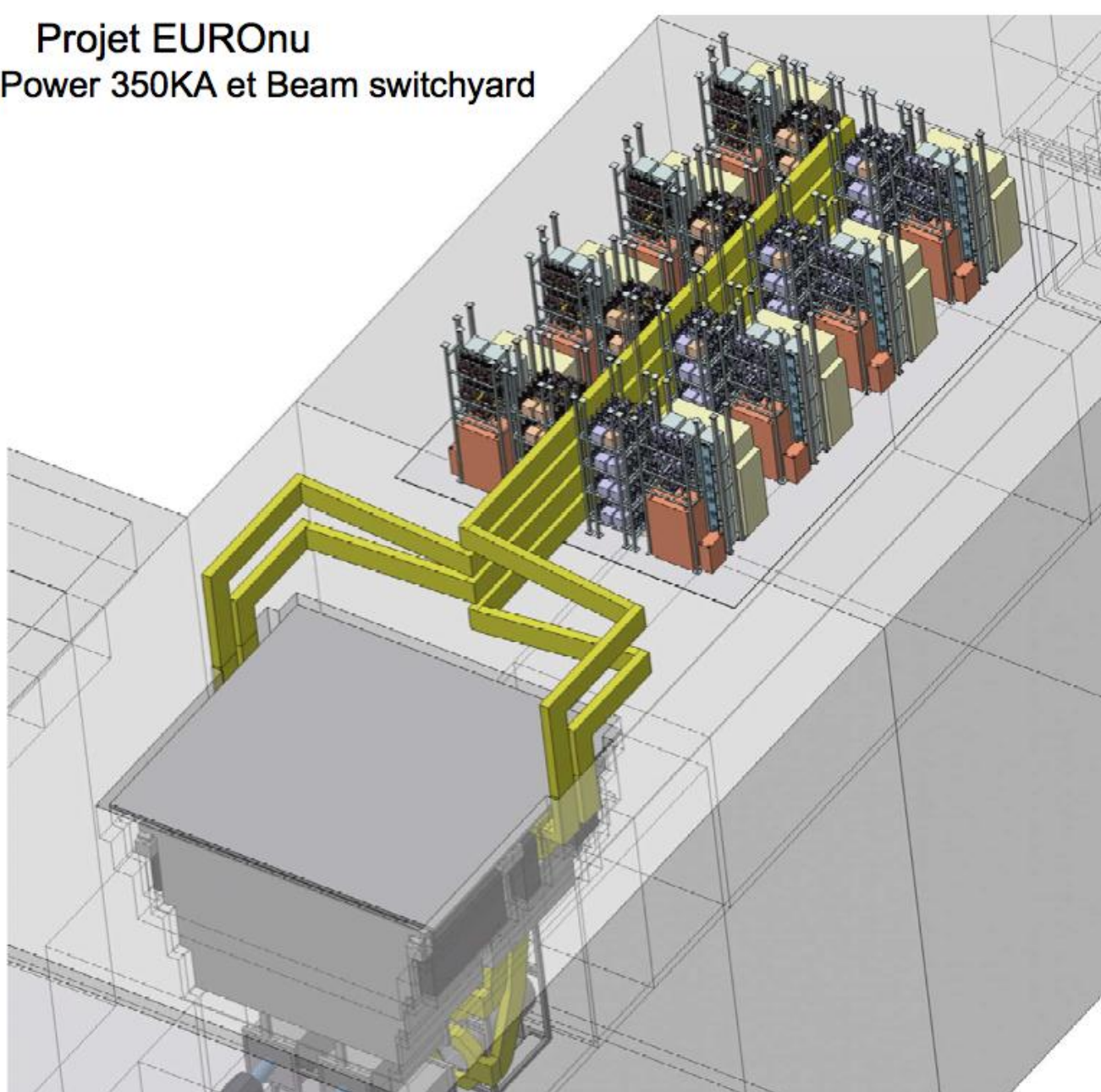
Table 1: Horn geometric parameters.

Parameters	Range	Reference value
Beam Power P_{beam} [MW]	-	4
Energy per pulse [kJ]	-	80
Kinetic energy of protons [GeV]	-	4.5
Number of pulse in 1s	-	50
Number of protons per pulse	-	1.11×10^{14}
Number of bunch per pulse	-	6
Number of protons per bunch	-	1.85×10^{13}
bunch duration [ns]	-	120
Energy per bunch [kJ]	-	13.33
Power for each bunch [GW]	-	111
repetition rate per horn [Hz]	-	12.5 (16.6)
Power per horn [MW]	1 ... 1.3	1.4
Peak Current I_0 [kA]	300 ... 350	350
Beam width σ [mm]	-	4
Current frequency per horn [Hz]	-	12.5 (16.6)

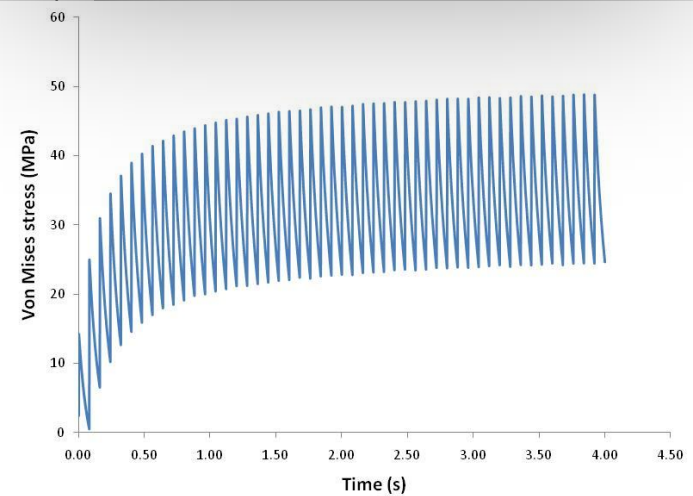
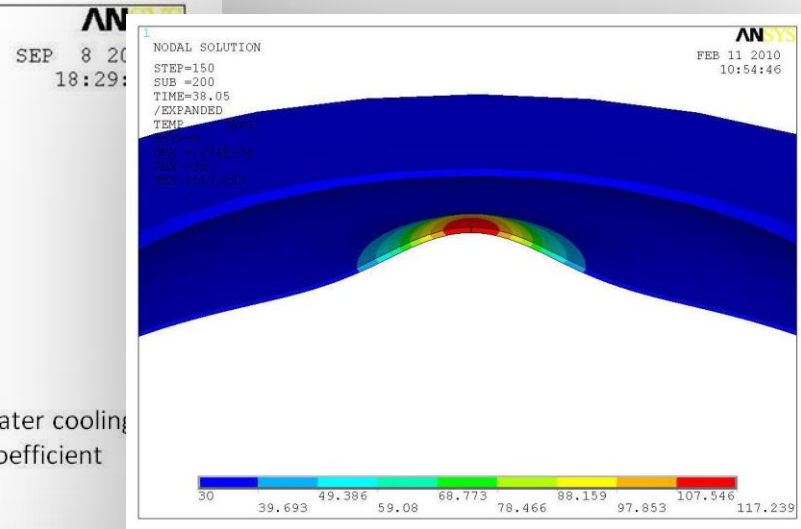
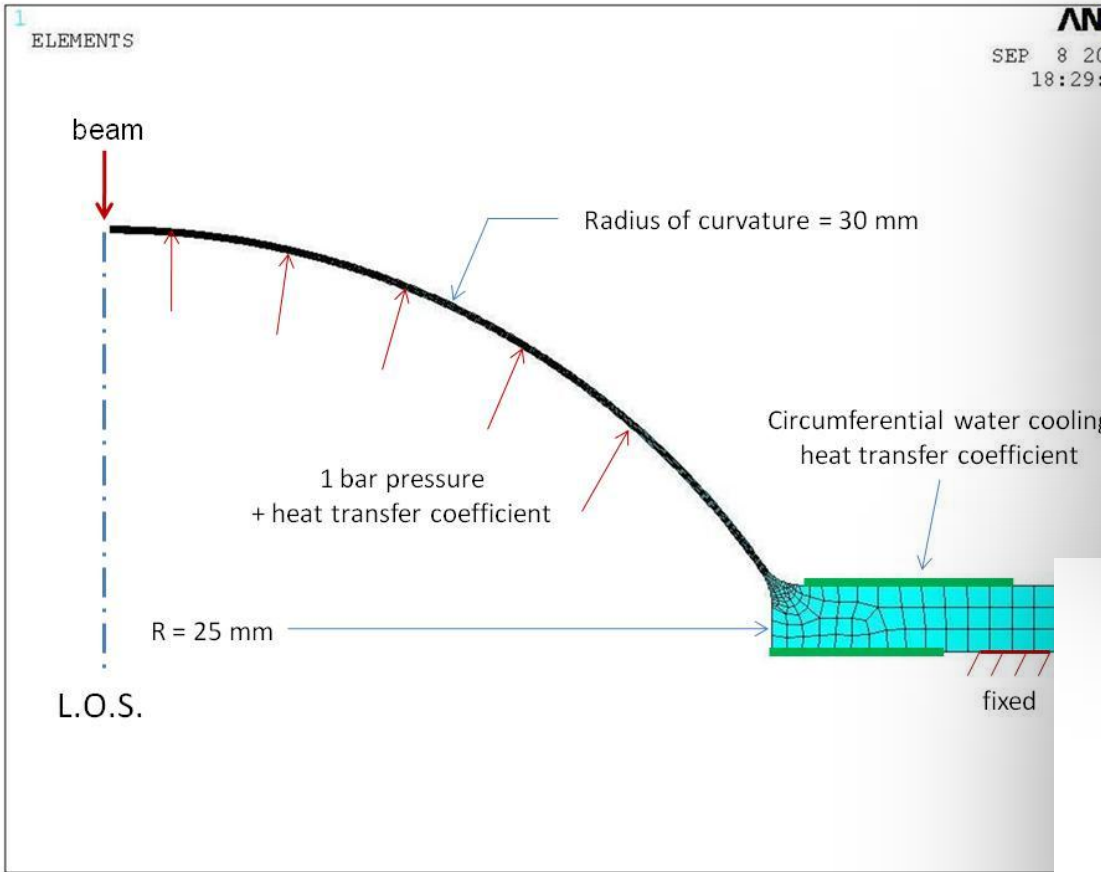
Table 2: Beam and horn parameters.

Projet EUROnu

Intégration Power 350KA et Beam switchyard



beam window



0.25 mm thick beryllium window
Circumferentially water cooled (assumes 2000 W/m²K)
Max temp ~ 180 °C Max stress ~ 50 MPa
(109°C and 39 MPa using He cooling)

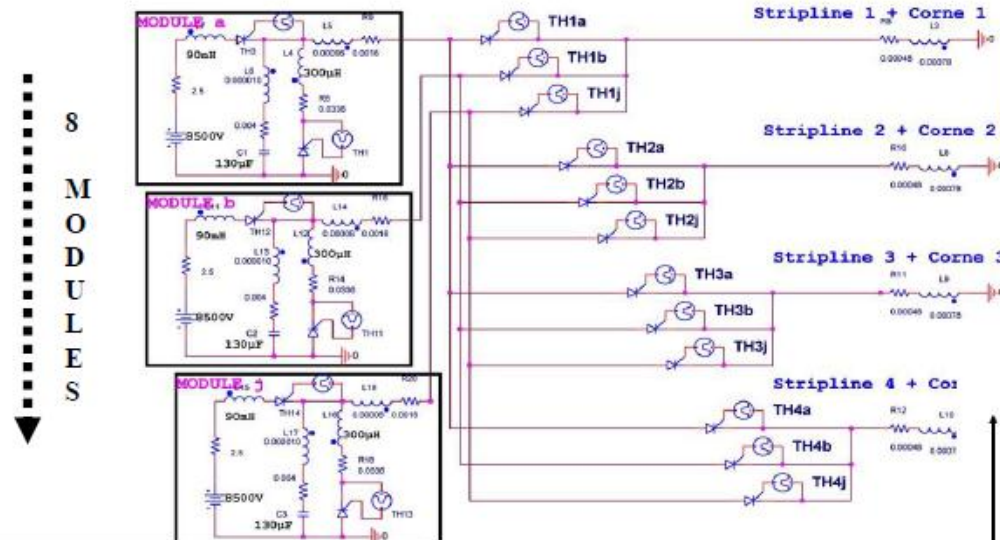
feasible

Matt Rooney/RAL

Power Supply



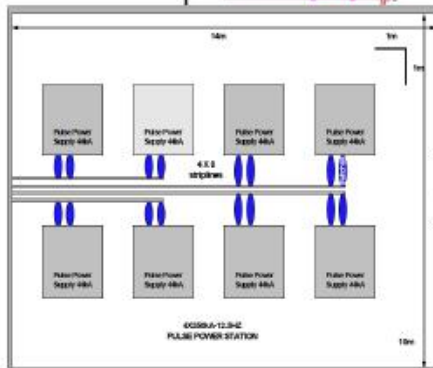
Power Supply for horn pulsing (another challenge)



► each MODULE delivers a current of 44kA max at F=50HZ

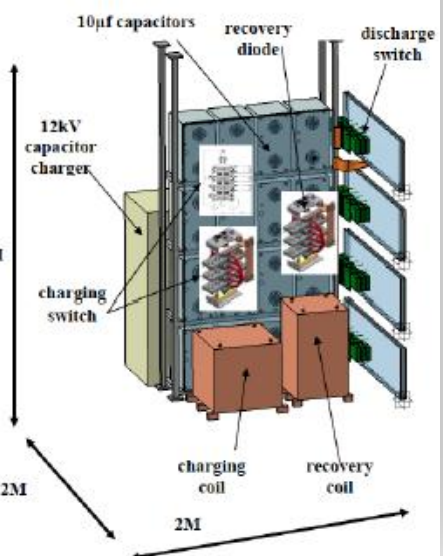
► For each HORN : current of 350kA max at 12.5HZ

8
M
O
D
U
L
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S



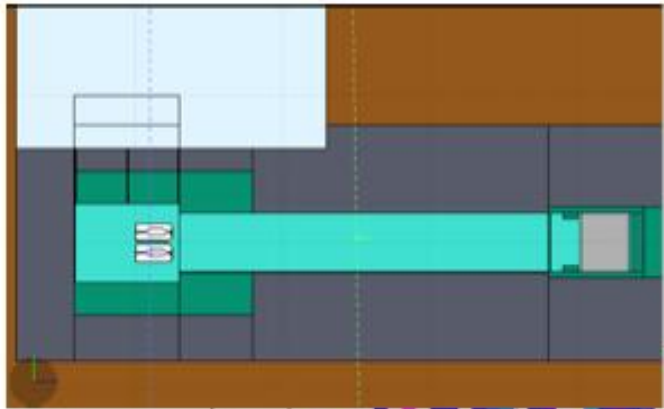
- energy recuperation (>90%) and reinjection
- lifetime > 13 Bcycles (10 years, 200 days/year)

M. Dracos

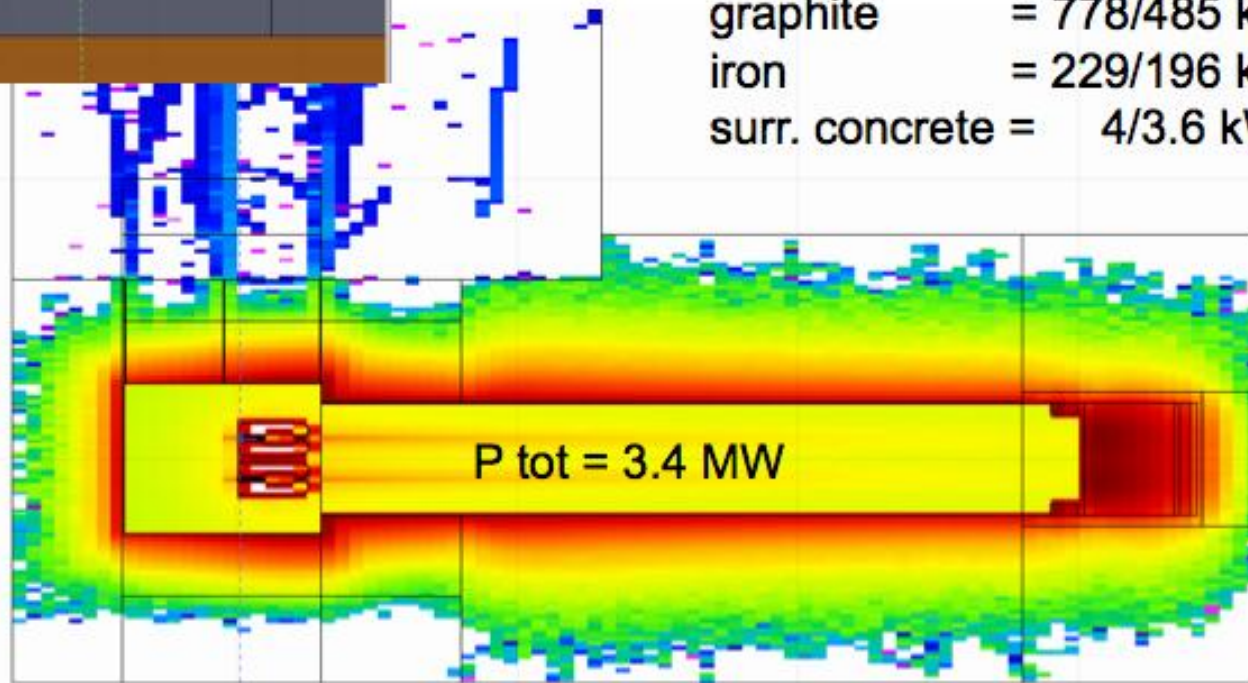


v/anti-v power distribution

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 = 390/392 kW
upstream iron = 610/775 kW
surr. concrete = 485/588 kW

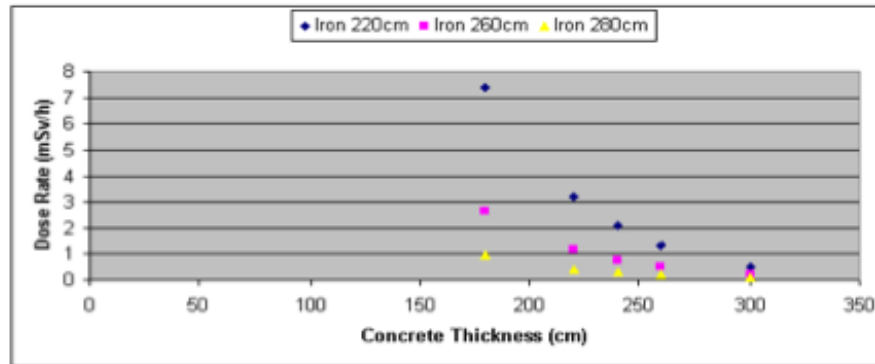


Figure 161: Evolution of the dose equivalent rate for several configuration of iron and concrete.

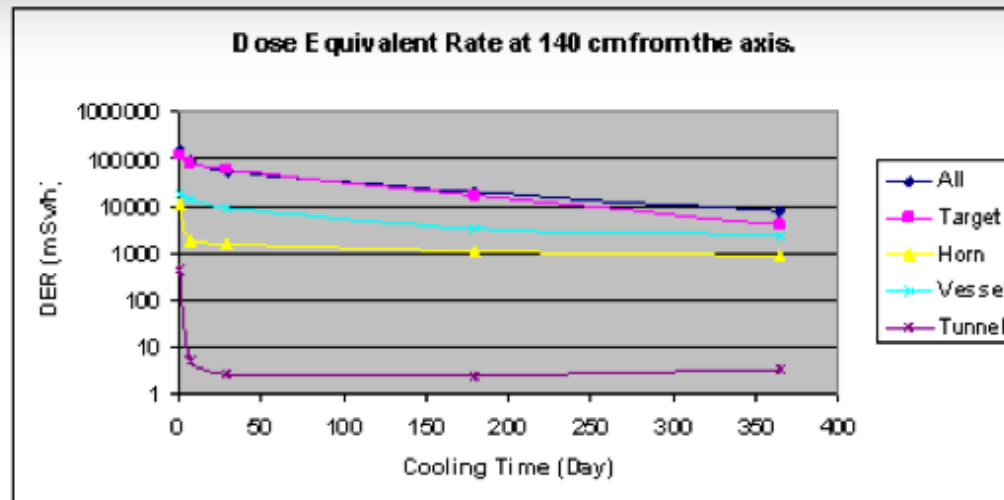


Figure 151: Dose equivalent rate contributions in mSv/h.